Measurements and modeling of land-use specific greenhouse gas emissions from soils in Southern Amazonia

by

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Summary

Conversion of natural vegetation into cattle pastures and croplands results in altered emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Their atmospheric concentration increase is attributed the main driver of climate change. Despite of successful private initiatives, e.g. the Soy Moratorium and the Cattle Agreement, Brazil was ranked the worldwide second largest emitter of GHG from land use change and forestry, and the third largest emitter from agriculture in 2012. N_2O is the major GHG, in particular for the agricultural sector, as its natural emissions are strongly enhanced by human activities (e.g. fertilization and land use changes). Given denitrification the main process for N_2O production and its sensitivity to external changes (e.g. precipitation events) makes Brazil particularly predestined for high soil-derived N_2O fluxes.

In this study, we followed a bottom-up approach based on a country-wide literature research, own measurement campaigns, and modeling on the plot and regional scale, in order to quantify the scenario-specific development of GHG emissions from soils in the two Federal States Mato Grosso and Pará. In general, N_2O fluxes from Brazilian soils were found to be low and not particularly dynamic. In addition to that, expected reactions to precipitation events stayed away. These findings emphasized elaborate model simulations in daily time steps too sophisticated for regional applications. Hence, an extrapolation approach was used to first estimate the influence of four different land use scenarios (alternative futures) on GHG emissions and then set up mitigation strategies for Southern Amazonia. The results suggested intensification of agricultural areas (mainly cattle pastures) and, consequently, avoided deforestation essential for GHG mitigation.

The outcomes of this study provide a very good basis for (a) further research on the understanding of underlying processes causing low N_2O fluxes from Brazilian soils and (b) political attempts to avoid new deforestation and keep GHG emissions low.

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List of Abbreviations

CANDY	Carbon And Nitrogen DYnamics
C_{org}	organic carbon
CH_4	methane
C:N	carbon-to-nitrogen ratio
CO_2	carbon dioxide
CO_2-eq	CO_2-equivalent
DDC	DailyDayCent
DNDC	DeNitrification and DeComposition
EF	emission factor
GHG	greenhouse gase
GIS	geoinformation system
GWP	global warming potential
HIP	Hole-In-the-Pipe model
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
LOFIT	lack of fit
LPJmL	Lund-Potsdam-Jena managed Land
LT	lifetime
LU	livestock units
LULCC	land use and land cover change
MONICA	Model of Nitrogen and Carbon dynamics in Agro-ecosystems
N_2	atmospheric nitrogen
N_2O	nitrous oxide
NCDC	National Climatic Data Center
NH_3^+	ammonium
NO_2^-	nitrite
NO_3^-	nitrate
NO_x	mono-nitrogen oxides
NPP	net primary production
ppb/ppm	parts per billion/million
R^2	coefficient of determination
RE	radiative efficiency
RMSE	root mean squared error

SOC	soil organic carbon
SOM	soil organic matter
SoyM	soy soratorium
STAR	STAtistical Regional Model
TC	technological change
WHO	World Health Organization
WFPS	water-filled pore space

1. Introduction

1.1 Overview

Tropical forests are among the most dynamic of terrestrial biomes (Luizão et al. 1989) and primary production, energy exchanges, and trace gas fluxes are maximized in tropical regions (McElroy & Wofsy 1986). Thus, they can be expected to play a large role in global air chemistry (Crutzen et al. 1985). Brazil holds about one-third of the world’s remaining rainforests, including the majority of the Amazon rainforest (60 %). At the same time the country is under rapid land cover change, particularly by the replacement of natural vegetation by cattle pastures and croplands.

The Brazilian Legal Amazon (Figure 1.1) has experienced large-scale forest conversion since the late 1970s and the deforestation rate was estimated to 5831 km² in 2015 (INPE 2015). This is an increase of 16 % in comparison to 2014 (5012 km²), but a reduction of 79 % in relation to the year 2004 (Figure 1.2).

Figure 1.1: Brazilian States which constitute the Legal Amazon (Amazônia Legal) (green): AC = Acre, AM = Amazonas, AP = Amapá, MA = Maranhão, MT = Mato Grosso, PA = Pará, RO = Rondônia, RR = Roraima, TO = Tocantins (Source: http://tenanbio.blogspot.de/2012/04/amazonia-legal-tem-188-de-seu.html).

Although expansion of cattle pastures is still the main driver of deforestation, the increase of croplands altered deforestation dynamics in the Amazon (Macedo et al. 2012), either by direct conversion of forest to cropland or by replacing existing cattle pastures which moved further into forested areas (Morton et al. 2006, Nepstad et al. 2006). Since 2006, deforestation decreased when soybean traders signed the “Soy Moratorium” (SoyM), agreeing not to purchase soy grown on lands that were deforested after 26 July 2006 in the Brazilian Amazon (Nepstad et al. 2014, Gibbs et al. 2015). In 2009, the largest beef processing companies agreed within the “Cattle Agreement” to exclude those livestock producers from their supply chains who deforested after October 2009. Since both contracts will expire in 2016, it is likely that agricultural land will expand and deforestation will increase again.

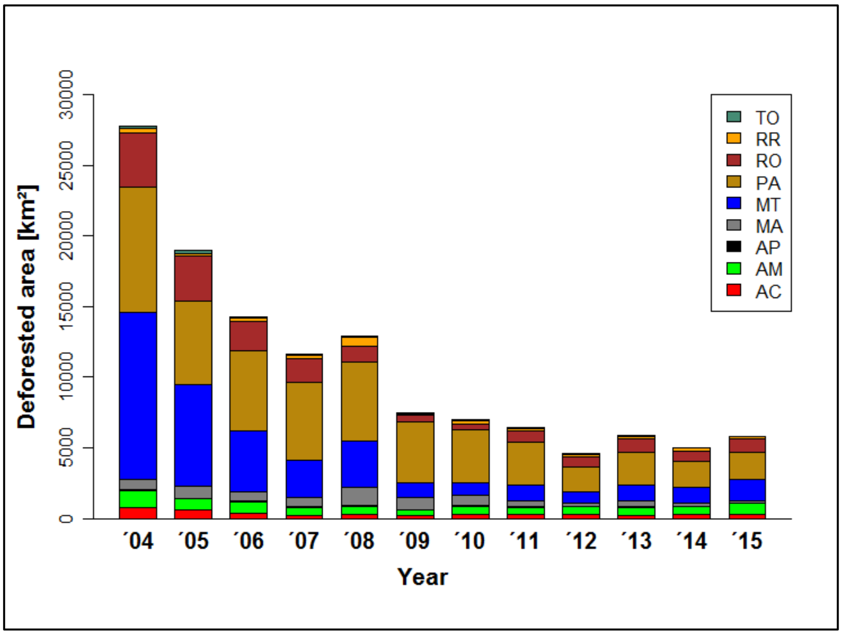

Figure 1.2: Annually deforested area [km²] from 2004 to 2015 in each Federal State included in the Legal Amazon (Source: INPE 2015).

Replacement of natural tropical vegetation by alternative land cover has notable biogeochemical consequences (Erickson & Keller 1997). On the one hand, substantial amounts of greenhouse gases (GHG) are released into the atmosphere during biomass burning (Crutzen et al. 1985). On the other hand, forest conversion alters the structure and functioning of natural ecosystems, which, among others, results in altered emissions of GHG fluxes from the land surface. In 2012, Brazil was ranked the second largest GHG emitter by land use change and forestry, and the third largest emitter by agriculture (FAO 2014) worldwide.

The Intergovernmental Panel on Climate Change (IPCC) attributes the concentration increase of the GHG carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere as the main driver of climate change (Ciais et al. 2013). Their concentrations were 391 ppm (CO_2), 1803 ppb (CH_4), and 324 ppb (N_2O) in 2011 and therewith exceeded the pre-industrial levels by about 40, 150, and 20 %, respectively (see Box 1.1). The reason commonly given are anthropogenic emissions resulting from burning of fossil fuels, but also from land use management (particularly agriculture), and land use changes. All three gases contribute to the current radiative forcing (Syakila & Kroeze 2011), but N_2O is also the major source of nitrogen oxides ($NO_x = NO + NO_2$), which have been shown to catalytically destroy ozone (Johnston 1971, Ravishankara et al. 2009). N_2O has an atmospheric lifetime of 121 years (Myhre et al. 2013) and its Global Warming Potential (GWP) - relative to CO_2 - is about 298 over a time horizon of 100 years (Forster et al. 2007).

70 % of the natural and anthropogenic N_2O production and exchange to the atmosphere take place in the soil (IPCC 1995) and particularly soils under natural vegetation represent the main natural source of N_2O worldwide (Denman et al. 2007, Signor & Cerri 2013) (Table 1.1). Anthropogenic N_2O fluxes from soil commonly derive from input of nitrogen fertilizers into agricultural systems (Mosier 1998) and resulting emissions range from 1.7 to 4.8 Tg

N_2O-N yr^{-1} (Ciais et al. 2013). The IPCC assumes the relationship between N fertilizer and N_2O emissions to be linear, implying that 1 kg of applied N fertilizer (1 %) is lost as N_2O-N.

Table 1.1: Global sources of N_2O [Tg N yr^{-1}] for the 1990s (adapted from Denman et al. 2007).

Source	**N_2O**
Natural sources	
Soils under natural vegetation	6.6
Oceans	3.8
Atmospheric chemistry	0.6
Natural total	**11.0**
Anthropogenic sources	
Fossil fuel combustion & industrial processes	0.7
Agriculture	2.8
Biomass & biofuel burning	0.7
Human excreta	0.2
Rivers, estuaries, coastal zones	1.7
Atmospheric deposition	0.6
Anthropogenic total	**6.7**
Total sources	**17.7**

Generally, both natural and anthropogenic N_2O production arises from microbial processes (Mosier 1998), as part of the nitrogen cycle. During nitrification ammonia (NH_3^+) is oxidized to first nitrite (NO_2^-) and further to nitrate (NO_3^-), while NO_3^- is reduced to NO_2^- and then atmospheric nitrogen (N_2) during denitrification (Figure 1.3).

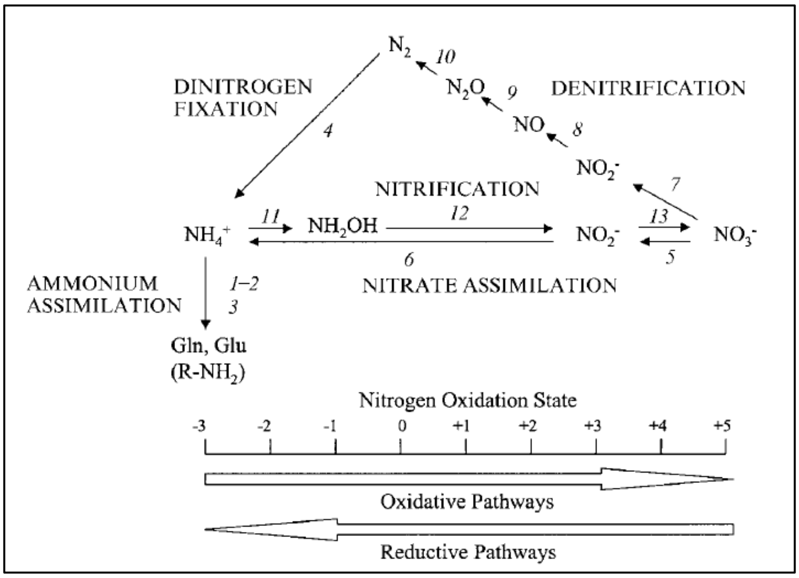

Figure 1.3: The biological nitrogen cycle. The different nitrogen compounds are arranged according to their oxidation states. The arrows indicate the main reductive or oxidative pathways. The numbers stand for the enzymes that are involved in the different pathways. For further details see Cabello et al. (2004).

It has been shown that N_2O is produced within the reductive process in which NH_4^+ oxidizing bacteria use NO_2^- as electron acceptor, as soon as oxygen is limiting (Poth & Focht 1985). However, denitrification was found to be the dominant source for N_2O production (Davidson 1992) and higher rates can be expected under hypoxic conditions. While nitrification can be acquired a relatively constant process in many ecosystems, denitrification rates have a high spatial and temporal variability and exact quantification of N_2O production rates is challenging (Folorunso & Rolston 1984). Nevertheless, understanding the process of denitrification is mandatory for predictions of any nitrogen (N) gas fluxes (Firestone & Davidson 1989).

The schematic “hole-in-the-pipe” model (HIP) of Firestone & Davidson (1989) provides a good basis for the process description, as it explains the reactions of N trace gases through the processes of microbiological production and consumption (Figure 1.4). Therewith the model addresses factors that (1) control nitrification and denitrification - shown as the rate of nitrogen flowing through the process pipes - and (2) control the partitioning of the N gases – indicated by the size of the holes in the pipes through which N_2O and NO escape. The leakage of N_2O and NO through the holes, and consequently the emission rate, is primarily determined by soil water content, as this appears the most important controller of N fluxes (N_2, N_2O, and NO) (Davidson et al. 1993). It directly affects soil aeration, which in turn has an effect on the soil microbial processes of N_2O production and consumption (Davidson et al. 2004).

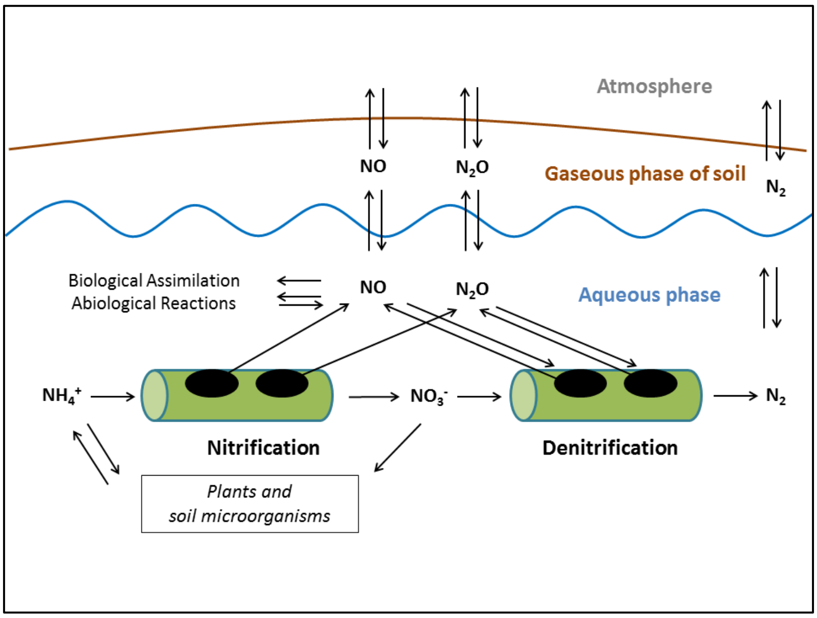

Figure 1.4: Schematic diagram of the conceptual “hole-in-the-pipe” model (Firestone & Davidson 1989). Regulating factors for soil N_2O and NO emissions are a) the amount of N available in the system; this is symbolized by the amount of N flowing through the pipes and affects the total emissions of NO and N_2O; b) soil moisture (or other factors); this is symbolized by the relative sizes of the holes in the pipes through which NO and N_2O “leak” and affect the ratio of N_2O:NO emissions (adapted from Davidson et al. 2000).

The idea of the HIP model was supported by Veldkamp et al. (1998) who found a relationship between NO and N_2O losses and water-filled pore space (WFPS). By that they showed that NO is primarily produced by nitrification and N_2O by denitrification (Figure 1.5). At the same time the authors highlight the importance of environmental factors, particularly the soil moisture regime, for calculating N_2O and NO emissions, rather than fertilizer composition.

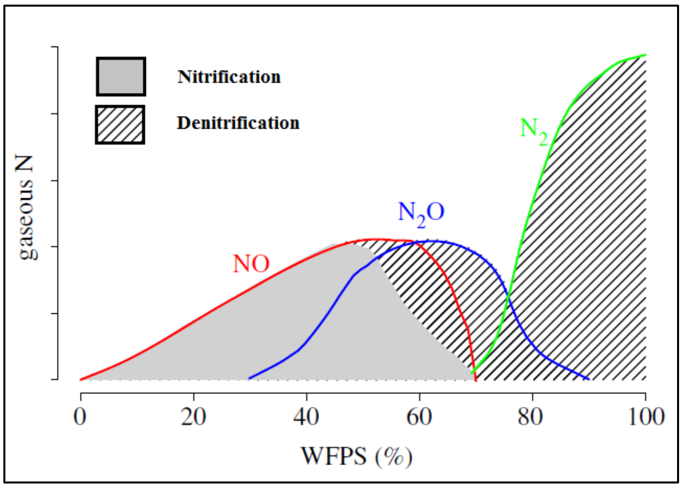

Figure 1.5: Relationship between water-filled pore space (WFPS) and relative fluxes of N gases (NO, N_2O and N_2) from nitrification and denitrification (Pilegaard 2013). While NO emissions occur from nitrification at 30 – 60 % WFPS, highest N_2O fluxes can be expected at 50 – 90 % WFPS when denitrification dominates. Above that, oxygen is strongly limited so that N_2O is consumed and N_2 becomes the main end product (Bouwman 1998).

Tropical forest areas are usually characterized by high temperatures and precipitation amounts, which lead to fast turnover rates and high soil moistures and hence accelerate both biotic and abiotic processes. While nitrogen is frequently limiting primary production in temperate and boreal ecosystems, in most tropical forests the biomass is relatively enriched in N (Vitousek & Sandford 1986). As this nutrient is often in excess and neither plants nor microorganisms actively retain N within their biomass, tropical ecosystems have a higher potential for N losses in the form of gases or leachate compared with temperate and boreal ecosystems (Vitousek & Matson 1992). Tropical forest soils are considered an important source for N_2O emissions (e.g. Keller et al. 1983, Matson & Vitousek 1987) and the global annual production is estimated to be more than 3 Tg N_2O-N annually (Matson & Vitousek 1990, Breuer et al. 2000). Reported fluxes are mostly higher than from temperate and boreal forests (Keller et al. 1983, Livingston et al. 1988). According to Keller et al. (1983), the high N_2O fluxes from tropical forests are mainly resulting from higher rates of denitrification. In contrast to rainforests, N_2O emissions from soils under cerrado vegetation have been observed to be low and even often below the detection limit (Verchot et al. 1999, Davidson et al. 2001). The cerrado biome includes semideciduous forests (Cerradão), tree and scrub woodland, and open tropical grassland (savanna) (Eiten 1972, Anderson & Poth 1998) and covers a fourth of the whole Brazil (Figure 1.6). Soils under this vegetation are usually characterized by a coarser texture and well-drained structure compared to rainforest soils. These patterns prevent the formation of hypoxic conditions in the soil and thus emissions from denitrification are rather uncommon (Davidson et al. 2001).

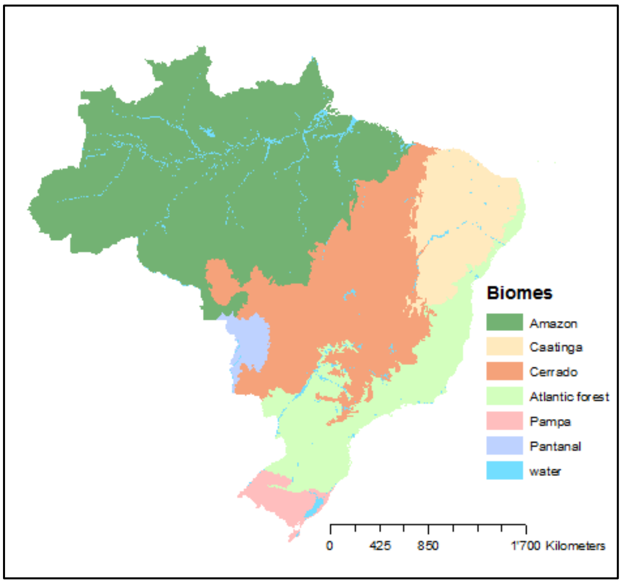

Figure 1.6: Distribution of Brazil according to six ecological zones (biomes). The largest biome is the Amazon, which covers approximately 49 % of the whole Brazil, followed by the Cerrado (24 %), the Atlantic forest (13 %), the Caatinga (10 %), and the Pampa and Pantanal, respectively (2 % each) (IBGE 2013).

Denitrification rates are strongly affected by deforestation, as has been shown by measurements of Robertson & Tiedje (1988) in the wet Atlantic lowlands of Costa Rica. They found high rates in primary forest and early successional sites (several weeks after clearance) compared to mid-successional sites (2 to 25 years after clearance). According to their findings, they highlighted the importance of denitrification as a major route of N losses from recently cleared and primary forest soils. Generally, the removal of plants as a sink for nutrients causes increased availability in soils (Bormans & Likens 1979), resulting in temporarily increased emissions of NO and N_2O (e.g. Keller & Matson 1994, Davidson et al. 2001). Though, cattle pastures, which immediately replace the natural forest vegetation, were found to suffer from decreasing soil N with increasing ages (years after conversion) (e.g. Verchot et al. 1999, Davidson et al. 2000, Erickson et al. 2001, Melillo et al. 2001, Neill et al. 2005), mainly because of decreasing mineralization and nitrification. Consequently, the higher N_2O emissions after the clear-cut follow a decreasing trend as the pastures age.

Most of the studies mentioned above report on measurements that have been conducted either sporadically or at rather large intervals (weeks or months) throughout the year. At the same time, most studies are based on data collected with surface chambers, which are well adapted to resolving topographic effects (Grant & Pattey 2003), but fix the observations to carefully or randomly selected plots. N_2O is known for its large temporal and spatial variability and its sensitive nature makes it particularly susceptible to external changes, e.g. frost-thaw cycles or precipitation events. Thus, decisive emission peaks will likely be missed. According to Grant & Pattey (2003), measurements based on low temporal resolution and small spatial scales are of limited value for long-term estimations of N_2O emissions at the landscape scale (e.g. Blackmer et al. 1982, Bouwman 1996, Bouwman et al. 2002). To overcome this, the authors suggest the usage of mathematical models which include current knowledge on N transformation and transport processes controlling N_2O emissions. Groffman et al. (2009) describe models as promising tools for evaluating the importance of external environmental changes, such as frost-thaw and dry-wet cycles on N_2O fluxes. In this context they highlight the need for the detection of the brief periods of high denitrification and thus, high emission, so called hot moments (McClain et al. 2003). The Amazon region underlies more or less pronounced dry and wet seasons and emission peaks are likely to occur during the transitional periods and wet season, respectively (e.g. Vitousek et al. 1989, Davidson et al. 2004). Measurements within these time periods will likely help to capture decisive emission peaks, further improve process understanding, and thus calibrate models to site-specific conditions.

So far, many studies solely respect the best possible adaptation of observed N_2O fluxes. Influencing variables, such as soil moisture, have either not been measured or are solely used for model comparison (e.g. Abdalla et al. 2009, Abdalla et al. 2010), but have been neglected during the optimization process. However, most process-oriented models simulating N_2O emissions are designed such that soil moisture has a large influence on N gas fluxes, since it at least influences the rate of decomposition of soil organic matter and therewith the rate of N mineralization and the availability of substrate for nitrifiers and denitrifiers. Consequently, successful simulation of N_2O emissions is likely dependent on the successful reproduction of observed soil moisture, and the appropriateness of model-internal linkage between simulated soil moisture, denitrification, and finally N_2O fluxes (Frolking et al. 1998). Since hydraulic functions are important for simulation of soil biogeochemical processes, their derivation is challenging for sites without detailed information about soil hydraulic parameters, such as field capacity, permanent wilting point, and hydraulic conductivity (Frolking et al. 1998). For site-specific purposes, adaptation of the models to observed soil moisture is likely the most obvious proceeding for successful description of N_2O emissions.

The areas within the Amazon region are mostly not easy to access and measurements are rather difficult to perform. However, on the larger scale and with regard to national budgeting, even remote areas have to be taken into account. Against the background of lack of time and financing, models can be considered as planning tools for measurement campaigns and specify particular timeframes important for N_2O fluxes. Furthermore, in order to frame policies that aim to reduce land-use related GHG, analysis of future land use trajectories using land use models is an essential element. Here, the combination of models and scenario techniques is a powerful tool to estimate the impacts of future land use and land cover changes (Lampin et al. 2000) and determine mitigation strategies in terms of climate change.

Box 1.1: The three main greenhouse gases (GHG) and their Global Warming Potentials (GWP)

The Global Warming Potential (GWP) is a metric that integrates the radiative efficiencies (RE) of various substances and their lifetimes (LT) in the atmosphere over a particular time horizon and relative to the reference gas carbon dioxide (CO_2) (IPCC 2013) (Table 1.2). CO_2, methane (CH_4), and nitrous oxide (N_2O) belong to the most influential atmospheric GHG (Forster et al. 2007) and their anthropogenic concentration increase (Figure 1.7) is extremely likely to account for more than half of the observed increase in global average surface temperature from 1951 to 2010 (0.5 – 1.3 °C; IPCC 2013).

Table 1.2: Lifetimes (LT), radiative efficiencies (RE), Global Warming Potentials (GWP) (IPCC 2007), and atmospheric concentrations before 1750 and in 2011 for the GHG CO_2, CH_4, and N_2O (Myhre et al. 2013).

Gas name	Chemical formula	LT [years]	RE [W m^{-2} ppb^{-1}]	GWP [100 years]	Atmospheric concentration [ppm]	
					before 1750	**2011**
Carbon dioxide	CO_2	variable	1.4 x 10^{-5}	1	280.0	391.0
Methane	CH_4	12	3.7 x 10^{-4}	25	0.700	1.803
Nitrous oxide	N_2O	114	3.03 x 10^{-3}	298	0.270	0.324

CO_2 is an important component of the global carbon (C) cycle and huge amounts of C are stored in vegetation living biomass, dead organic matter in litter and soils, as well as in wetland and permafrost soils (Ciais et al. 2013). It is removed from the atmosphere by plant photosynthesis and the C is fixed into plant litter, tissues, and in the soil. Soils are the second largest global C pool after oceans and followed by the atmosphere, and plant biomass. Since the beginning of the industrial era, burning of fossil fuels and changes in land use (e.g. deforestation) are the major sources of anthropogenic CO_2.

CH_4 is produced by methanogenic organisms in strictly anaerobic (without oxygen) environments, such as wetlands, flooded rice fields and wet forests. While wetlands have been found the largest natural source for CH_4 emissions, oxidation by OH in the troposphere, biological oxidation in drier soil, and the loss to the stratosphere are sinks for CH_4 (Denman et al. 2007). Although natural sources accounted for 91 % of the global annual pre-industrial CH_4 emissions, the present-day CH_4 budget is dominated by anthropogenic emissions, accounting for more than 60 % of the total global budget (Denman et al. 2007).

N_2O is naturally produced under both aerobic (nitrification) and anaerobic (denitrification) conditions. Soils under natural vegetation, e.g. forests, are the major natural sources of atmospheric N_2O, while agriculture represents the main anthropogenic source (Table 1.1). Since pre-industrial times, atmospheric N_2O concentrations increased by a factor of 1.2 (IPCC 2013).

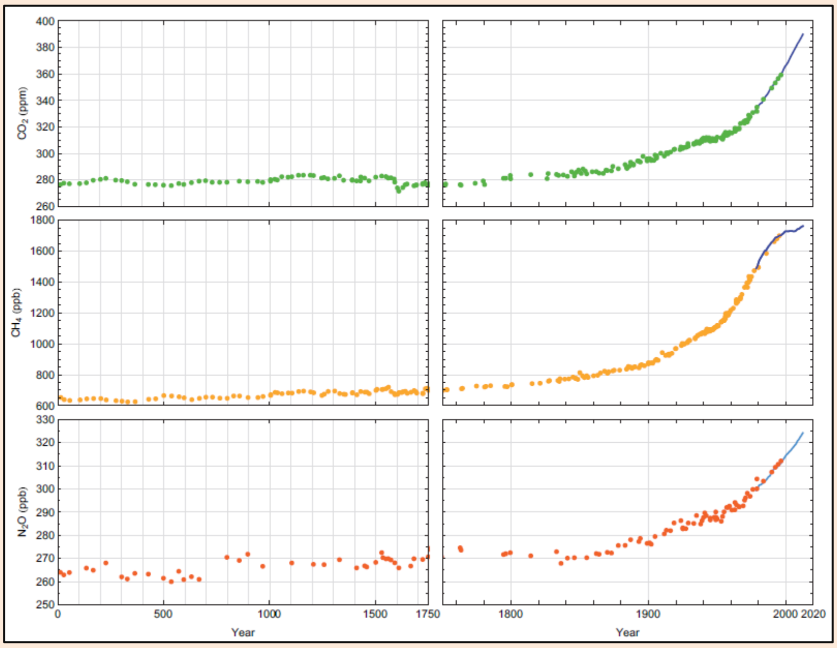

Figure 1.7: Atmospheric CO_2, CH_4, and N_2O concentrations history from the years 0 to 1750 (left) and over the industrial era (right) (Ciais et al. 2013).

1.2 Objectives

The present PhD thesis was conducted as part of the research project “Carbiocial – Carbon optimized land management strategies for Southern Amazonia“, funded by the Federal Ministry for Education and Research (BMBF). The project adresses the above mentioned land use issue in Southern Amazonia, which is a hotspot of global change research. In order to identify possible starting points for essential local and regional changes, the project focusses on soil, water, climate, agro-economics, society, and politics. By creating reliable linkages between local and regional land use patterns, Carbiocial improves the data basis for future political decisions and sets up scenarios for simulation of future land use development.

This thesis is based on the work of subproject 02 (SP02), which aims to assess GHG emissions from soils under changing land use and management in a very dynamic region of Southern Amazonia.

In particular, the objectives of this study were to (a) extract patterns of direct N_2O emissions from soils of different Brazilian ecosystems, (b) assess the application of mechanistic models as prediction tools to Brazilian conditions, and (c) estimate impacts of future land use scenarios on GHG emissions in order to point out possible future pathways for Southern Amazonia.

These objectives have been worked out within four scientific articles which build up upon each other. The two recent studies (*chapters 4* and *5*) derive from collaborations with other subprojects of the Carbiocial project (co-authorship) (Figure 1.8).

Within the *chapters 2 – 5* the following hypotheses were tested:

Chapter 2: (1) N_2O emissions from Brazilian soils exceed those reported from European studies, (2) emission levels strongly depend on the land use type, and (3) soil and management properties can serve as indicator for N_2O fluxes.

Chapter 3: (1) emission dynamics are higher during the rainy season when soil moisture rises and denitrification takes place, (2) correct reproduction of observed soil moisture is essential when simulating N_2O emissions, and (3) mechanistic models can be used to identify important time periods for N_2O fluxes.

Chapters 4 and *5*: (1) future land development will have a strong impact on GHG emissions from agricultural soils and (2) agricultural management is an important factor for GHG mitigation strategies.

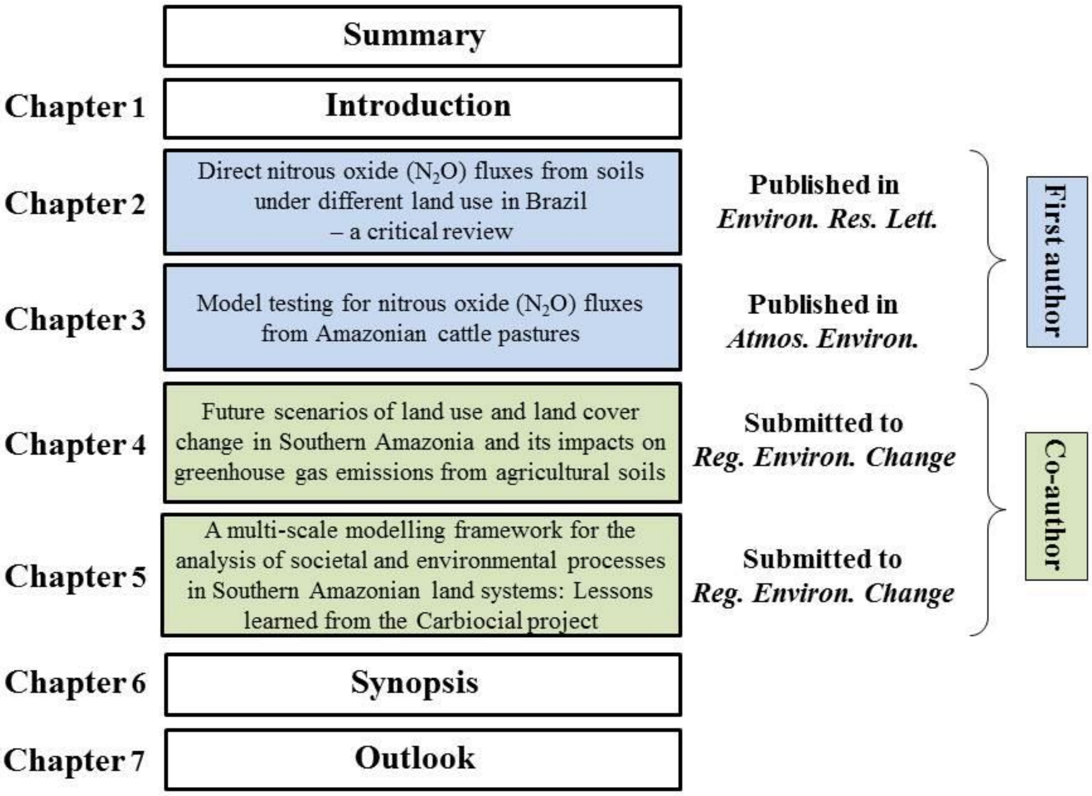

Figure 1.8: Structure of the present thesis. Blue and green filled boxes identify scientific articles under leading and co-authorship, respectively.

1.3 Study Area

The Carbiocial project aims to investigate viable carbon-optimized land management strategies by analyzing carbon turnover, climate, ecosystem functions, and socio-economic processes along Brazil’s Cuiabá-Santarém highway BR-163. This meanwhile widely paved highway primarily serves as export corridor for soybeans from Northern Mato Grosso via the Amazon River. Reconstruction and pavement accelerated forest loss in the area in the form of deforestation and illegal logging (Fearnside 2007). Furthermore, it allows already-established agriculture in the South to access potential agricultural areas in the North (Gerold et al. 2014). The three investigation areas of the project are located in Central and Northern Mato Grosso (Campo Verde and Sinop), as well as in Southern Pará (Novo Progresso), which all belong to the “Deforestation Arc”. These site selections represent a gradient, not only in a climatological sense (semi-humid tropical savanna climate in Cuiabá to humid tropical rainforest climate in Novo Progresso (Moreno & Souza 2005)), but also in land use (Figure 1.9). While colonization in Central Mato Grosso started in the 1975 – 1990 with cattle and soy, the soybean sector expanded to Northern Mato Grosso in 1990, and a strong human influence has already reached Southern Pará (mainly cattle pastures, but already first soy trials).

The measurement data presented in *chapter 2* derive from three cattle pastures near Novo Progresso.

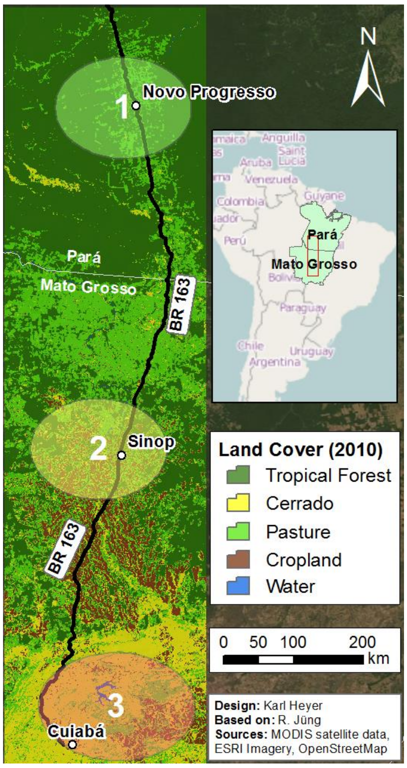

Figure 1.9: Investigation areas along the BR-163 in the Federal States of Pará and Mato Grosso: 1. Novo Progresso, 2. Sinop, and 3. Cuiabá.

References

Abdalla M, Wattenbach M, Smith P, Ambus P, Jones M, and Williams M 2009 Application of the DNDC model to predict emissions of N_2O from Irish agriculture *Geoderma* **151** 327 – 337.

Abdalla M, Jones M, Yeluripati J, Smith P, Burke J, and Williams M 2010 Testing DayCent and DNDC model simulations of N_2O fluxes and assessing the impact of climate change on the gas flux and biomass production from a humid pasture *Atmos. Environ.* **44** 2961 – 2970.

Anderson IC and Poth MA 1998 Control of Fluxes of Trace Gases from Brazilian Cerrado Soils *J. Environ. Qual.* **27** 1117 – 1124.

Barona E, Ramankutty N, Hyman G, and Coomes OT 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon *Environ. Res. Lett.* **5** (2010) 024002, doi: 10.1088/1748-9326/5/2/024002.

Blackmer AM, Robbins SG, and Bremner, JM 1982 Diurnal Variability in Rate of Emission of Nitrous Oxide from Soils *Soil Sci. Soc. Am. J.* **46** 937 – 942.

Bouwman AF 1996 Direct emission of nitrous oxide from agricultural soils *Nutr. Cycl. Agroecosys.* **46** 53 – 70.

Bouwman AF 1998 Nitrogen oxides and tropical agriculture *Nature* **392** 866 – 867.

Bouwman AF, Boumans LJM, and Batjes NH 2002 Emissions of N_2O and NO from fertilized fields: Summary of available measurement data *Global Biogeochem. Cycles* 16 (4) 1058, doi:10.1029/2001GB001811.

Breuer L, Papen H, and Butterbach-Bahl K 2000 N_2O emission from tropical forest soils of Australia *J. Geophys. Res.* **105** (D21) 26,353 – 26,367.

Cabello P, Roldán MD, and Moreno-Vivián C 2004 Nitrate reduction and the nitrogen cycle in archaea *Microbiology* 150 3527 – 3546.

Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M, Jones C, Le Quéré C, Myneni RB, Piao S, and Thornton P 2013 Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, TF, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex and PM Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Crutzen PJ, Delany AC, Greenberg J, Haagenson P, Heidt L, Lueb R, Pollock W, Seiler W, Wartburg A, and Zimmerman P 1985 Tropospheric Chemical Composition Measurements in Brazil During the Dry Season *J. Atmos. Chem.* **2** 233 – 256.

Davidson EA 1993 Sources of Nitric Oxide and Nitrous Oxide following Wetting of Dry Soil *Soil Sci. Soc. Am. J.* **56** 95 – 102.

Davidson EA, Matson PA, Vitousek PM, Riley R, Dunkin K, García-Méndez G, and Maass JM 1993 Processes regulating soil emissions of NO and N_2O in a seasonally dry tropical forest *Ecology* **74** (1) 130 – 139.

Davidson EA, Keller M, Erickson HE, Verchot LV, and Veldkamp E 2000 Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides *BioScience* **50** (8) 667 – 680.

Davidson EA, Bustamante MMC, and Pinto A de Siqueira 2001 Emissions of Nitrous Oxide and Nitric Oxide from Soils of Native and Exotic Ecosystems of the Amazon and Cerrado Regions of Brazil *The Scientific World* **1** (S2) 312 – 319, doi: 10.1100/tsw.2001.261.

Davidson EA, Ishida FY, and Nepstad DC 2004 Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest *Global Change Biol.* **10** 718 – 730, doi: 10.1111/j.1529-8817.2003.00762.x.

Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran S, da Silva Dias PL, Wofsy SC, and Zhang X 2007 Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Eiten G 1972. The Cerrado Vegetation of Brazil *Bot. Rev.* **38** (2) 201 – 341.

Erickson HE and Keller M 1997 Tropical land use change and soil emissions of nitrogen oxides *Soil Use Manage.* **13** 278 – 287.

Erickson H, Keller M, and Davidson EA 2001 Nitrogen Oxide Fluxes and Nitrogen Cycling during Postagricultural Succession and Forest Fertilization in the Humid Tropics *Ecosystems* **4** 67 – 84, doi: 10.1007/s100210000060.

Fearnside PM 2007 Brazil's Cuiabá-Santarém (BR-163) Highway: The Environmental Cost of Pavind a Soybean Corridor Through the Amazon *Environ. Manage.* **39** 601 – 614, doi: 10.1007/s00267-006-0149-2.

Firestone MK and Davidson EA 1989 Microbiological Basis of NO and N_2O Production and Consumption in Soil. In: Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere [M.O. Andrae and D. S. Schimel (eds)], pp. 7 – 21. John Wiley & Sons Ltd.

Food and Agriculture Organization (FAO) 2014. FAOSTAT Emissions Database. Obtained from Climate Data Explorer (CAIT). World Resources Institute. Available at: http://cait.wri.org.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, and Van Dorland R 2007 Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Frolking SE, Mosier AR, Ojima DS, Li C, Parton WJ, Potter CS, Priesack E, Stenger R, Haberbosch C, Dörsch P, Flessa H, and Smith KA 1998 Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year-round measurements by four models *Nutr. Cycl. Agroecosys.* **52** 77 – 105.

Gerold G, Jungkunst HF, Wantzen KM, Schönenberg R, Amorim RSS, Couto EG, Madari B, and Hohnwald S (eds) 2014 Interdisciplinary Analysis and Modeling of Carbon-Optimized Land Management Strategies for Southern Amazonia. Carbiocial Status Conference in Cuiabá, October 7 – 8, 2013, pp 181, Universitätsverlag Göttingen. ISBN: 978-3-86395-138-2.

Gibbs HK, Rausch L, Munger J, Schelly I, Morton DC, Noojipady P, Soares-Filho B, Barreto P, Micol L, and Walker NF 2015 Brazil's Soy Moratorium *Science* **347** (6220) 337 – 378, doi: 10.1126/science.aaa0181.

Grant RF and Pattey E 2003 Modelling variability in N_2O emissions from fertilized agricultural fields *Soil Biol. Biochem.* **35** 225 – 243.

Groffman PM, Butterbach-Bahl K, Fulweiler RW, Gold AJ, Morse JL, Stander EK, Tague C, Tonitto C, and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* 93 49 – 77.

Instituto Brasileiro de Geografia e Estatística (IBGE) 2013 Síntese Descrição BIOMAS. Available at: ftp://geoftp.ibge.gov.br/mapas_tematicos/mapas_murais/shapes/

Instituto Nacional de Pesquisas Espaciais (INPE) 2015 Coordenação-Geral de Observação da Terra – OBT. Projecto Prodes – Monitoramento da Floresta Amazônica Brasileira por Satélite. Available at: http://www.obt.inpe.br/prodes/index.php.

Intergovernmental Panel on Climate Change (IPCC) 1995 Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. In: Houghton JT (ed) Climate Change (1994). Published for the IPCC. Cambridge University Press, Cambridge, 337 pp.

Intergovernmental Panel on Climate Change (IPCC) 2007.Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, and HL Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Intergovernmental Panel on Climate Change (IPCC) 2013 Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, D Qin, GK Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, and PM Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Johnston H 1971 Reduction of Stratospheric Ozone by Nitrogen Oxide Catalysts from Supersonic Transport Exhaust *Science* **173** 517 – 522.

Keller M, Gorean TJ, Wofsy SC, Kaplan WA, and Elroy MB 1983 Production of nitrous oxide and consumption of methane by forest soils *Geophys. Res. Lett.* **10** (12) 1156 – 1159.

Keller M and Matson PA 1994 Biosphere-Atmosphere Exchange of Trace Gases in the Tropics: Evaluating the Effects of Land Use Changes. In: Global Atmospheric-Biospheric Chemistry. Prinn RG (eds.) pp. 103 – 117, Plenum Press, New York, NY, doi: 10.1007/978-1-4615-2524-0_7.

Lambin EF, Rounsevell MDA, and Geist HJ 2000 Are agricultural land-use models able to predict changes in land-use intensity? *AGR. ECOSYST. ENVIRON.* **82** 321 – 331.

Livingston GP, Vitousek PM, and Matson PA 1988 Nitrous oxide flux and nitrogen transformations across a landscape gradient in Amazonia *J. Geophys. Res.* **93** (D2) 1593 – 1599.

Luizão F, Matson P, Livingston G, Luizão G, and Vitousek P 1989 Nitrous oxide fluxes following tropical land clearing *Global Biogeochem. Cy.***3** (3) 281 – 285.

Macedo MN, DeFries RS, Morton DC, Stickler CM, Galford GL, and Shimabukuro YE 2012 Decoupling of deforestation and soy production on the southern Amazon during the late 2000s *P. Natl. Acad. Sci. USA* **109** (4) 1341 – 1346, doi: 10.1073/pnas.1111374109.

Matson PA and Vitousek PM 1987 Cross-system comparison of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems *Global Biogeochem. Cy.* **1** (2) 163 – 170.

Matson PA and Vitousek PM 1990 Ecosystem Approach to a Global Nitrous Oxide Budget *BioScience* **40** (9) 667 – 672.

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, and Pinay G 2003 Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems *Ecosystems* **6** 301 – 312.

McElroy MB and Wofsy SC 1986 Tropical forests: interactions with the atmosphere. In G. T. Prance (Ed.). Tropical rainforests and the world atmosphere, pp. 33 - 60. Westview, Boulder, Colorado.

Melillo JM, Steudler PA, Feigl BJ, Neill C, Garcia D, Piccolo MC, Cerri CC, and Tian H 2001 Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon *J. Geophys. Res.* **106** (D24) 34,179 – 34,188.

Moreno G and Souza Higa TC (eds.) 2005 Geografia de Mato Grosso. Território, Sociedade, Ambiente. Entrelinhas, Cuiabá Entrelinhas, Cuiabá.

Mosier AR 1998 Soil processes and global change *Biol. Fertil. Soils* **27** 221 – 229.

Morton DC, DeFries RS, Shimabukuro YS, Anderson LO, Arai E, Espirito-Santo F del Bon, Freitas R, and Morisette J 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *P. Natl. Acad. Sci. USA* **103** (39) 14637 – 14641, doi: 10.1073/pnas.0606377103.

Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, and Zhang H 2013 Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker TF, D Qin, GK Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, and PM Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Neill C, Steudler PA, Garcia-Montiel DC, Melillo JM, Feigl BJ, Piccolo MC, and Cerri CC 2005 Rates and controls of nitrous oxide and nitric oxide emissions following conversion of forest to pasture in Rondônia *Nutr. Cycl. Agroecosys.* **71** 1 – 15.

Nepstad DC, Stickler CM, and Almeida OT 2006 Globalization of the Amazon Soy and Beef Industries: Opportunities for Conservation *Conserv. Biol.* **20** (6) 1595 – 1603, doi: 10.1111/j.1523.2006.00510.x.

Nepstad DC, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, Motta RS da, Armijo E, Castello L, Brando P, Hansen MC, McGrath-Horn M, Carvalho O, and Hess L 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains *Science* **344** (6188) 1118 – 1123, doi: 10.1126/science.1248525.

Pilegaard K 2013 Processes regulating nitric oxide emissions from soils *Phil. Trans. R. Soc. B* **368** 20130126, doi: 10.1098/rstb.2013.0126.

Poth M and Focht DD 1985 ^{15}N Kinetic Analysis of N_2O Production by *Nitrosomonas europaea*: an Examination of Nitrifier Denitrification *Appl. Environ Microb* **49** (5) 1134 – 1141.

Ravishankara AR, Daniel JS, and Portmann RW 2009 Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century *Science* 326 123 – 125.

Robertson GP and Tiedje JM 1988 Deforestation alters denitrification in a lowland tropical rain forest *Nature* **336** (22/29) 756 – 759.

Signor D and Cerri CEP 2013 Nitrous oxide emissions in agricultural soils: a review *Pesq. Agropec. Trop., Goiânia* **43** (3) 322 – 338.

Syakila A and Kroeze C 2011 The global nitrous oxide budget revisited *Greenhouse Gas Measurement and Management* **1** (1) 17 – 26.

Veldkamp E, Keller M, and Nuñez M 1998 Effects of pasture management on N_2O and NO emissions from soils in the humid tropics of Costa Rica *Global Biogeocheml. Cy.* **12** (1) 71 – 79.

Verchot LV, Davidson EA, Cattânio JH, Ackerman IL, Erickson HE, and Keller M 1999 Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia *Global Biogeochem. Cy.* **13** (1) 31 – 46.

Vitousek PM and Sandford PA 1986 Tropical Forests and Trace Gases: Potential Interactions between Tropical Biology and the Atmospheric Sciences *Biotropica* **24** (2) 233 – 239. Part B. Special Issue: OTS Silver Anniversary Symposium. Resource Availability and Tropical Ecosystems.

Vitousek P, Matson P, Volkmann C, Maass JM, and Garcia G 1989 Nitrous oxide flux from dry tropical forests *Global Biogeocheml. Cy.* **3** (4) 375 – 385.

Vitousek PM and Matson RL 1992 Nutrient Cycling in Moist Tropical Forest *Annu. Rev. Ecol. S.* **17** 137 – 167.

2. Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – a critical review

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Abstract

Brazil typifies the land use changes happening in South America, where natural vegetation is continuously converted into agriculturally used lands, such as cattle pastures and croplands. Such changes in land use are always associated with changes in the soil nutrient cycles and result in altered greenhouse gas fluxes from the soil to the atmosphere. In this study, we analyzed literature values to extract patterns of direct nitrous oxide (N_2O) emissions from soils of different ecosystems in Brazil. Fluxes from natural ecosystems exhibited a wide range: whereas median annual flux rates were highest in Amazonian and Atlantic rainforests (2.42 and 0.88 kg N ha^{-1}), emissions from cerrado soils were close to zero. The decrease in emissions from pastures with increasing time after conversion was associated with pasture degradation. We found comparatively low N_2O-N fluxes from croplands (-0.07 to 4.26 kg N ha^{-1} yr^{-1} , median 0.80 kg N ha^{-1} yr^{-1}) and a low response to N fertilization. Contrary to the assumptions, soil parameters, such as pH, C_{org}, and clay content emerged as poor predictor for N_2O fluxes. This could be a result of the formation of micro-aggregates, which strongly affect the hydraulic properties of the soil, and consequently define nitrification and denitrification potentials. Since data from croplands mainly derived from areas that had been under natural cerrado vegetation before, it could explain the low emissions under agriculture. Measurements must be more frequent and regionally spread in order to enable sound national estimates.

Keywords: N_2O fluxes, soil, land use change, micro-aggregation

1. Introduction

The Food and Agriculture Organization of the United Nations (FAO 2014) has ranked Brazil as the third largest emitting country of greenhouse gases (GHG) from agriculture for the year 2012. One reason is the significant increase in area used for agriculture in recent years (Cederberg *et al* 2009). However, GHG budgeting at national scales is full of uncertainties, particularly for such large countries, and too little is known about the processes that affect such estimations. Literature reviews are one viable first step towards improvements (e.g. Jungkunst *et al* 2006), which can eventually lead to further extrapolations to the national scale (e.g. Brocks *et al* 2014). For the agricultural sector nitrous oxide (N_2O) is one of the most important GHG. It is emitted from soils by natural processes, which can be enhanced and potentially reduced by anthropogenic activities, such as fertilization and land use changes. The principle underlying prerequisite for N_2O emission is the availability of nitrogen. Nitrogen in soils is increased by fertilization, which usually leads to increased N_2O emissions. The Intergovernmental Panel on Climate Change (IPCC 2006) assumes this relationship between N fertilization and N_2O emissions to be linear and define an emission factor (EF) of 1 % (1 kg of every 100 kg of applied N fertilizer is lost as N_2O-N). At the same time, the IPCC strives to improve this approximation to more detailed region-specific approaches. Based on data from temperate climates (e.g. Boeckx and van Cleemput 2001), as well as global scale data (Shcherbak *et al* 2014), a single emission factor is imprecise. Shcherbak *et al* (2014) rather proposed a nonlinear relationship at the global scale. These insights lead to the conclusion that the relationship between fertilizer input and N_2O emissions must vary according to environmental settings like climate and soil conditions (Jungkunst *et al* 2006). Considerably less data exists for the tropics compared with temperate regions (Sherbak *et al* 2014). However, data available from tropical areas indicate that the emission factor used by the IPCC overestimates measured fluxes (Madari *et al* 2007, Jantalia *et al* 2008, Alves *et al* 2010, Cruvinel *et al* 2011, Alvarez *et al* 2012, Carmo *et al* 2013, Lessa *et al* 2014, Carvalho *et al* 2013).

Estimations for national N_2O inventories are challenging, because soils are diffusive emitters and direct N_2O fluxes show extremely high temporal and spatial heterogeneities (e.g. Groffman *et al* 2009). Largest emissions of N_2O mainly result from denitrification under hypoxic conditions (Davidson *et al* 2000); especially during changes between well-aerated (WFPS at 40 – 60 %) and wet (WFPS ≥ 80 %) conditions (Vor *et al* 2003). Consequently, when soil moisture increases during wet seasons, N_2O emissions commonly increase as well (e.g. Luizão *et al* 1989). In irrigation experiments by Vasconcelos *et al* (2004) and Carvalho *et al* (2013), N_2O fluxes increased after irrigation during the dry season in Brazil.

Luizão *et al* (1989) and Sotta *et al* (2008) reported that finer textured soils have a higher N availability. Additionally, Matson *et al* (1990) and Sotta *et al* (2008) measured higher N_2O losses from a clay compared to a sand soil. Since tropical soils of Brazil are commonly rich in clay and experience regular changes in moisture through seasonal rainfall patterns, Brazilian soils should emit higher amounts of N_2O than temperate soils. However, reported measurements show fairly low emission levels. Stable micro-aggregates, which form due to adhesion of fine soil particles and (iron-)oxides, are known to create a coarser structure. This leads to better drainage and more oxic conditions than would be expected by measured clay contents. When compared with other predominant soils at the global scale, the general role of the clay content as an indicator for N_2O fluxes can be questionable.

Besides accounting for N_2O emission from specific land use types, the N_2O dynamics during the actual land use changes should be accounted for, particularly with respect to the rapid land use change happening in Brazil. The expansion of cattle ranching is suggested to be the main driver of recent deforestation in the Legal Amazon (e.g. Barona *et al* 2010). However, Morton *et al* (2006) reported an increasing trend of cropland deforestation (direct conversion of forest to cropland) between 2001 and 2004 in the state of Mato Grosso.

Tropical forests have high rates of biological turnover and rapid decomposition rates. High soil moisture and high N availability increases these soils emissions of relevant amounts of N_2O (Davidson *et al* 2000). Breuer *et al* (2000) estimated a N_2O budget of 3.55 Tg N_2O-N yr^{-1} from tropical rainforest soils. In contrast to rainforests, reported emissions from soils under natural cerrado vegetation (forest to treed grassland ecosystems) were usually very low (Davidson *et al* 2001) or even negative (e.g. Carvalho *et al* 2013). Consequently, knowing the natural ecosystem present before the land use change may be as important for estimating N_2O emissions as knowing the current agricultural land use.

Here, we focus on the regional scale within Brazil in order to improve estimates for atmospheric N_2O increase. Considering single studies without a systematic scientific compilation is neither sufficient to identify regional measurement gaps nor to identify underlying key processes. The value of understanding specific soil and management properties to indicate N_2O fluxes not only lies in better approximations, but also feeds process-based models that are eventually needed for scenario calculations to derive mitigation strategies. A systematic review additionally can help to derive research strategies and to set the base for regional and temporal N_2O measurement recommendations, based on revealed relationships with environmental parameters. The improved process understanding enables better national estimations.

To provide this we used reported emissions of N_2O-N from soils under different land use. Specifically, we aimed to (1) compare reported N_2O-N fluxes from different land use types and define average annual emissions, (2) evaluate if specific soil and management properties can serve as an indicator of N_2O fluxes, and (3) determine knowledge gaps for improvements of future national N_2O inventory and process understanding.

2. Materials and Methods

2.1 Data collection and calculation

We searched English literature for N_2O-N flux data from soils under different land use across Brazil using online databases (Web of Science, Science Direct, Scielo (Brazilian)) and search engines (Google Scholar) over the period between March 2014 and January 2015. Search queries initially included the keywords “N_2O” AND “soil” AND “Brazil”, which resulted in large numbers of studies (e.g. 73 studies in the Web of Science). We further specified the search by adding the keyword “conversion”. Additional specification of the single land use types (AND “rainforest”/”pasture”/”cropland”) or geography (AND “Amazon”/”Southern Brazil”) did not result in additional studies. According to the guidelines of Aiassa et al. (2015) on how to proceed on systematic reviews, we made use of personal contacts and contacted research groups in Brazil (EMBRAPA) to improve and expand our search strategies towards Portuguese studies that might have been missed using the Scielo database and due to linguistic difficulties. No time frame was set in terms of the age of the studies - the aim was rather a good geographic coverage of Brazil. Only tabular values were analyzed; we did not extract data from graphs. Data sets were divided into three categories: 1) data from natural landscape units (Amazon forest, Atlantic forest, and cerrado), 2) land that was converted to pastures, and 3) land under agricultural management and fertilizer application. Since the third category contained long-term (one year or more), as well as short-term experiments (weeks or months), studies within this category were again divided according to the duration of the measurements. Short-term experiments usually presented cumulative fluxes over the specific time period rather than annual emissions. Nevertheless, we treated short-term experimental data as long-term data if authors extrapolated to annual values (e.g. Metay *et al* 2007). Similarly, cumulative data resulting from different crops within a rotation (e.g. corn/bean rotation, Cruvinel *et al* 2011) were extrapolated to annual values, if the whole rotation cycle covered one year. Reported units varied among the studies, thus we converted data sets to identical units (e.g. kg N ha^{-1} for N_2O fluxes and fertilizer inputs, or g kg^{-1} for C_{org}). If N_2O fluxes were not given in annual emissions, but mean daily values were given, reported data were projected to one year. For studies which distinguished between dry and wet season, the length of the specific period was used in the extrapolation. Soil types were classified according to the World Reference Base (IUSS 2014). Soil texture, usually expressed as clay content, carbon content, and pH have been shown to influence N_2O-N emissions. Thus, we looked at correlations with available soil properties, as well as with the amount of applied fertilizer. The latter did not include studies with soybean because legumes are treated differently by the IPCC. Forests and cerrados were not included in the regression analysis because information on the specific soil properties derived from the mineral soil, but not from the overlying humus layer. We differentiated between fertilized and unfertilized plots (usually pastures and croplands). Except for correlations with the amount of applied fertilizer, we only regarded fertilizer-induced emissions (N_2O-N/added N). Data from pastures was ordered according to the time since establishment, as pasture ages turned out to be a meaningful factor in forest areas converted to pastures (e.g. Wick *et al* 2005, Neill *et al* 2005).

2.2 Statistical analyses

We used the linear regression method to analyze the relationships between soil properties and N_2O-N emissions. The influence of the applied fertilizer was additionally adapted by a non-linear model, following the suggestions of Shcherback et al (2014). Relationships were regarded as being statistically significant for a p value of (or smaller than) 0.05. The regression analyses and creation of graphics were conducted with the R software (version 2.15.0).

3. Results

In total, 37 study sites were analyzed based on land use, soil properties, management, and fertilization (Table A.1).

The geographical locations of the sites (Figure 2.1) divided Brazil into regional land use types: Studies conducted in the northern states (e.g. Pará, Rondônia) mainly dealt with N_2O-N emissions from rainforest and cattle pastures. These land use types represented the fundamental land use change (deforestation) in the Amazon region. In contrast, studies from the central and southern states focused on conversion of cerrado area to croplands and the influence of different crop rotations, management, and fertilization strategies.

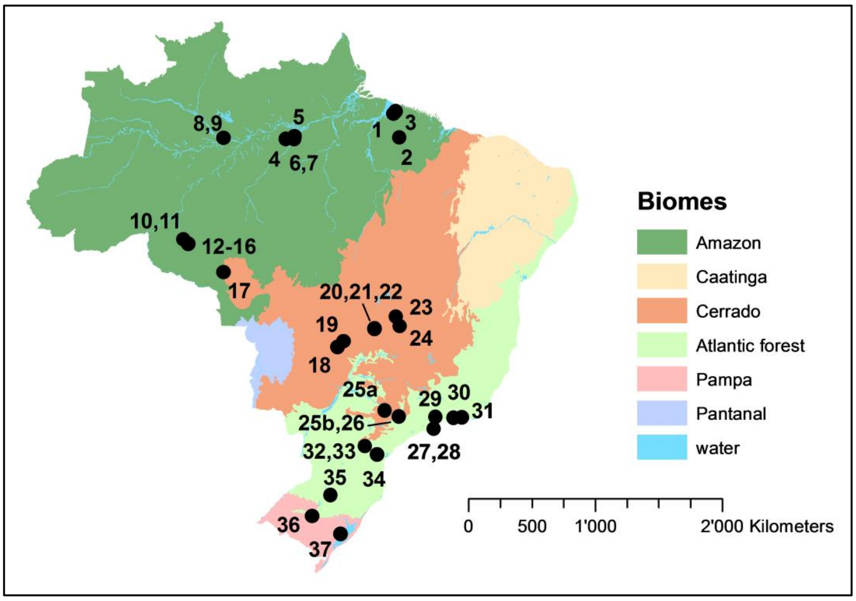

Figure 2.1: Sites with available N_2O-N flux data in different biomes in Brazil (IBGE 2013). Numbers are according to Table A.1 in the appendix.

Annual N_2O-N emissions collected in this study (Tables 2.1 to 2.3) differentiated according to the land use type. Table 2.1 summarizes data from forest (Amazon and Atlantic forest), cerrado, and pasture sites. Table 2.2 summarizes data from experiments on cropland. Table 2.3 gives an overview of N_2O-N fluxes from short-term experiments on grassland, pasture and cropland.

3.1 Soil under natural vegetation

In general, N_2O emissions from forest soils were higher than emissions from pasture sites (e.g. Verchot *et al* 1999, Steudler *et al* 2002, Wick *et al* 2005, Carmo *et al* 2012). Reported N_2O-N fluxes from forest soils were positive without exception, but varied from 0.38 up to 16.20 kg N ha^{-1} yr^{-1}. Rainforests (Amazonas and Atlantic rainforest) differ considerably from cerrado: The highest emission (16.20 kg N_2O-N ha^{-1} yr^{-1}) was reported from a forest site in the Amazon, whereas the maximum emission from Atlantic forest was much lower (3.42 kg N_2O-N ha^{-1} yr^{-1}). In contrast, emissions from cerrado sites were exceptionally low (median:

0.14 N_2O-N ha^{-1} yr^{-1} with a maximum of 1.19 N_2O-N ha^{-1} yr^{-1}), and often below the detection limit (< 0.6 ng cm^{-2} h^{-1}).

Data presented in Table 2.1 includes studies conducted in primary or moderately altered forests. Studies from Verchot *et al* (1999), Vasconcelos *et al* (2004), and Coutinho *et al* (2010) present data from secondary forests of 12, 20, and 34 years after reforestation. Here, annual N_2O-N emissions amount to 0.35, 0.94, and 0.88 kg ha^{-1}, respectively. These results are lower than the median annual emission from primary forests reported in this study and are in the range of annual emissions from pastures.

Table 2.1: Annual N_2O emissions with minimum, median, and maximum value from forest, cerrado, and pasture soils. References are according to Table A.1.

Biome	Annual N_2O emissions [kg N ha^{-1}]			Reference
	Min	Median	Max	
Forest	0.38	2.29	16.20	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 27, 28, 31
Amazon Rainforest	0.38	2.42	16.20	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14
Atlantic Rainforest	0.44	0.88	3.42	27, 28, 31
Cerrado	-0.09	0.14	1.19	2, 17, 18, 19, 23, 24
Pasture [age]				
≤ 10	1.32	2.52	10.16	9, 10, 12, 14
> 10	-0.27	0.90	3.62	2, 10, 11, 12, 14, 18, 19, 23, 28, 29

3.2 Pasture soil

N_2O-N fluxes from pasture soils varied widely, too, but emissions from pastures younger than 10 years were significantly ($p < 0.05$) higher than from older pastures (Table 2.1, Figure 2.2). Thus, we differentiated data from pastures 10 years and younger from those older than 10 years. Neill *et al* (2005) modeled the behavior of annual N_2O emissions from forests and pasture sites of different ages as an exponential function. When we fitted an exponential function to our data ($y = 0.65 + 4.15 * \exp(-0.10\,x)$, with y = flux of N_2O-N [kg ha^{-1} yr^{-1}] and x = pasture age), we found a similar decrease in N_2O-N emissions with pasture age (Figure 2.2).

For short-term experiments on pastures under additional fertilization and soil management (Table 2.3), highest emissions were reported from pastures under urine application and tillage management (5.87 and 2.23 kg N ha^{-1}). These studies were not included in the nonlinear regression (Figure 2.2).

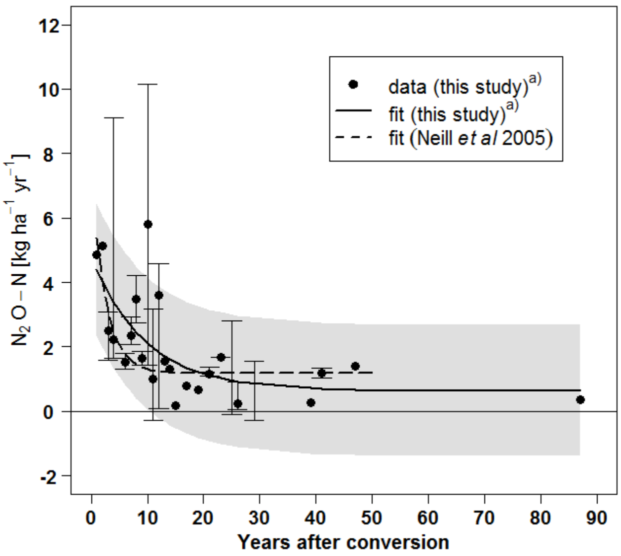

Figure 2.2: An exponential model of annual N_2O-N flux data dependent on years after conversion (n = 24, R² = 0.48). Pasture ages varied from 1 to 87 years. The gray shaded area represents the 95 % confidence interval. The broken line is the fit of Neill *et al* (2005), based on N_2O-N emissions from pastures of different ages (n = 9) in the state of Rondônia ($y = 1.18 + 6.21 * \exp(-0.39\,x)$). In their study, pasture ages varied from 1 to 41 years.
$^{a)}$ Including data of Neill *et al* (2005).

3.3 Cropland soil

Highest annual emissions occurred from crop-pasture rotations (4.26 kg N ha^{-1} yr^{-1}) and cropland under tillage treatment (2.42 kg N ha^{-1} yr^{-1}). The overall median from cropland soils was 0.80 kg N ha^{-1} (Table 2.2).

We could use only 6 studies (15, 16, 22, 26, 34, and 36 in Table A.1) for calculating an emission factor (EF) because these allowed for subtraction of background emissions. Of these, only study 22 (Santos *et al* 2008) was a long-term measurement focusing on corn and bean cultivation. EFs were 0.24 % for corn and 0.13 % for bean. EFs from short term experiments (Table 2.3) ranged from 0.13 to 5.14 %, with a median of 0.38 %.

Except for pH (R² = 0.21, p = 0.06), correlations with N_2O-N/added N were significant (Figures 2.3 a - c and Table 2.4), but not important. Clay contents covered a range from 13 to 86 %, and the linear regression implied only a slightly increasing trend for fertilized plots (0.0009) and a slightly decreasing trend (-0.003) for unfertilized plots with higher clay contents. N_2O-N/added N slightly decreased with increasing pH (-0.03) or carbon content (-0.06). On unfertilized plots, emissions increased with increasing pH (0.41), but emissions decreased with increasing carbon content (-1.38).

N_2O-N fluxes increased with applied N fertilizer (Figure 2.3 d). In their global meta-analysis, Shcherbak et al (2014) found that a nonlinear model better described the relationship between N_2O fluxes and fertilization than a linear model. In contrast, we found that a nonlinear model of the Brazilian data did not result in a better description of the relationship between emissions and fertilization compared with a linear model (R² = 0.20* for both linear and nonlinear model). Our nonlinear model ($y = 0.93 + 1.98 \bullet x - 0.15 \bullet x^2$, with y = N_2O-N flux [kg ha^{-1} yr^{-1}] and x = applied fertilizer [kg N ha^{-1}]) does not compare well with that of Shcherbak *et al* (2014) (Figure 2.3 d). Besides the different intercept, which is caused by reported N_2O-N fluxes at low and even zero fertilization, our model has a lower slope, due to the low emissions. Table 2.4 shows more detailed results of the regressions.

Table 2.2: Land use, treatment, N application, and annual N_2O fluxes from soils under agricultural use in Brazil. Site numbers are according to Table A.1.

Site No.	Land use	Treatment	Duration [days]	Applied N [kg N ha^{-1}]	Annual N_2O [kg N ha^{-1}]
3	cropland (agroforestry)	improved fallow plot	~ 365		
		inga edulis		0	0.71
		acacia mangium		0	0.88
		control		0	0.82
17	cropland	conventional tillage:			
		rice (1year)		7 [a]	0.85
		rice (2years)		15	0.63
19	cropland	crop succession		92	0.57
		crop-pasture rotation		222	2.00
20	cropland	disc harrowing (15 cm)	~ 182	114	0.04 [b]
		direct seeding		114	0.01 [b]
22	cropland	corn	365	0	0.35
				80	0.54
		beans		0	0.20
				80	0.30
25	a) cropland (*plant cane*)	MF (NPK)	~ 365	60	
		MF (NK) + filter cake		122	
		MF (NP) + vinasse		87	
		MF (N), + vinasse + filter cake		149	
	b) cropland (*ratoon cane*)	MF	~ 242	120	
		MF + vinasse		142	
		7 Mg trash, MF		120	
		7 Mg trash, MF + vinasse		142	
		14 Mg trash, MF		120	
		14 Mg trash, MF + vinasse		142	
		21 Mg trash, MF		120	
		21 Mg trash, MF + vinasse		142	
32	cropland	tillage	365	165	2.42
		no-tillage		165	1.26

continued

33	pasture/cropland	integrated crop-livestock (corn/grazed annual-ryegrass)	365	225 (+ excreta)	4.26
	cropland	continuous crop (annual-ryegrass)		165	1.26
		native vegetation		0	0.65
35	cropland	no tillage:			
		sorghum/wheat (year 1 and 2) [b]	365	195/253	0.65
		corn/wheat (year 1 and 2) [c]		162/94	0.71
		conventional tillage:			
		sorghum/wheat (year 1 and 2) [b]	365	171/253	0.71
		corn/wheat (year 1 and 2) [c]		141/78	0.80
37	cropland	pigeon pea + corn	~ 347	367.6	1.32
		lablab + corn		167.5	1.12
		vetch + corn		144.8	0.81
		black oat + corn		98.3	-0.07
		black oat + vetch/corn + cow pea		231.7	1.32
median					0.80

MF: Mineral fertilizer

[a] from Carvalho *et al* (2007)

[b] reported as annual emissions

[c] soybean/vetch (year 1), sorghum/wheat (year 2)

[d] maize/wheat (year 1), soybean/vetch (year 2)

Table 2.3: Land use, treatment, N application, and cumulative N_2O fluxes from soils under agricultural use in Brazil. Site numbers are according to Table A.1.

Site No.	Land use	Treatment	Duration [days]	Applied N [kg N ha^{-1}]	Cum. N_2O [kg N ha^{-1}]
15	pasture	control	~ 182	0	0.07
		tillage		42	0.23
		no-till, co-planting rice		33	1.10
		no-till, co-planting soybean		0	1.10
16	pasture	control	180	0	0.07
		tillage		42	2.23
		no-tillage		33	1.62
21	pasture	urine application	94/37	396 ds)/683 ws)	
		dung application	94/37	188 ds)/346 ws)	
24	cropland	corn	173	155.3	0.20
		irrigated bean	135	102.7	0.20
		soybean	153	21.2	0.10
		cotton	258	0	0.10
26	grassland	control	30	0	0.02
		urine application		860	1.69
30	grassland	vegetation cycles			
		V1	162	80	0.44
		V2	178	100	0.57
		V3	149	80	1.47
34	pasture	control	90	0	0.04
		urine application		2200	5.87
		dung application		1110	1.43
36	cropland	fertilization with pig slurry	28		
		no-tillage		191	0.40
		conventional tillage		191	0.51

ds) dry season

ws) wet season

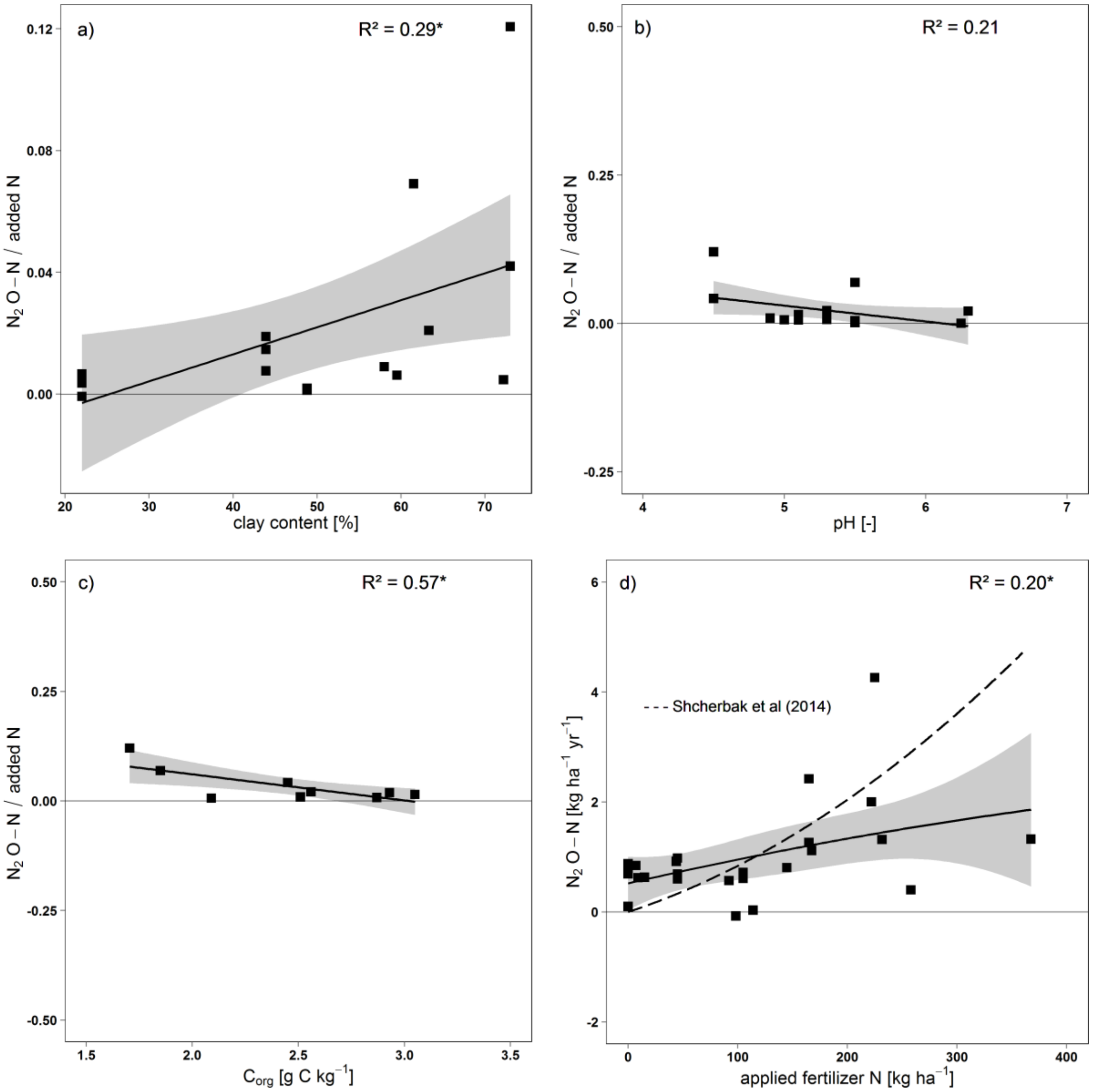

Figure 2.3: Relationships between N_2O-N fluxes [kg ha^{-1} yr^{-1}] per added N [kg N ha^{-1} yr^{-1}] and (a) soil clay content [%], (b) pH, (c) carbon content [%], and relationship between N_2O-N fluxes and (d) the annual amount of applied fertilizer N [kg ha^{-1} yr^{-1}]. Figure 2.3 d) also includes the model of Shcherbak *et al* (2014) (excluding N-fixing crops) (broken line). Only fertilized plots (croplands and pastures) are presented. Gray shaded areas represent the 95 % confidence intervals; see Table 2.4 for more precise information on the regressions. * = p-value < 0.05.

Table 2.4: Intercepts and slopes (including the lower and upper values of 95 % confidence interval) for linear regression between soil properties and N_2O-N/added N ratio for fertilized and unfertilized plots, and applied N and N_2O-N fluxes for the linear and nonlinear regression. * = p-value < 0.05.

Regression parameter	**Clay content**		**pH**		**C_{org}**		**Applied N**	
	fertilized	**unfertilized**	**fertilized**	**unfertilized**	**fertilized**	**unfertilized**	**linear**	**nonlinear**
intercept	-0.22	1.68	0.16	-1.29	0.18	3.84	0.544	0.93
slope	0.0009*	-0.003	-0.03	0.41*	-0.06*	-1.38	0.004	1.98*
lower	0.0002	-0.017	-0.06	0.07	-0.10	-9.04	0.0009	0.43
upper	0.0016	0.010	0.002	0.74	-0.02	6.28	0.0068	3.54
slope								-0.15
lower								-1.71
upper								1.41
R²	0.29*	0.007	0.21	0.51*	0.57*	0.23	0.20*	0.20*

4. Discussion

4.1 Importance of land use

4.1.1 Natural vegetation

The different emissions from cerrado and rainforest reveal the high variability of natural N_2O fluxes. While emissions from Brazilian rainforest sites were generally high (2.29 kg N_2O-N ha^{-1}), but still within the range of emissions reported for temperate (-0.1 to 4.9 N_2O-N ha^{-1} yr^{-1}, Jungkunst *et al* 2004) and Australian tropical forests (1.15 to 5.36 N_2O-N ha^{-1} yr^{-1}, Breuer *et al* 2000), N_2O fluxes from cerrado soils were often close to zero, below detection limits (e.g. Pinto *et al* 2002, Varella *et al* 2004) or negative (Verchot *et al* 1999). Nitrification is a more important source of N_2O emissions in cerrado soils because of the better drainage caused by the coarse soil structure (Pinto *et al* 2002). Consequently, these soils become increasingly important in terms of nitric oxide (NO) emissions. Pinto *et al* (2002) assumed low nitrification rates and low NO_3^- contents resulted in low N_2O fluxes. However, further attention should be paid to cerrado soils, in order to identify the underlying processes.

The Amazonian forest soils in the north of Brazil showed higher emissions than those of the coastal Atlantic forests in the south-east of the country. Only 3 studies dealt with the Atlantic forest, but 13 were found for the Amazonian rainforest. More studies from the Atlantic forest would help to confirm this difference between the two forest types. Emissions from secondary forests (12, 20, and 34 years after reforestation) ranged between 0.35 and 0.94 kg N_2O-N ha^{-1} yr^{-1} and were lower than from primary forests. This suggests that N cycles in these reforested areas had not completely recovered. Regardless of the high emissions from rainforest soils compared with soils under other land use, precise knowledge concerning emissions during the conversion from rainforest to pasture is missing. This is a key aspect, since some studies report increased N_2O emissions from soil after conversion of forest to pasture (Keller *et al* 1993, Veldkamp *et al* 1999, Davidson *et al* 2001, Melillo *et al* 2001). They explain this event with a temporal increase of N availability. The removal of plants as a sink for nutrients causes very high nutrient availability in soils (Bormann and Likens 1979), which is known to increase N_2O emissions at barren sites (Repo *et al* 2009). In addition to the emissions from the soil to the atmosphere, soil-water degassing can be an important source for N_2O fluxes directly after forest clear-cutting (Bowden & Bormann 1986).

4.1.2 Pastures

According to Keller and Reiners (1994) and Melillo *et al* (2001), young pastures have increased emissions directly after a clear-cut, followed by decreasing emissions as the pastures age. Decreasing denitrification rates (N_2O + N_2) in mid-successional sites compared with primary forest and early successional sites may explain this trend (Robertson and Tiedje 1988).

The duration of higher N_2O emissions after the creation of a pasture varies from 3 months (Elligson *et al* 2000), to over 2 years (Melillo *et al* 2001), to up to 10 years (Keller *et al* 1993). In our review, we found that N_2O emissions from young pastures (≤ 10 years) were significantly higher than from older pastures. According to Davidson *et al* (2001), *Brachiaria spp.* grasses, which were introduced from Africa (Boddey *et al* 2004) and are commonly used for pastures in Amazonia, can be effective sinks for soil N. Quick immobilization of the nitrogen that is released after the disturbance of the soil might delay the degradation of the pasture. Subbarao *et al* (2009) found a reduction in N_2O emissions of more than 90 % under plots with *Brachiaria* species compared with soybean plots. The *Brachiaria* roots produce and deliver nitrification inhibitors to soil-nitrifier sites (Subbarao *et al* 2009). In grazed *Brachiaria* pastures, intense uptake of nitrogen by grazing animals degrades pastures (Boddey *et al* 2004). The decrease of available N in the litter leads to a reduction in the amount of N available for plant growth. Cerri *et al* (2005) and Hohnwald *et al* (2006) also report that many pastures suffer from degradation (declining fertility and grass productivity, and increasing weed cover) already 4 to 10 years after establishment. Thus, pastures are unsustainable – a point supported by our finding of decreasing N_2O fluxes from pastures about 10 years after conversion.

4.1.3 Croplands

Except for one study (Site No. 3), data from croplands derived from areas that had been under cerrado vegetation before. This might justify the low emissions from cropland, since cerrado soils appear to be a less considerable source for N_2O fluxes. Although N fertilization increased emissions for short periods of 3 to 7 days after application, the reaction of the soil to N addition at the annual scale was very low. For application rates below 100 kg N ha^{-1}, which are frequently applied, the reaction was negligible. The data collected in this study did not fully agree with the global nonlinear model suggested by Shcherbak *et al* (2014). Their model includes data from 84 locations worldwide, and is consequently designed for a much larger scale than our country-specific analysis. This difference emphasizes that large scale or global relationships may be inappropriate to apply to more regional aspects.

Annual fluxes of N_2O-N from cropland soils in Brazil ranged from -0.07 to 4.26 kg N ha^{-1}, with a median of 0.80 kg N ha^{-1} (Table 2.2). This value is much lower than emissions reported by Roelandt *et al* (2005) from croplands in Canada (2.27 kg N_2O-N ha^{-1} yr^{-1}), Europe (2.47 kg N_2O-N ha^{-1} yr^{-1}), and the United States (3.35 kg N_2O-N ha^{-1} yr^{-1}). Highest emissions (Figure 2.3 d) occurred from the two cropland areas that were under either conventional tillage (2.42 kg N_2O-N ha^{-1} yr^{-1}; Piva *et al* 2012) or integrated cropping systems (4.26 kg N_2O-N ha^{-1} yr^{-1}; Piva *et al* 2014).

4.2 Importance of soils

4.2.1 Soil texture and structure

Soil texture and structure are highly relevant driving factors for N_2O emissions, mainly as controllers of water balances and nutrient availability. Generally, finer textured soils have a higher N availability (Luizão *et al* 1989) and consequently emit higher amounts of N_2O than sandy soils (Matson *et al* 1990). In a laboratory experiment, N losses from heavily weathered tropical soils were higher in a clay textured soil variation than from a sandy variation (Sotta *et al* 2008). Based on these findings Sotta *et al* (2008) suggest a higher N availability in a clay compared with a sand soil in Amazonian forests. Due to the good drainage of sandy soils, anaerobic conditions are rare and the potential for denitrification is low. In this study, clay proved to be a poor predictor for N_2O emissions from fertilized (slope = 0.0009) and unfertilized plots (slope = - 0.003), most likely due to the formation of micro-aggregates and the associated different water retention properties. Tomasella *et al* (2000) mention the rapid decrease in water content between saturation and -100 kPa, and underline that Brazilian soils behave more like coarse-textured soils. As a result, the water holding capacity does not necessarily increase with increasing clay content, and nitrification is more likely to occur than denitrification. Therefore, tropical soils with high clay contents, formation of micro-aggregates, and high drainage can be expected to emit less N_2O than is reported for temperate soils. Thus, the clay content is not necessarily a reliable indicator for N_2O-N emissions from Brazilian soils.

4.2.2 Soil chemical properties

In this study, neither pH nor C_{org} content seemed to have an influence on N_2O-N fluxes. However, fertilized and unfertilized plots differed. On fertilized plots, linear regression slopes were negative for both pH (-0.03) and C_{org} content (-0.06). For unfertilized plots, pH (slope = 0.41) turned out to be more predictive than C_{org} (slope = -1.38). Although both parameters have been reported to influence denitrification rates (Knowles 1982), the general findings within this study suggest that N_2O fluxes occur from nitrification. Thus, pH and C_{org} are of secondary importance. The contribution of pH and especially C_{org} in the formation of micro-aggregates, however, should be further investigated.

4.3 Knowledge gaps

Considerable data gaps exist for certain biomes. We found no reported N_2O emissions from the biomes Caatinga and Pantanal. Except for one site, data from croplands derived from areas that had been established in cerrado areas, which were found to be extreme low emitting soils under natural vegetation. This lack of data hinders our ability to explain the low emissions from croplands, even after fertilizer application, and points out the need for measurements from additional land use types.

Since N_2O emissions exhibit short-termed emission peaks caused by environmental changes, high temporally resolved measurements are needed in order to explain mechanisms. Automated measurements enable continuous data acquisition, but the establishment of such studies is restricted to sites with a power supply and, for certain approaches, flat topography. Therefore, to achieve an adequate spatial measurement distribution across a large nation such as Brazil, we still have to rely on manual measurements that also take into consideration environmental (dry/wet cycles) and human induced (land conversion) changes. Biweekly measurements throughout the year, as done by most authors, are no longer suitable for increasing our understanding of biogeochemical processes. Furthermore, exact knowledge of how N_2O-N emissions change during land conversion is missing and desperately needed, since this time frame may likely account for large emission pulses that need to be accounted for in national budgeting.

Improving the existing understanding of the underlying processes, especially during land conversion can only be ensured by consistent monitoring and frequent measurements. Such monitoring data could provide the basis for further model refinement and allow for spatial and temporal extrapolations. The goal would be to develop regional solutions to improve national inventories. At this point, most process-oriented models have been developed for temperate conditions and application to tropical conditions is challenging. The different hydraulic conditions caused by micro-aggregates need to be considered, since adequate description of the soil moisture is a prerequisite for modeling N_2O-N fluxes from soils.

5. Conclusions

This systematic review on N_2O fluxes from Brazilian soils provides a good basis for further estimations and inventories on the national scale and eventually for explaining atmospheric N_2O increases. The land use types differed in direct N_2O fluxes from soils, but emissions were generally low. Systematic regional measurement gaps were identified, of which the Caatinga biome in northeastern Brazil is the most prominent example. Furthermore, land use types were not randomly distributed between biomes. In other words, pastures were studied in rainforest biomes, and croplands in cerrado biomes. Therefore, no predictions can be made on the behavior of N_2O fluxes from croplands in the rainforest biome. Soil parameters, such as pH, C_{org}, and clay content, had proven to be unsuitable as indicators for N_2O fluxes. Oddly enough, N_2O itself was found to be an indicator for the degradation stage of pastures, as emission levels decrease along with the productivity and years since conversion. A kind of tipping point from high to low N_2O emissions was found to be in the range of 10 – 15 years after forest conversion. N_2O is known to have high event-based emissions, which the current measurement concept did not account for. Future studies must focus on high temporal resolutions in order to promote process understanding. Otherwise, sound national inventories will not be possible.

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References

Aiassa E, Higgins JPT, Frampton GK, Greiner M, Afonso A, Amzal B, Deeks J, Dorne J L, Glanville J, Lövei GL, Nienstedt K, O'Connor AM, Pullin AS, Rajic A, and Verloo D 2015 Applicability and feasibility of systematic review for performing evidence-based risk assessment in food and feed safety *Crit. Rev. Food Sci. Nutr.* **55** 1026 – 1034.

Alvarez C, Constantini A, Alvarez CR, Alves BJR, Jantalia CP, Martellotto EE, and Urquiaga S 2012 Soil nitrous oxide emissions under different management practices in the semiarid region of the Argentinian Pampas *Nutr. Cycl. Agroecosys.* **94** 209–220.

Alves BJR, Jantalia CP, Madari BE, Machado PLOA, Franchini JC, Santos JC, Boddey RM, and Urquiaga S 2010 Emissões de óxido nitroso de solos pelo uso de fertilizantes nitrogenados em áreas agrícolas *Comunicado técnico* **126** Seropédica: Embrapa Agrobiologia 6 p.

Barneze AS, Mazzetto AM, Zani CF, Misselbrook T, and Cerri CC 2014 Nitrous oxide emissions from soil due to urine deposition by grazing cattle in Brazil *Atmos. Environ.* **92** 394 – 397.

Barona E, Ramankutty N, Hyman G, and Coomes OT 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon *Environ. Res. Lett.* **5** 024022 1 – 9.

Boddey RM, Macedo R, Tarré RM, Ferreira E, Oliveira OCP, Rezende C, Cantarutti RB, Pereira JM, Alves BJR, and Urquiaga S 2004 Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline *Agr. Ecosyst. Environ.* **103** 389 – 403.

Boeckx P and van Cleemput A 2001Estimates of N_2O and CH_4 fluxes from agricultural lands in various regions of Europe. *Nutr. Cycl. Agroecosys.* **60** 35-47.

Bormann FH and Likens GE 1979 Pattern and process in a forested ecosystem. Springer-Verlag, New York, pp 253.

Bowden WB and Bormann FH 1986 Transport and loss of nitrous oxide in soil water after forest clear-cutting *Science* **233** 867 – 869.

Breuer L, Papen H, and Butterbach-Bahl K 2000 N_2O emission from tropical forest soils of Australia *JGR* **105** 26,353 – 26,367.

Brocks S, Jungkunst HF, and Bareth G 2014 A regionally disaggregated inventory of nitrous oxide emissions from agricultural soils in Germany – A GIS-based empirical approach *Erdkunde* **68** (2) 125 – 144.

Carmo JB, Neill C, Garcia-Montiel DC, Piccolo MD, Cerri CC, Steudler PA, Andrade CA, Passianoto CC, Feigl BJ, and Melillo JM 2005 Nitrogen dynamics during till and no-till pasture restoration sequences in Rondônia, Brazil *Nutr. Cycl. Agroecosys.* **71** 213-225.

Carmo JB do, Neto ER de Sousa, Duarte-Neto PJ, Ometto JP, Ometto JPHB, and Martinello LA 2012 Conversion of the coastal Atlantic forest to pasture: Chronosequences for the nitrogen cycle and soil greenhouse gas emissions *Agr. Ecosyst. Environ.* **148** 37 – 43.

Carmo JB do, Filoso S, Zotelli LC, Neto ER de Sousa, Pitombo LM, Duarte-Neto PJ, Vargas VP, Andrade CA, Gava GJC, Rossetto R, Cantarella H, Neto A, and Martinelle LA 2013 Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation *Global Change Biol. Bioenergy* **5** 267–280.

Carvalho JLN, Cerri CEP, Cerri CC, Feigl BJ, Piccolo MC, Godinho VP, and Herpin U 2007 Changes of chemical properties in an oxisol after clearing of native Cerrado vegetation for agricultural use in Vilhena, Rondônia State, Brazil *Soil Till. Res.* **96** 95 – 102.

Carvalho MT de Melo, Madari BE, Leal WG de Oliveira, Costa AR, Machado PLO de Almeida, Silveira PM, Moreira JAA, and Heinemann AB 2013 Nitrogen fluxes from irrigated common-bean as affected by mulching and mineral fertilization *Pesq. Agropec. Bras.* **48** 478 – 486.

Carvalho JLN, Raucci GS, Frazao LA, Cerri CEP, Bernoux M, and Cerri CC 2014 Crop-pasture rotation: A strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado *Agr. Ecosyst. Environ.* **183** 167 – 175.

Cederberg C, Meyer D, and Flysjö A 2009 SIK Report No 792. Life cycle inventory of greenhouse gas emissions and use of land and energy in Brazilian beef production. ISBN 978-91-7290-283-1.

Cerri CC, Melillo JM, Feigl BJ, Piccolo MC, Neill C, Steudler PA, Carvalho MS, Godinho VP, Cerri CE, and Bernoux M 2005 Recent history of the agriculture of the Brazilian Amazon Basin *Outlook Agr*. **34** 2015 – 223.

Coutinho RP, Uriquiaga S, Boddey RM, Alves BJR, Torres AQA, and Jantalia CP 2010 Estoque de carbono e nitrogenio e emissao de N_2O em diferentes usos na Mata Atlantica *Pesq. Agropec. Bras.* **45** 195 – 203.

Cruvinel EBF, Bustamante MMC, Kozovitsc AR, and Zeppd AR 2011 Soil emissions of NO, N_2O and CO_2 from croplands in the savanna region of central Brazil *Agr. Ecosyst. Environ.* **144** 29–40.

Davidson EA, Keller M, Erickson HE, Verchot LV, and Veldkamp E 2000 Testing a conceptual model of soil emissions of nitrous and nitric oxides *Bioscience* **50** 667 – 680

Davidson EA, Bustamante MMC, and Pinto A de Siqueira 2001 Emissions of nitrous oxide and nitric oxide from soils of native and exotic ecosystems of the Amazon and Cerrado regions of Brazil. In: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proceedings of the 2nd International Nitrogen Conference on Science and Policy. *TheScientificWorld* **1** 312–319.

Davidson EA, Ishida FY, and Nepstadt DC 2004 Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest *Global Change Biol*. **10** 718 – 730.

Elligson LJ, Kauffman JB, Cummings DL, Sanford RL Jr, and Jaramillo VJ 2000 Soil N dynamics associated with deforestation, biomass burning and pasture conversion in a Mexican tropical dry forest *Forest Ecol. Manag.* **137** 41 – 51.

Food and Agriculture Organization of the United Nations (FAO) 2014 FAOSTAT. Rome. Obtained by World Resources Institute, CAIT Climate Data Explorer 2015 Washington DC, http://cait.wri.org.

Garcia-Montiel DC, Steudler PA, Piccolo M, Melillo JM, Neill C, and Cerri CC 2001 Controls on soil nitrogen oxide emissions from forest and pastures in the Brazilian Amazon *Global Biogeochem. Cy.* **15** 1021 – 1030.

Garcia-Montiel DC, Steudler PA, Piccolo M, Neill C, Melillo J, and Cerri CC 2003 Nitrogen oxide emissions following wetting of dry soils in forest and pastures in Rondônia, Brazil *Biogeochemistry* **64** 319 – 336.

Giacomini SJ, Jantalia CP, Aita C, Urquiaga SS, and Alves BJR 2006 Nitrous oxide emissions following pig slurry application in soil under no-tillage system *Pesq. Agropec. Bras.* **41** 1653-1661.

Gomes J, Bayer C, Costa F, Piccolo M, Zanatta JA, Vieira FCB, and Six J 2009 Soil nitrous oxide emissions in long-term cover crops-based rotations under subtropical climate *Soil Till. Res.* **106** 36 – 44.

Groffman PM, Butterbach-Bahl K, Fulweiler RW, Gold AJ, Morse JL, Stander EK, Tague C, Tonitto C, and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* **93** 49 – 77.

Hohnwald S, Rischkowsky B, Camarao AP, Schultze-Kraft R, Rodrigues Filho JA, and King JM 2006 Integrating cattle into the slash-and-burn cycle on smallholdings in the Eastern Amazon, using grass-capoeira or grass-legume pastures *Agr. Ecosyst. Environ.* **117** 266 – 176.

IBGE 2013 *Instituto Brasileiro de Geografia e Estatística*, ftp://geoftp.ibge.gov.br/mapas_tematicos/mapas_murais/shapes/

IPCC 2007 *Climate Change 2007: The Physical Science Bases* Solomon S, Qin D, Mannung M, Chen Z, Marquis M, Averyt K B, Tignor M, and Miller H L (eds) International Panel on Climate Change (Cambridge) Cambridge University Press pp 996, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html.

IUSS World Reference Base 2014 World Reference Base for Soil Resources 2014. International soil classification system for naming and creating legends for soil maps. World Soil Resources Reports No- 106. FAO, Rome, Italy.

Jantalia CP, Santos HP, Urquiaga S, Boddey RM, and Alves BJR 2008 Fluxes of nitrous oxide from soil under different crop rotations and tillage systems in the South of Brazil *Nutr. Cycl. Agroecosys.* **82** 161-173.

Jungkunst H F, Fiedler S, and Stahr K 2004 N_2O emissions of a mature Norway spruce (Picea abies) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern *Geophys. Res.* **109** DO7302.

Jungkunst HF, Freibauer A, Neufeldt H, and Bareth G 2006 Nitrous oxide emissions from agricultural land use in Germany – a synthesis of available annual field data *J. Plant Nutr. Soil Sci.* **169** 341 – 351.

Keller M, Veldkamp E, Weitz AM, and Reiners WA 1993 Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica *Nature* **365** 244 – 246.

Keller M and Reiners WA 1994 Soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica *Global Biogeochem.Cy.* **8** 399 – 409.

Keller M, Varner R, Dias JD, Silva H, Crill P, Oliviera RC Jr, and Asner GP 2005 Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil *Earth Interaction* **9** 1 – 28.

Knowles R 1982 Denitrification *Microbiol. Rev.* **46** 43 – 70.

Lessa ACR, Madari BE, Paredes DS, Boddey RM, Uriquiaga S, Jantalia CP, and Alves BJR 2014 Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions *Agr. Ecosyst. Environ.* **190** 104 – 111.

Livingston GP, Vitousek PM, and Matson PQ 1988 Nitrous oxide flux and nitrogen transformations across a landscape gradient in Amazonia *J.Geophys.Res.*93 1593 – 1599.

Luizão F, Matson P, Livingston G, Luizão R, and Vitousek P 1989 Nitrous oxide flux following tropical land clearing *Global Biogeochem. Cy.* **3** 281 – 285.

Madari BE, Costa AR, Jantalia CP, Machado PLO, Cunha MB, Martins DR, Santos JHG, and Alves BJR 2007 Fator de emissão de óxido nitroso (N_2O) para a fertilização com N na cultura do feijoeiro comum irrigado no Cerrado *Comunicado técnico* **144** Santo Antônio de Goiás: Embrapa Arroz e Feijão.

Maddock JEL, Santos MBP, and Prata KR 2001 Nitrous oxide emission from soil of the Mata Atlantica, Rio de Janeiro State, Brazil *J. Geophys. Res.* **106** 055 – 060.

Matson PA, Vitousek PM, Livingston GP, and Swanberg N A 1990 Sources of variation in nitrous oxide flux from Amazonian ecosystems *J. Geophys. Res.* **95** 6789 – 6798.

Melillo JM, Steudler PA, Feigl BJ, Neill C, Garcia D, Piccolo MC, Cerri CC, and Tian H 2001 Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon *J. Geophys. Res.* **106** 179 – 188.

Metay A, Oliver R, Scopel E, Douzet JM, Moreira JAA, Marauy F, Feigl BJ, and Feller C 2007 N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiânia (Cerrados, Brazil) *Geoderma* **141** 78-88.

MMA/IBAMA - Instituto Brasileiro do meio ambiente e dos recursos naturais renováveis 2006 *Reserva Biológica do Tinguá – RJ. Plano de Manejo*. Créditos técnicos e institucionais (Brasília) p 951.

Morais RF, Boddey RM, Urquiaga S, Jantalia CP, and Alves BJR 2013 Ammonia volatilization and nitrous oxide emissions during soil preperation and N fertilization of elephant grass (Pennisetum purpureum Schum.) *Soil Biol. Biochem.* **64** 80 – 88.

Morton DC, DeFries RS, Shimabukuro YE, Anderson LO, Arai E, Espirito-Santo F del Bon, Freitas R, and Morisette J 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon *P. Natl. Acad. Sci. USA* **103** 14637 – 14641.

Neill C, Steudler PA, Garcia-Montiel DC, Melillo JM, Feigl BJ, Piccolo MC, and Cerri CC 2005 Rates and controls of nitrous oxide and nitric oxide emissions following conversion of forest to pasture in Rondônia *Nutr. Cycl. Agroecosys.* **71** 1 – 15.

Neto ES, Carmo JB, Keller M, Martins SC, Alves LF, Vieira SA, Piccolo MC, Camargo P, Couto HTZ, Joly CA, and Martinelli LA 2011 Soil-atmosphere exchange of nitrous oxide, methane and carbon dioxide in a gradient of elevation in the coastal Brazilian Atlantic forest *Biogeosciences* **8** 733 – 742.

Neto MS, Piccolo M de Cassia, Costa C Jr, Cerri CC, and Bernoux M 2011 Emissao de gases do efeito estufa em differentes usos da terra no bioma cerrado. Divisao 2 – Processos e propriedades so solo. 2.1 – Biologia do solo *R. Bras. Ci. Solo* **35** 43 – 76.

Passianoto CC, Ahrens T, Feigl BJ, Steudler PA, Carmo JB do, and Melillo JM 2003 Emissions of CO_2, N_2O, and NO in conventional and no-till management practices in Rondônia, Brazil *Biol. Fertil. Soils* **38** 200-208.

Pinto A de Siqueira, Bustamante MMC, Kisselle K, Burke R, Zepp R, Viana LT, Varella RF, and Molina M 2002 Soil emissions of N_2O, NO and CO_2 in Brazilian Savannas: effects of vegetation type, seasonality, and prescribed fires *J. Geophys. Res.* **107** 8089-8095.

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A, Pauletti V, Tomazim M, and Pergher M 2012 No-till reduces global warming potential in a subtropical Ferralsol *Plant Soil* **361** 359–373.

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A de, Tomazi M, Pauletti V, Barth G, and Piccolo M de Cassia 2014 Soil gaseous N_2O and CH_4 emissions and carbon pool due to integrated crop-livestock in a subtropical Ferralsol *Agr. Ecosyst. Environ.* **190** 87 – 93.

Repo ME, Susiluoto S, Lind SE, Jokinen S, Elsakov V, Biasi C, Virtanen T, and Martikainen PJ 2009 Large N_2O emissions from cryoturbated peat soil in tundra *Nat Geosci* **2** 189 – 192.

Robertson GP and Tiedje JM 1988 Deforestation alters denitrification in a lowland tropical rain forest *Nature* **336** 756 – 759.

Roelandt C, van Wesemael B, and Rounsevell M 2005 Estimating annual N_2O emissions from agricultural soils in temperate climates *Global Change Biol.* **11** 1701 – 1711.

Santos JHG, Costa AR, Madari BE, Machado PL, and Alves BJR 2008 Emissao de oxido nitroso derivada do cultivo de feijoeiro comum (3^a safra) seguido de milho em latossolo de cerrado *Documentos* IAC Campinas **85** 1125 – 1128

Shcherbak I, Millar N, and Robertson GP 2014 Global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen *P. Natl. Acad. Sci. USA* **111** 9199 – 9204.

Silver WL, Thompson AW, McGroddy ME, Varner RK, Dias JD, Silva H, Crill PM, and Keller M 2005 Fine root dynamics and trace gas fluxes in two lowland tropical forest soils *Global Change Biol.* 11 290 – 306.

Sordi A, Dieckow J, Bayer C, Alburquerque MA, Piva JT, Zanatta JA, Tomazi M, Machado C da Rosa, and Moraes A 2014 Nitrous oxide emission factors for urine and dung patches in a subtropical Brazilian pastureland *Agr. Ecosyst. Environ.* **190** 94 – 103.

Sotta ED, Corre MD, and Veldkamp E 2008 Differing N status and N retention processes of soils under old-growth lowland forest in Eastern Amazonia, Caxiuana, Brazil *Soil Biol. Biochem.* **40** 740 – 750.

Steudler PA, Garcia-Montiel DC, Piccolo MC, Neill C, Melillo JM, Feigl BJ, and Cerri CC 2002 Trace gas responses of tropical forest and pasture soils to N and P fertilization *Global Biogeochem. Cy.* **16** 102-108.

Subbarao GV, Nakahara K, Hurtado M P, Ono H, Moreta DE, Salcedo AF, Yoshihashi A T, Ishikawa T, Ishitani M, Ohnishi-Kameyama M, Yoshida M, Rondon M, Rao IM, Lascano CE, Berry WL, and Ito O 2009 Evidence for biological nitrification inhibition in Brachiaria pastures *P. Natl. Acad. Sci. USA* **106** 17302 – 17307.

Tomasella J, Hodnett MG, and Rossato L 2000 Pedotransfer functions for the estimation of soil water retention in Brazilian soils *Soil Sci. Soc. Am. J.* **64** 327 – 338.

Varella RF, Bustamante MMC, Pinto AS, Kisselle KW, Santos RV, Burke RA, Zepp RG, and Viana LT 2004 Soil fluxes of CO_2, CO, NO, and N_2O from an old pasture and from native savanna in Brazil *Ecol. Appl.* **14** 221-231.

Varner RK, Keller M, Robertson JR, Dias JD, Silva H, Crill PM, McGroddy M, and Silver WL 2003 Experimentally induced root mortality increased nitrous oxide emission from tropical forest soils *Geophys. Res. Lett.* **30** 114.

Vasconcelos SS, Zarin DJ, Capaun M, Littell R, Davidson EA, Ishida FY, Santos EB, Araujo MM, Aragao DV, Rangel-Vasconcelos LGT, Oliveira FA, McDowell WH, and Carvalhi CJR 2004 Moisture and substrate availability constrain soil trace gas fluxes in an eastern Amazonian regrowth forest *Global Biogeochem. Cy.* **18** GB2009.

Veldkamp E, Davidson EA, Erickson HE, Keller M, and Weitz A 1999 Soil nitrogen cycling and nitrogen oxide emissions along a pasture chronosequence in the humid tropics of Costa Rica *Soil Biol. Biochem.* **31** 387-394.

Verchot LV, Davidson EA, Cattanio JH, Ackerman IL, Erickson HE, and Keller M 1999 Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia *Global Biogeochem.Cy.* **13** 31– 46.

Verchot LV, Brienza S Jr, Costa V de Oliveira, Mutegi JK, and Cattanio JH, and Davidson EA 2008 Fluxes of CH_4, CO_2, NO, and N_2O in an improved fallow agroforestry system in eastern Amazonia *Agr. Ecosyst. Environ.* **126** 113 – 121.

Vor T, Dyckmans J, Lotfield N, Beese F, and Flessa H 2003 Aeration effects on CO_2, N_2O, and CH_4 emission and leachate composition of a forest soil *J. Plant Nutr. Soil Sci.* **166** 39 – 46.

Wick B, Veldkamp E, Mello WZ de, Keller M, and Crill P 2005 Nitrous oxide fluxes and nitrogen cycling along a pasture chronosequence in Central Amazonia, Brazil *Biogeosciences Discussions* **2** 499 – 535.

3. Model testing for nitrous oxide (N_2O) fluxes from Amazonian cattle pastures

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Abstract

Process-oriented models have become important tools in terms of quantification of environmental changes, for filling measurement gaps, and building of future scenarios. It is especially important to couple model application directly with measurements for remote areas, such as Southern Amazonia, where direct measurements are difficult to perform continuously throughout the year. Processes and resulting matter fluxes may show combinations of steady and sudden reactions to external changes. The potent greenhouse gas nitrous oxide (N_2O) is known for its sensitivity to e.g. precipitation events, resulting in intense but short-term peak events (hot moments). These peaks have to be captured for sound balancing. However, prediction of the effect of rainfall events on N_2O peaks is not trivial, even for areas under distinct wet and dry seasons. In this study, we used process-oriented models in both a pre-and post-measurement manner in order to (a) determine important periods for N_2O-N emissions under Amazonian conditions and (b) recalibrate the models to Brazilian pastures based on measured data of underlying processes (soil moisture and C_{org}) and subsequently on measured N_2O-N fluxes. During the measurement period (early wet season), observed emissions from three cattle pastures did not react to precipitation events, as proposed by the models. Here both process understanding and models have to be improved by long-term data in high resolution in order to prove or disprove a lacking of N_2O-N peaks. We strongly recommend the application of models as planning tools for field campaigns, but we still suggest model combinations and simultaneous usage.

Keywords: N_2O-N fluxes; modeling; cattle pasture; Southern Amazonia

Highlights

- models were used to identify hot moments for N_2O-N in Southern Amazonia.
- observed emissions from pastures were low and did not react to rainfall events.
- calibration and validation primarily aimed to reproduce underlying processes.
- strong need for further process understanding and highly resolved measurements.

1. Introduction

In recent years, the importance of process-oriented models was strengthened by the demand for quantitative and sound assessments of impacts of environmental change. The models aim to reflect our current knowledge of the underlying processes for a specific target variable based on ecosystem-specific factors (Blagodatsky and Smith, 2012). In the course of knowledge gain, process-oriented models have constantly improved to a degree that they might now be used in a pre-measurement manner and not only in a post-measurement way filling measurement gaps and building future scenarios. In this context, greenhouse gas (GHG) exchanges between soil and atmosphere are a prominent example, as principle underlying biogeochemical processes are well known (Butterbach-Bahl et al., 2013) but only partially implemented into mechanistic models (Blagodatsky and Smith, 2012). Thus, the unsteady and sensitive nature of GHG dynamics from soils still leads to considerable deviations between model experiences and associated measurement results and requires intensive site-specific testing. The common way of combined model-measurement approaches would be first to measure and second to test the model on observed data. Depending on the accordance of the model output, a calibration of specific model parameters will be done in order to meet observed data. Nowadays, this would be the most efficient way to optimize model-measurement-approaches.

Continuous testing to various locations and conditions improves the model’s flexibility. This quality is particularly important when dealing with areas which underlie rapid and serious environmental changes (e.g. land use changes) on the one hand and are not easily accessible for daily scientific research on the other hand. Especially remote areas, like the Brazilian Amazon region, are amongst the most essential areas in terms of closing knowledge gaps. This circumstance is an excellent opportunity to use models for improving measurements: Since intensive field studies in remote areas are extremely difficult to perform and very often require special demands to the measurement system, preceding applications of widely tested models could be a good way to optimize scarce measurement time to periods of so-called hot moment events. Hot moments (McClain et al., 2003) describe short time periods of high activity, e.g. during which high emissions of GHG are occurring. Particularly nitrous oxide (N_2O), a potent GHG, is known for its peak events and about half of the annual emission rate can be emitted during these specific periods (Flessa et al., 1995). Three emission patterns (background, events, and season) were identified by Brumme et al. (1999) to satisfyingly describe the interruption of generally low background emissions by either temporary (event-based, e.g. from frost/thaw or rewetting) or longer termed emission increases following moderate decreases (e.g. seasonal temperature and soil moisture changes). Since Southern Amazonia typically underlies distinctly separated seasons (dry and wet), it is challenging to predict occurrences of short/high and long/low peak emissions.

The seasonal patterns are triggered by distinct dry and wet seasons, whereas first intensive rainfall events during the transitional period from dry to wet season (Breuer et al., 2002) may be even more decisive in terms of impulse emissions. In any case, measurements performed during these periods will obviously lead to a better model calibration to local conditions and better include this area into national budgeting. Following Frolking et al. (1998), successful modelling of N_2O fluxes is closely linked to the successful description of measured soil moisture - one of the main driving factors for any biogeochemical process in soils - and the appropriateness of model algorithms linking simulated soil moisture to denitrification and N_2O fluxes. This parameter can usually be determined easily in the field, even at remote sites.

Within the project Carbiocial, our task was the determination of N_2O emissions from cattle pastures along the BR-163 in the state of Pará. Dealing with remote areas and the limitations regarding the planning and realization of measurement campaigns, we used pre-simulations with process-oriented models in order to identify the best measurement periods and develop an adequate measurement design. After that we performed field measurements in high temporal resolution during the identified period of hot moments, and calibrated the models based on measured data and with a special focus on the satisfying description of underlying parameters (soil moisture and C_{org}).

2. Materials and Methods

2.1 Models

The process-oriented biogeochemical models CANDY (Franko et al., 1995), DNDC (Li et al., 1992), and DailyDayCent (DDC) (Del Grosso et al., 2002; Parton et al., 1998) were used to perform pre- and post-measurement modeling. The models run in daily time-steps and thus require information about weather conditions, such as precipitation, air temperature, and global radiation in daily resolution. Additional input parameters are land management and soil properties. Daily climate data for the spin-up and pre-measurement simulations were taken from the online database of the National Climatic Data Center (NCDC) (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/) (Table 3.1). During the field studies a weather station and rain gauges were installed on the studied sites, delivering relevant climate data. Soil data derived from studies of Strey et al. (2016). Model adaptation was made for three pastures, which allowed for a calibration and two subsequent validation processes. Pasture management was defined as year-round grazing and without additional fertilizer application, as indicated by the local farmers. This management was also used during the pre-simulation (Table B.1).

2.1.1 CANDY

The model CANDY (Carbon And Nitrogen DYnamics) was developed by Franko et al. (1995). It is based on data from long-term experiments in Germany (Franko et al. 1997) and has been applied to experiments in the UK (Smith et al. 1997), as well as to the European scale in order to calculate carbon stocks under cropland (Franko et al. 2011). In addition to sub-models for soil water, soil temperature, and crop growth, CANDY simulates soil nitrogen, considering a soil nitrate and soil ammonium pool. Emissions of N_2O-N are expressed as a result of denitrification and thereby soil temperature and water content. The soil column is considered to consist of 20 homogeneous and 10 cm thick layers.

In CANDY, hydrological processes are modeled by the capacity concept, which means that downward water flux is only possible if a soil-specific value of field capacity is exceeded. As this occurs, gravitation forces lead to the draining of the water. Losses of nitrogen may occur as leaching of NO_3-N with the percolation water, or gaseous losses, such as ammonia volatilization and N_2O-N emission. Gaseous losses from nitrate N are triggered by the anaerobic turnover. The calculation of denitrification involves soil moisture and temperature reduction functions, the size of the NO_3 pool and the amount of the carbon in the active soil organic matter pool. The rate is controlled by a rate constant *k_deni* and limited to a maximum. During denitrification, N_2 and N_2O are considered conjointly but are split by a partitioning coefficient, which depends on the water filled pore space, the CO_2 production, and the nitrate concentration, as described by Parton et al. (1996).

2.1.2 DNDC

The DNDC (DeNitrification and DeComposition) model (Li et al. 1992) simulates decomposition and rain event-driven denitrification at the field scale. Predictions of soil temperature, moisture, pH, redox potential and substrate concentration profiles, as well as gas fluxes from the plant-soil systems, are realized by six sub-models, embedded within two main components. Soil water and temperature dynamics are described by a cascade model approach, which assumes that each layer (2 cm thickness) has a uniform temperature and moisture content. Consequently, vertical downward water flow occurs as soon as the field capacity of the specific layer is reached (Zhang et al. 2002). N_2O emissions under aerobic conditions (nitrification) are calculated as a function of soil temperature and soil ammonium concentration. A maximum fraction of 0.06 % loss from gross nitrification is assumed for N_2O production during nitrification (Li et al. 2000). Precipitation events are assumed to start at midnight, have a constant intensity, but a variable duration. As soon as a layer is saturated with water, denitrification starts. Both nitrifying and denitrifying rates are determined based on soil oxygen content via the concept of the anaerobic balloon (Li et al. 2000). This concept divides the soil into an aerobic (outside the balloon) and an anaerobic (inside the balloon) part, based on the Nernst equation to calculate the soil redox potential. The size of the balloon and the reductive and oxidizing processes are calculated with the Michaelis-Menten equation. DNDC includes a database with already parameterized soil types, which can be adapted, according to available soil information. The forest version of DNDC (PnET-N-DNDC) has been tested for tropical rainforest (Kiese et al. 2005) and the model was, for instance, used for estimating methane (CH_4) and N_2O emissions from Brazilian beef cattle feedlots (Costa et al. 2014).

In this study, the latest DNDC version (9.5, downloaded in January 2015) was used.

2.1.3 DailyDayCent

DailyDayCent (DDC) is a daily version of the monthly time-step model CENTURY, developed by Parton et al. (1998). DDC incorporates all of the ecosystem processes represented in CENTURY, which means it simulates fluxes of carbon and nutrients in different ecosystems, such as cropland, grassland, and savanna. The model consists of four main sub-models focusing on soil organic matter, water budget, temperature, and the behavior of nitrogen in the soil. In addition to that, sub-models for phosphorus and sulfur can be switched on individually. The structure of the soil layers is recommended to 15 cm per layer up to a soil depth of 60 cm and 30 cm per layer below. DDC includes a semi-dynamic water model which means that it adopts the capacity concept but describes infiltration and water distribution more dynamically due to multiple soil layers and more realistic and mechanical modifications (Yuan et al. 2011). Unsaturated water flow to each layer is calculated as bidirectional vertical flow using Darcy's equation, which is additionally multiplied by a damping multiplier. Direct nitrogen losses appear as NO_3 leaching, mineralization, denitrification and nitrification and volatilization from crops or grassland. Emissions of N_2, NO_x and N_2O are a result of both nitrification and denitrification. N_2O and NO_x emissions from nitrification are calculated as a function of soil NH_4^+, water content, temperature, pH, and texture. N_2O flux from nitrification is supposed to be proportional to the nitrification rate. The fraction of nitrified N, which is lost as N_2O flux is expressed by a specific factor (K_2 = 2 % per default), based on the comparison of observed and simulated flux data (Frolking et al. 1998; Parton et al. 2001). Emissions from denitrification depend on soil NO_3^-, water content, labile C availability, and soil texture properties that have an impact on the gas diffusion rates (Del Grosso et al. 2002). N losses from denitrification are calculated as $N_2 + N_2O$ and by using a specific ratio function, the proportions of N_2 and N_2O losses are determined (Parton et al. 2001).

In studies in Southern and Southeastern Brazil, Galdos et al. (2009), Bortolon et al. (2011), and Lima et al. (2011) found adequate results with the CENTURY model for simulating soil carbon dynamics under sugarcane, estimating the development of soil organic carbon under different agricultural management scenarios, and changes in organic carbon stocks under eucalyptus rotations, respectively.

2.2 Pre-simulations

The models were applied to typical Southern Amazonian climate, soil, and management conditions (Table B.1) in order to determine the optimal measurement periods for nitrous oxide (N_2O) emissions. The simulation period was from 2007 – 2011. All three models reacted to precipitation events with increasing soil moisture (0 – 10 cm) and resembled in the general course (Figure B.1). However, the CANDY model showed the highest sensitivity to strong rainfall events and simulated soil moisture temporarily exceeded soil porosity. Although uncalibrated and therefore different in calculated emission levels, the model outputs underlined the dry season as negligible and the beginning of the wet season as considerable for N_2O-N fluxes (Figure B.2).

2.3 Site description

Field studies on cattle pastures were conducted on two farms in the municipality of Novo Progresso, Pará (7.14694°S 55.3819°W). The average annual temperature is 25.8 °C and annual precipitation is more than 2200 mm. The rainy season lasts from December until May. Three pastures of different ages were chosen for the field campaign from December 2012 to February 2013, as well as from November to December 2013. On all sites rainforest as native vegetation has been replaced by *Brachiaria (brizantha)* grass. Major soils under these land use types were Acrisol and Ferralsol (Table 3.1), classified according to the World Reference Base (IUSS, 2014).

Table 3.1: Soil properties and years of conversion of the studied pasture sites. The given values refer to the depth 0 – 10 cm (Strey et al. 2016).

Site	**Bulk density [Mg m^{-3}]**	**Clay [g kg^{-1}]**	**C_{org} [g C kg^{-1}]**	**C:N**	**pH**	**Soil type [WRB]**	**Year of conversion**
young	1.39	340	14.5	14.00	4.94	Ferralsol	2001
medium	1.05	440	23.9	11.95	5.07	Ferralsol	1988 (1998[a])
old	1.33	190	18.3	13.25	4.80	Acrisol	1983

[a)] ploughed for degradation reasons and once more sown

2.4 Soil gas flux measurements

The closed chamber method (Flessa et al. 1995) was used to analyze the soil N_2O release. For each study site, PVC rings (A = 0.062 m²) were inserted into the soil (approximately 10 cm) one day before the start of the measurement campaign. They acted as fixed anchors during the field campaign and the previous installation allowed the soil to equilibrate and aimed to prevent detection of fluxes caused by soil disturbances during the ring installation. A capture hood (V = 0.016 m³) that was set on each anchor during the actual measurement for a total period of 90 minutes every day, while headspace samples were taken after 0 (T0), 45 (T1), and 90 (T3) minutes. Samples were taken with a syringe and stored in pre-evacuated 5.9 ml exetainer vials. In order to ensure a representative headspace sample, a small fan (25 x 25 x 10 mm, 5.1 m³ h^{-1}) was used inside each chamber to homogenize the headspace air. The fan was activated from the outside with a battery for 60 seconds before, as well as during each sampling. Subsequently, the exetainer were flushed with a total volume of 50 ml of headspace air. Pressure equilibration was achieved by a vent tube. The outputs of the pre-simulation suggested that precipitation events lead to emission peaks of different heights and durations and this highlighted the need for frequent (daily) measurements. Measurements were taken between 7:00 am and 2:00 pm with 5 repetitions. Because an immediate analysis was not possible, the exetainer were stored on their heads to prevent the escape of gas. Trace gas analysis was carried out by a gas chromatography system consisting of an autosampler unit coupled online to a GC (APS 96/20-K, ESWE Gera Analysentechnik GmbH, Germany, coupled to a GC-14B, Shimadzu, Japan). Gas flux was calculated according to the increase or decrease of gas concentration over time. Assuming a representative flux measurement for the sites, the resulting N_2O flux was projected to a full day and taken as daily average. Additional parameters, such as the temperature inside and outside the chamber, soil water content, and soil temperature were determined for each chamber.

2.5 Model setup

Achieving the best agreement between measurements and model outputs usually requires the adjustment of internal model parameters. Considering model adaptation to N_2O-N fluxes, additional state variables and environmental parameters have to be represented adequately. Being in the inner tropics the daily averaged temperatures are fairly constant and relevant differentiation in N_2O-N fluxes due to temperature differences are highly unlikely. Furthermore, measured soil temperature data was restricted to the duration of the measurements, but the models perform on mean daily temperatures. Therefore, they are not included in calibration and validation. According to our objectives, we followed the approach of first describing carbon stocks and soil moisture of each site (calibration and validation) as best as possible before modifying parameters for N_2O-N fluxes. The latter were only adapted during the calibration, but kept the validation process. Generally, the models CANDY and DNDC were run over a 7 year period with a spin-up of 5 years, whereas simulations with DDC were started in 2000 B.C.

2.5.1 Calibration to observed soil moisture

Soil moisture is mentioned as the main driver for N_2O-N emissions because the decrease in O_2 availability in the soil influences biogeochemical reactions and, consequently, greenhouse gas production (Hall et al., 2012). Being a critical determinant of N_2O fluxes (Dobbie and Smith, 2001; Keller and Reiners, 1994) , over- or underestimation of soil moisture may result in strong discrepancies between measured and modelled N_2O fluxes. This knowledge is implemented in all three models and soil moisture influences nitrification and denitrification processes and rates.

Hence, we initially adapted field capacity, wilting point, and saturated hydraulic conductivity individually for each site and model based on the observed soil moisture dynamics.

2.5.2 Calibration to observed carbon stocks

N_2O emissions have often been reported to being directly influenced by the SOC content and mineralization, respectively. Denitrifiers are heterotrophic organisms which depend on carbon to survive. The turnover of SOC leads to anaerobic conditions in the soil which favors denitrification (e.g. Burford & Bremner 1975, Senbayram et al. 2012). Thus, correct representation of the observed C_{org} content and carbon stocks, respectively, by the models can be expected to have an impact on modelled N_2O-N fluxes. For DNDC, SOC has been found a very sensitive factor regarding N_2O fluxes (Li et al. 1996).

CANDY and DNDC allow the user to use information on soil carbon as input data based on the assumption of an equilibrium or steady state in the soil. Initial values for C_{org} (CANDY) or depth distribution of soil organic carbon (DNDC) were adapted, in order to meet measured SOC (0 - 30 cm depth) by the end of the simulation. In DDC, the soil carbon equilibrium has to be developed by a spin-up of several thousand years. Following this, we started the simulation in 2000 B.C., assuming tropical rainforest as natural vegetation. Conversion was simulated by a clear-cut of the rainforest, followed by a ploughing event, and application of cattle pasture in the specific year. This assumption is in accordance to proceedings at the studied sites. In order to simulate carbon contents under cattle pasture, we adjusted the timing of clear-cut and ploughing, the C:N ratios of material entering different SOM pools (*VARAT*), and the corresponding decomposition rates of SOM with intermediate turnover (*DEC5*). The effect of a ploughing event on decomposition can be adapted by cultivation factors (*CLTEFF*) for the different SOM pools. These factors multiply decomposition rates in the month of the cultivation. *CLTEFF*, *VARAT*, and the timing of forest conversion and ploughing were kept within the validation process, but *DEC5* was adapted for each site. We used the output parameter *somtc,* which describes the total soil carbon including undecayed root litter and appeared us to be closest to measured C stocks (0 – 20 cm depth).

2.5.3 Calibration to observed N2O-N fluxes

N_2O-N flux parameters (one for CANDY and one for DDC) were calibrated based on data from the old pasture. Consistent to the soil physical parameters (see 2.5.2 Calibration to observed soil moisture), the optimization was performed using the Optimizer tool, described by Oelschlägel et al. (2015). This tool uses the downhill simplex method of Nelder and Mead (1965), aiming to find a local minimum of a nonlinear function with more than one independent variable (Press et al., 1992). Calibrated N_2O-N flux parameters were kept during the simulations of the medium-aged and young pasture in order to enable a validation process.

2.6 Model validation

Models were validated using N_2O-N flux data from the medium-aged and young pasture, since they were not part of the model calibration. During the validation phase we kept plant and emission specific parameters for each model as adjusted during the calibration phase. Considering the different soil types (Acrisol vs. Ferralsol) and the differences in clay and carbon contents of the sites chosen for validation (Table 3.1), we adjusted soil physical parameters and carbon stocks. The duration and spin-up data was the same for calibration and validation.

2.7 Statistical methods and model accuracy

Data was analyzed and plotted using the statistical tool R 2.15.0. Results were assumed to be significant for a p value equal or smaller than 0.01.

Model accuracy was based on median values of observed data of soil moisture [Vol %] and N_2O-N fluxes [kg N ha^{-1}]. Quality criteria were the root mean squared error (RMSE, Eq. 3.1) and the lack of fit (LOFIT, Eq. 3.2). Latter was described by Whitmore (1991) and evaluates the difference between measured and simulated values excluding error associated with variations in the measurements and repetitions, respectively. If replicates are available, LOFIT provides a very thorough analysis of coincidence (Smith & Smith 2007) and states whether the model error is greater than the error in the measurements.

In both cases the lower the values – given in the specific unit - the better the fit between observed and simulated data. The RMSE has an optimum value of 0 representing a perfect match. In contrast to this, the LOFIT not only accounts for the observed mean value being simulated, but also considers the variance within the repetitions and can best be interpreted in comparison with other sites.

$$RMSE = \left(\sum_{i=1}^{n}(O_i - P_i)^2 / n\right)^{1/2} \qquad \text{(Eq. 3.1)}$$

$$LOFIT = \sum_{i=1}^{n} m_i(O_i - P_i)^2, \qquad \text{(Eq. 3.2)}$$

where O and P stand for the observed and predicted values, n is the number of data, and m represents the number of repetitions. Significance of the LOFIT was tested by comparison of the F value with the critical 1 % F value.

3. Results and discussion

3.1 Calibration site

3.1.1 Soil moisture

Strong precipitation events were reproduced by increasing soil moisture by all models, but not always observed in the field (e.g. Figure 3.1; 90 mm precipitation at the end of December 2012). This cannot necessarily be reduced to model inaccuracy, but to the timing of the daily measurements. After adjusting default values of field capacity, wilting point, and saturated hydraulic conductivity (Table B.2), the models were able to reproduce the temporal patterns of the measured soil moisture (Figure 3.1 a-c, Table 3.4).

The CANDY model strongly reacted to single precipitation events and simulated soil moisture exceeded soil porosity after heavy rainfall at all sites. This is caused by the inclusion of simulated puddle water (ponding) in the water balance of the first soil layer, as it was observed in the field after strong precipitation events. Soil moisture measurements were focused to a depth of 0 - 10 cm, as this depth is assumed to be of great importance for N_2O production (Hosen et al., 2000). Thus, a further segmentation of the first soil layer could be helpful. However, this shallow depth turned out to be inappropriate for testing CANDY’s water submodule. Following the process understanding, the standing water acts as diffusion barriers and consequently hinders N_2O fluxes and leads to lower net emissions. In order to get useful optimization results for soil physical parameters, simulated values which were equal or higher than the soil porosity were excluded from the optimization process.

The semi-dynamic model DDC matched best with observed soil moisture (RMSE = 4.69 Vol %). The DNDC model over- and underestimated observations and thus suggested even stronger dynamics in the water balance than found in the field (RMSE = 7.75 Vol %). Especially on days without rainfall, simulated soil moisture fell below observed values. This is a result of the high hydraulic conductivities that were found within the optimization process (Table B.2).

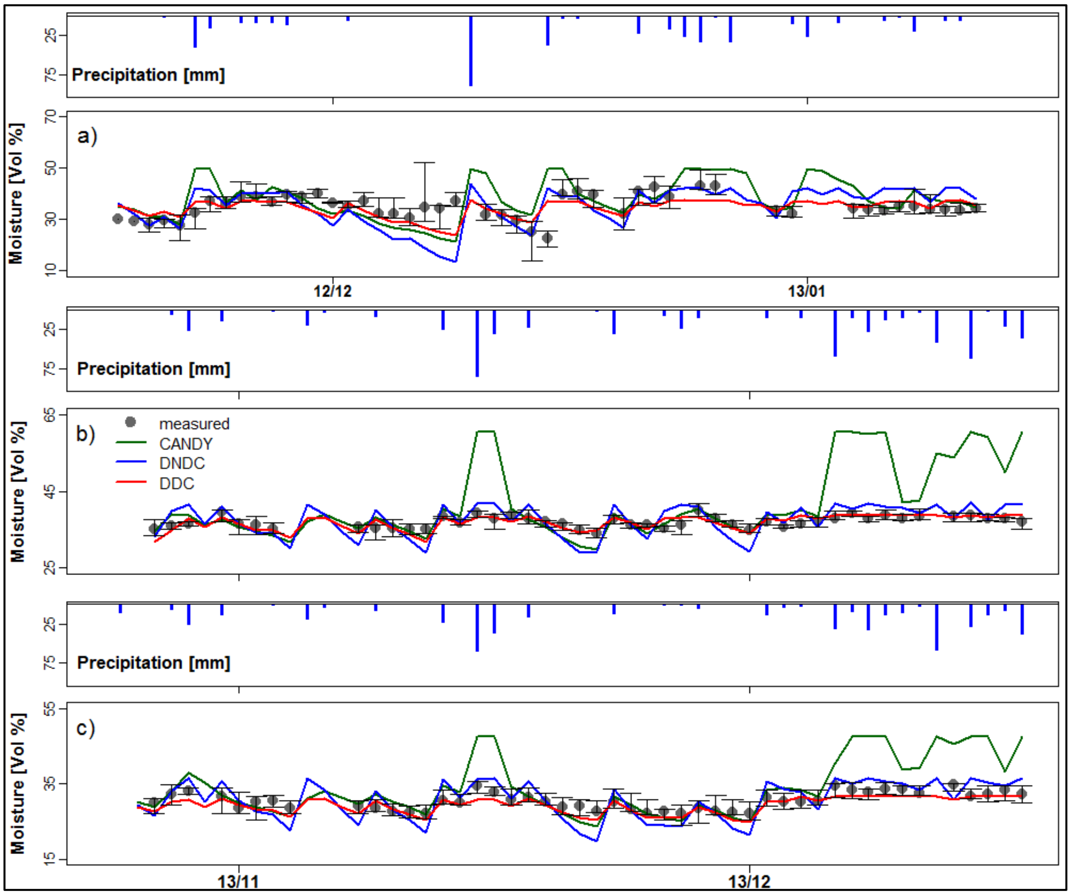

Figure 3.1: Adaptation of CANDY, DNDC, and DDC to observed soil moisture [Vol %] (0 – 10 cm) from an old (a), a medium-aged (b), and a young (c) cattle pasture.

3.1.2 Carbon stock

The models satisfyingly calculated measured carbon stocks after adjustments (Table 3.3). On the old cattle pasture, the difference between the carbon content of the first (0 – 10 cm, C_{org} = 18.3 g C kg^{-1}) and the second layer (10 – 30 cm, C_{org} = 6.81 g C kg^{-1}) was large. CANDY and DNDC consider this horizon distribution in the outputs and the observed carbon decrease with soil depth was provided by large differences in the initial horizon-specific parameterization (CANDY) and a high decreasing content with soil depth (DNDC), respectively (Table B.2). For DNDC, we adapted the initial SOC content and decrease of carbon content along the soil profile for each site, and assumed a uniform SOC content in the first 10 cm of each profile.

For DDC we adjusted the maximum C:N ratio of material entering various soil pools (*VARAT*), as well as the maximum decomposition rates of soil organic matter (SOM) pools with intermediate turnover (*DEC5*) in order to meet measured carbon stocks. Although information about the year of pasture establishment was available, we did not know about the exact timing of the cut-down of the rainforest. Best results were gained by a clear-cut within the first 6 month of the specific year and a ploughing event after 50 more days. The effect of a ploughing event on decomposition can be adapted by cultivation factors (*CLTEFF*) for the different SOM pools. These factors multiply decomposition rates in the month of the cultivation. During the calibration, we set the cultivation factors for surface organic matter, soil organic matter with intermediate and slow turnover to the maximum value of 2.

Attention has to be paid to the different output depths: DDC calculates carbon stocks only for the first 0 – 20 cm of the soil profile, whereas CANDY and DNDC allow a more horizon-specific calculation and output. The adapted parameters for each model are listed in Table B.2.

Table 3.2: Measured and modeled carbon stocks in the depths 0 – 20 cm (DDC) and 0 – 30 cm (CANDY and DNDC) after parameter adjustments.

Site	**Measured**		**CANDY**	**DNDC**	**DDC**
	0 – 20 cm [a)]	0 – 30 cm	0 – 30 cm		0 – 20 cm
			[t ha^{-1}]		
old	34.13	43.94	43.80	44.10	34.15
medium	39.60	55.67	55.64	56.70	39.56
young	31.11	42.76	42.98	42.48	31.10

[a)] recalculated based on the results for 0 – 30 cm

3.1.3 N_2O fluxes

Average emissions were highest from the young (183 µg m^{-2} d^{-1}) and lowest from the old pasture (38 µg m^{-2} d^{-1}) (Table 3.3). This is consistent with findings of Neill et al. (1995), Melillo et al. (2001), and Meurer et al. (2016) who reported on decreasing N_2O fluxes with pasture age. No significant difference was found between the young and medium-aged pasture ($p = 0.23$), but both were significantly different from the old pasture ($p < 0.01$). Negative emissions were only observed on the medium-aged and old pasture. Some studies still dismiss measured fluxes from the atmosphere to the soil, but Chapuis-Lardy et al. (2007) strongly highlight the importance of N_2O uptake for estimating global N_2O budgets, even if they are low. However, consideration of negative N_2O emissions is implemented in none of the three models used in this study.

Table 3.3: Minimum, median, and maximum N_2O fluxes [$\mu g\ N\ m^{-2}\ d^{-1}$] from pasture sites in Novo Progresso.

Site	**N_2O fluxes [$\mu g\ N\ m^{-2}\ d^{-1}$]**		
	Min	**Median**	**Max**
young	28	183	1254
medium	-30	164	768
old	-79	38	425

Simulated N_2O-N emissions from the old cattle pasture are shown in Figure 3.2. Emissions calculated by the CANDY model followed the low course of the measurements (RMSE = 0.86 x 10^{-3} kg N ha^{-1}). The denitrification rate constant *k_deni* was found to be optimal at a value of 1.75 x 10^{-5} d^{-1} during the calibration based on emission data from the old pasture. However, total N_2O-N fluxes over the period were underestimated by 22 % (Table 3.5). Similar patterns were simulated by the DDC model, which showed no noticeable response to precipitation events. The K_2 factor, which describes the amount of nitrified N that is lost as N_2O, was optimized to a value of 0.2. This parameterization resulted in an almost perfect match with cumulative fluxes – the upwards deviation from the measured values was 4 % (0.001 kg N ha^{-1}). The RMSE was slightly higher than from the CANDY model (0.88 x 10^{-3} kg N ha^{-1}). DNDC has a high sensitivity to soil organic carbon and rainfall and simulated emission peaks, which were not observed in the field. A particular increase occurred on the old pasture following the strong precipitation event (90 mm) at the end of December 2012, by which the simulated water filled pore space increased from 0.27 to 0.88. The model suggested that the influence of this rainfall event on N_2O-N fluxes maintains over a longer period (several days) and is taken up by subsequent rainfall, resulting in another longer lasting emission peak. At the same time, the simulated soil nitrogen did not decrease during the simulated period, but rather accumulated, which consequently increased the amount of N available for N_2O-N fluxes. As a consequence of these strong upwards outliers, cumulative fluxes were overestimated by almost 4,400 % (Table 3.5). The RMSE was two magnitudes higher compared to the CANDY and DDC model (33.3 x 10^{-3} kg N ha^{-1}, Table 3.4).

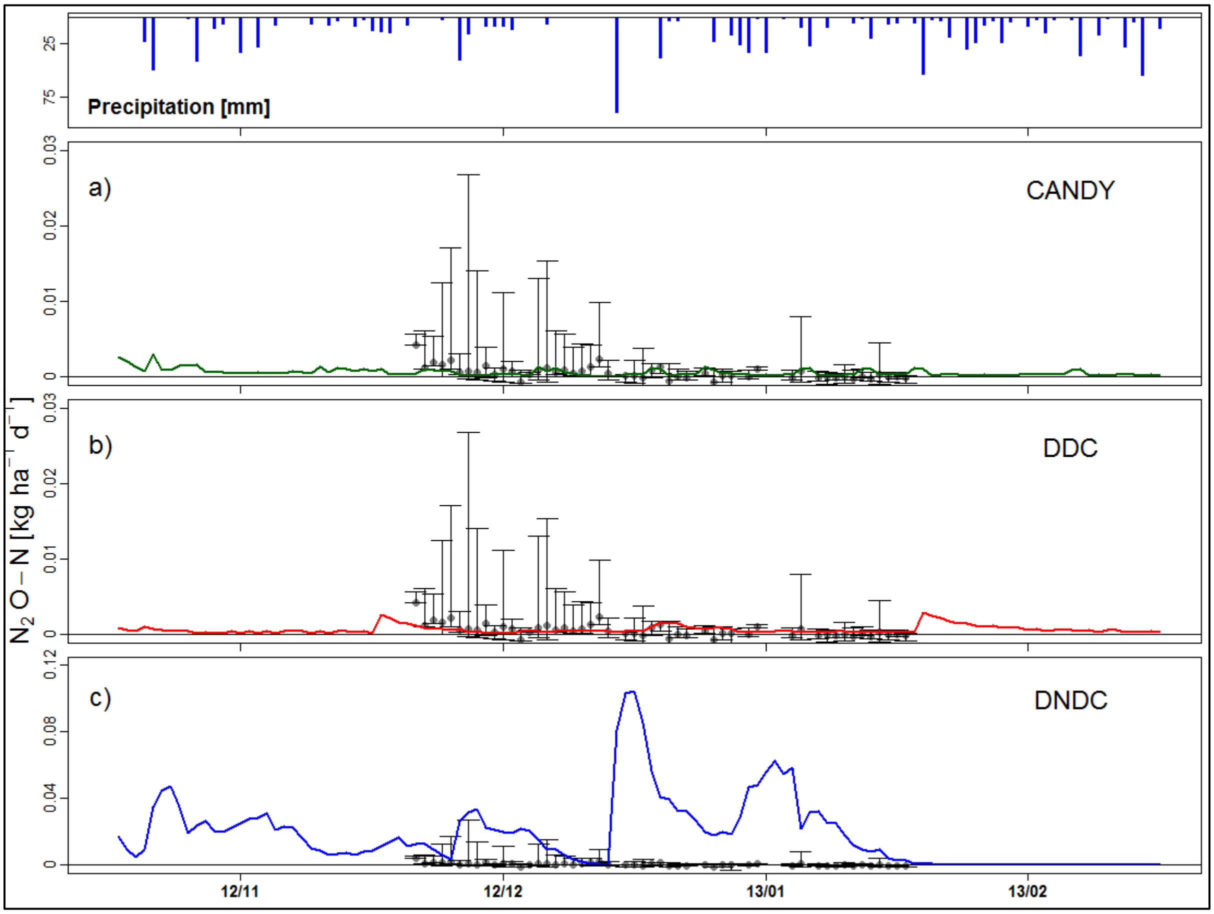

Figure 3.2: Adaptation of CANDY (a), DDC (b), and DNDC (c) to observed soil N2O-N fluxes from an old cattle pasture. Observed data is presented as median, error bars represent minimum and maximum observations.

Table 3.4: Root mean squared error (RMSE) and lack of fit (LOFIT) of the adapted model outputs regarding soil moisture [Vol %] and N_2O flux [kg N ha^{-1}] for three cattle pastures.

			RMSE		**LOFIT**	
	Site	**Model**	**Soil moisture [Vol %]**	**N_2O flux [kg N ha^{-1} d^{-1}]**	**Soil moisture [Vol %]**	**N_2O flux [kg N ha^{-1} d^{-1}]**
Cali-bration	*old*	CANDY	5.71 $^{a)}$	0.89 x 10^{-3}	6543 $^{a)}$	0.56 x 10^{-3}
		DDC	4.69	0.88 x 10^{-3}	4816	0.59 x 10^{-3}
		DNDC	7.75	33.3 x 10^{-3}	12430	535 x 10^{-3}
Validation	*medium*	CANDY	5.14 $^{a)}$	2.02 x 10^{-3}	4980 $^{a)}$ *	45.6 x 10^{-3}
		DDC	1.29	3.09 x 10^{-3}	377	46.7 x 10^{-3}
		DNDC	3.34	33.0 x 10^{-3}	2569	279 x 10^{-3}
	young	CANDY	3.32 $^{a)}$	3.01 x 10^{-3}	13042 $^{a)}$	0.12 x 10^{-3}
		DDC	1.69	2.86 x 10^{-3}	713	0.11 x 10^{-3}
		DNDC	3.60	28.4 x 10^{-3}	2992	1.82 x 10^{-3}

$^{a)}$ after exclusion of soil moisture ≥ pore volume

* = model error is significantly greater than measurement error

Table 3.5: Duration of measurement period [d] and cumulative measured and modeled N_2O fluxes [kg N ha^{-1}]. *Diff* specifies the deviation of cumulative measured and modeled fluxes.

Site	Duration	Measured	CANDY	Diff	DNDC	Diff	DDC	Diff
	[d]	[kg N ha^{-1}]						
old	57	0.027	0.023	- 0.004	1.209	+ 1.182	0.028	+ 0.001
medium	52	0.094	0.026	- 0.068	1.193	+ 1.099	0.157	+ 0.063
young	53	0.119	0.022	- 0.097	0.974	+ 0.855	0.029	- 0.090

3.2 Validation sites

3.2.1 Soil moisture

After adaptation of soil physical parameter within the CANDY model, RMSEs ranged from 3.38 (young) to 5.16 Vol % (medium-aged pasture). With regard to the medium-aged pasture, the model error (deviations of model results from observations) was even greater than the error within the measurement repetitions, as indicated by the significant LOFIT (7,447; Table 3.4). The variance within the measurements was low on this site, compared to the old pasture, and this consequently increases the importance of the error caused by model deviations. Best description of observed soil moisture on the medium-aged and young pasture was given by DDC (RMSEs: 1.29 Vol % and 1.69 Vol %, respectively). DNDC still strongly over- and underestimated observed soil moisture, as a result of precipitation events and periods without rainfall, respectively. RMSEs were 3.34 and 3.60 Vol % for the medium-aged and young pasture; however, the error within the measurements was still greater than the model error.

3.2.2 Carbon stocks

Observed carbon stocks from the medium-aged and young pasture were satisfyingly reproduced by the models (Table 3.2) after adaptation of initial SOC contents and depth distributions (CANDY and DNDC, respectively). For DDC, calibrated values for C:N ratio of material entering the soil pools and the cultivation factor for decomposition were kept during the validation process and only decomposition rates were adapted site-specifically (Table B.2).

3.2.3 N_2O fluxes

Simulated N_2O-N emissions for the validation sites (medium-aged and young pasture) are shown in Figures 3.3 and 3.4. For both models CANDY and DDC, adaptation of the calibrated parameters (*k_deni* for CANDY and K_2 for DDC) resulted in strong under- and overestimations of observed fluxes from the medium-aged and young cattle pasture. While fluxes from both pastures were strongly underestimated by the CANDY model (-73% at medium-aged and -84 %

at young pasture), DDC underestimated observations from the young pasture (-76 %), but overestimated emissions from the medium-aged pasture by 67 %. Comparable over- and underestimations were reported from Abdalla et al. (2010) for simulations of N_2O-N fluxes from Irish pastures with (+ 38 %) and without (- 50 %) fertilization. In this study, the model output from DDC was still in the range of the measured variances for both sites, as indicated by the non-significant LOFITs (46.7 x 10^{-3} (medium-aged) and 11.0 x 10^{-3} kg N ha^{-1} (young)). However, these results of the CANDY and DDC model suggest that the adoption of the optimized factors *k_deni* (1.75 x 10^{-5} d^{-1}) and K_2 (0.2) to younger pastures is not optimal. Following the assumption of decreasing N_2O fluxes with increasing pastures ages, as mentioned by the authors above and found in this study, further consideration of the total nitrogen balance of the sites is mandatory. In this study, none of the models showed a suchlike trend.

In the DNDC model, emission peaks resulting from precipitation events led to strong overestimation of cumulative fluxes (1,169 % (medium-aged) and 718 % (young)). These values are clearly higher than overestimation of observed fluxes found by Beheydt et al. (2007) on grazed grassland sites in Germany (+ 154 %) and by Abdalla et al. (2010) for annual fluxes from fertilized (+ 132 %) and unfertilized (+ 258 %) pastures. Despite these upward deviations, the LOFIT still did not indicate significant errors between measured and modeled data (Table 4). However, RMSEs for DNDC were 10 times higher than for CANDY or DDC (33.0 x 10^{-3} (medium-aged) and 28.4 x 10^{-3} kg N ha^{-1} (young)).

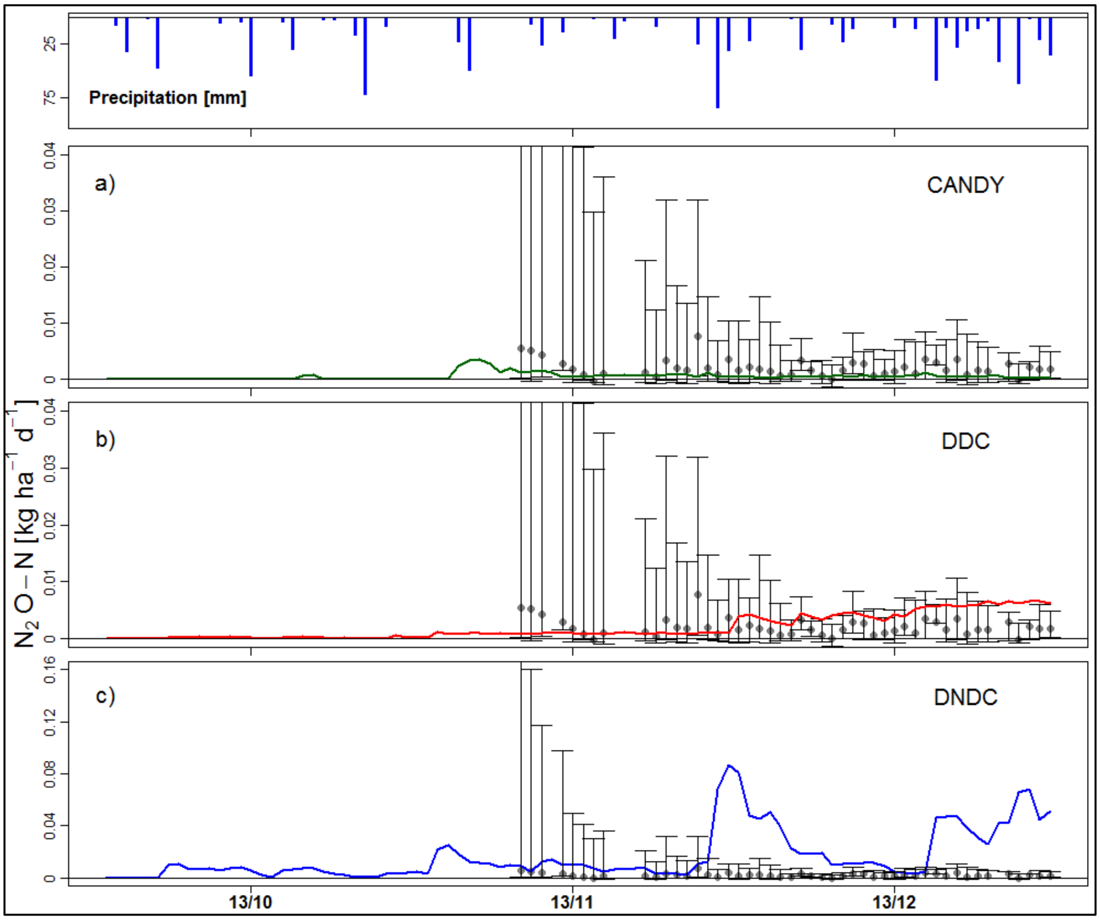

Figure 3.3: Model simulations with CANDY (a), DDC (b), and DNDC (c) for N_2O-N fluxes from a medium-aged cattle pasture used for model validation.

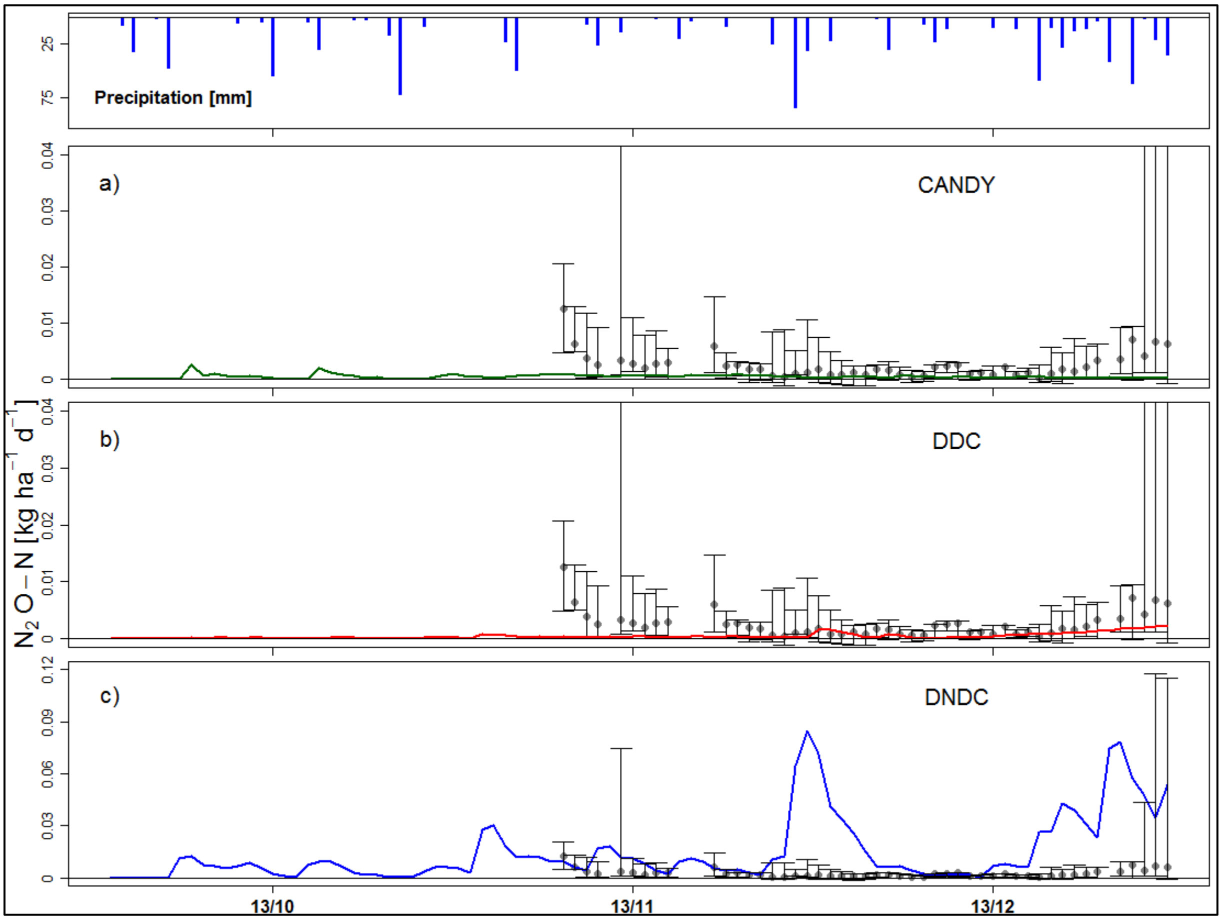

Figure 3.4: Model simulations with CANDY (a), DDC (b), and DNDC (c) for N_2O-N fluxes from a young cattle pasture used for model validation.

Simulated all-season N_2O-N fluxes from the young pasture for the second half of 2012 and the whole 2013 (Figure 3.5) confirmed that the field studies fell within the most active emission periods. However, they did not capture the effective end of the dry season, which is accounted by the CANDY model as period with high, but short-term emission peaks, following single precipitation events. In contrast to DNDC, which suggested an emission decline to zero from the second half of the rainy season until the beginning of the next rainy season, CANDY and DDC still react to the almost daily rainfalls.

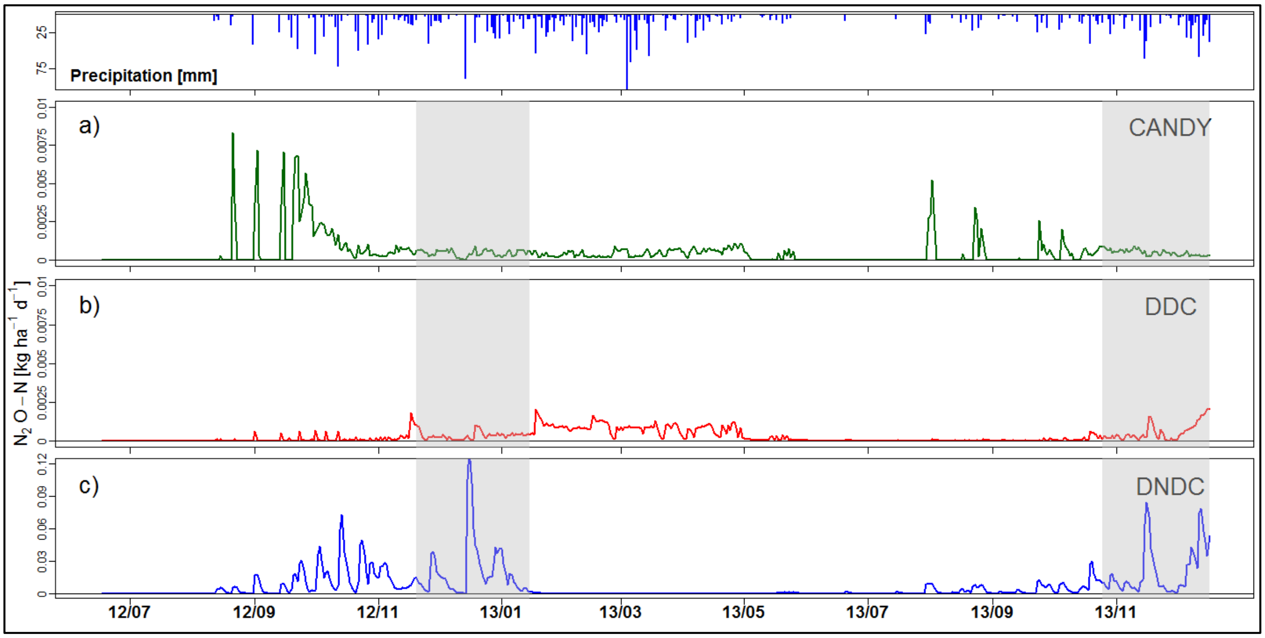

Figure 3.5: Simulated all-season N_2O-N fluxes from the young pasture with calibrated CANDY (a), DDC (b), and DNDC (c) for the second half of the year 2012 and the whole year 2013. Gray shaded areas represent the time periods of the field studies.

4. Conclusions

In this study, the hot moments that were predicted by the models were not measured in the field. This may be because (a) they did not happen or (b) they only occurred during the first precipitation events at the end of the dry season and hence were missed. There is still a lack of process understanding regarding the influence of pasture ages on the decrease of N availability and consequently on N_2O emissions is not regarded by the models. This is especially important when modeling Brazilian cattle pastures, since the *Brachiaria* grass rather immobilizes soil nitrogen. Here, process understanding has to be improved and gained knowledge has to be implemented into the models. In particular, data in higher resolution (daily) over a considerable period (full year) is needed, in order to prove or disapprove a lacking of emission peaks. In addition to that, we do not recommend the usage of only one model for tropical cattle pastures. We rather suggest further model improvement with regard to tropical ecosystems, as well as model combination. To that effect, development of an overarching tool to operate these (and additional) models simultaneously may be useful.

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References

Blagodatsky S and Smith P 2012 Soil physics meets soil biology: Towards better mechanistic prediction of greenhouse gas emissions from soil *Soil Biol. Biochem.* **47** 78-92.

Bortolon ESO, Mielniczuk J, Tornquist CG, Lopes F, and Bergamaschi H 2011 Validation of the Century model to estimate the impact of agriculture on soil organic carbon in Southern Brazil *Geoderma* **167-168** 156-166.

Breuer L, Kiese R, and Butterbach-Bahl K 2002 Temperature and Moisture Effects on Nitrification Rates in Tropical Rain-Forest Soils. *Soil Sc. Soc. Am. J.* **66** 834 - 844.

Brumme R, Borken W, and Finke S 1999 Hierarchical control on nitrous oxide emission in forest ecosystems *Global Biogeochem. Cy.* **13** (4) 1137-1148.

Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, and Zechmeister-Boltenstern S 2013 Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philos. T. R. Soc. B.* **368** (1621) 20130122.

Chapuis-Lardy L, Wrage N, Metay A, Chotte JL, and Bernoux M 2007 Soils, a sink for N_2O? A review. *Global Change Biol.* **13** (1), 1-17.

Costa CJ, Li C, Cerri CEP, and Cerri CC 2014 Measuring and modeling nitrous oxide and methane emissions from beef cattle feedlot manure management: First assessments under Brazilian condition *J. Environ. Sci. Heal. B.* **49** (9) 696 - 711.

Moraes JM de, Schuler AE, Dunne T, Figueiredo RdO, and Victoria RL 2006 Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia *Hydrol. Process.* **20** (12) 2509-2526.

Del Grosso SJ, Ojima D, Parton WJ, Mosier AR, Peterson G, and Schimel DS 2002 Simulated effects of dryland cropping intensification on soil organic matter and GHG exchanges using the DAYCENT ecosystem model *Environ. Pollut.* **116** S75 - S83.

Dobbie KE and Smith KA 2001. The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol *Eur. J. Soil Sci.* **52** 667 - 673.

Flessa H, Dörsch P, and Beese F 1995. Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in southern Germany *J. Geophys. Res.* **100** (D11) 23,115 - 123,124.

Franko U, Crocker GJ, Grace PR, Klir J, Körschens M, Poulton PR, and Richter DD 1997 Simulating trends in soil organic carbon in long-term experiments using the CANDY model *Geoderma* **81** 109 - 120.

Franko U, Oelschlägel B, and Schenk S 1995 Simulation of temperature-, water- and nitrogen dynamics using the model CANDY *Ecol. Model.* **81** 213 - 222.

Frolking SE, Mosier AR, Ojima DS, Li C, Parton WJ, Potter CS, Priesack E, Stenger R, Haberbosch C, Dörsch P, Flessa H, and Smith, KA 1998 Comparison of N_2O emissions from soils at three temperate agricultural sites. Simulations of year-round measurements by four models *Nutr. Cycl. Agroecosys.* **52** 77 - 105.

Galdos MV, Cerri CC, Cerri CEP, Paustian K, and Van Antwerpen R 2009 Simulation of Soil Carbon Dynamics under Sugarcane with the CENTURY Model *Soil Sc. Soc. Am. J.* **73** (3) 802.

Hall SJ, McDowell WH, and Silver WL 2012 When Wet Gets Wetter: Decoupling of Moisture, Redox Biogeochemistry, and Greenhouse Gas Fluxes in a Humid Tropical Forest Soil *Ecosystems* **16** (4) 576-589.

Hosen Y, Tsuruta H, and Minami K 2000 Effects of the depth of NO and N_2O production in soil on their emission rates to the atmosphere: analysis by a simulation model *Nutr. Cycl. Agroecosys.* **57** 83 - 98.

IUSS 2014. World Reference Base for Soil Resources 2014, World Soil Resources Reports, Rome.

Keller M and Reiners WA 1994 Soil-atmosphere exchange of nitrous oxide, nitric oxide and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica *Global Biogeochem. Cy.* **8** (4) 399 - 409.

Kiese R, Li C, Hilbert DW, Papen H, and Butterbach-Bahl K 2005 Regional application of PnET-N-DNDC for estimating the N_2O source strength of tropical rainforests in the Wet Tropics of Australia *Global Change Biol.* **11** (1) 128-144.

Li C, Aber J, Stange F, Butterbach-Bahl K, and Papen H 2000 A process-oriented model of N_2O and NO emissions from forest soils: 1. Model development *J. Geophys. Res.* **105** (D4) 4369 - 4384.

Li C, Frolking S, and Frolking TA 1992 A Model of Nitrous Oxide Evolution From Soil Driven by Rainfall Events. *J. Geophys. Res.* **97** (D9) 9759 - 9776.

Lima AMN, Silva IRd, Stape JL, Mendonca ES, Novais RF, Barros NFd, Neves JCL, Paul J, Schulthais F, Polglase P, Raison J, and Soared EMB 2011Modeling changes in organic carbon stocks for distinct soils in southeastern Brazil after four eucalyptus rotations using the Century model *Rev. Bras. Cienc. Solo* **35** 833 - 847.

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, and Pinay G 2003 Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems *Ecosystems* **6** (4) 301-312.

Melillo JM, Steudler PA, Feigl BJ, Neill C, Garcia D, Piccolo MC, Cerri CC, and Tian H 2001 Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon *J. Geophys. Res.* **106** (D24) 34179.

Meurer KHE, Franko U, Stange CF, Rosa JD, Madari BE, and Jungkunst HF 2016 Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil - a critical review *Environ. Res. Lett.* 11 (2016) 023001, doi: 10.1088/1748-8326/11/2/023001.

Neill C, Piccolo MC, Steudler PA, Melillo JM, Feigl BJ, and Cerri CC 1995 Nitrogen dynamics in soils of forest and active pastures in the western Brazilian Amazon Basin *Soil Biol. Biochem.* **27** (9) 1167 - 1175.

Nelder JA and Mead R 1965 A simplex method for function minimization *Comput. J.* **7** (4) 308 - 313.

Oelschlägel B, Franko U, Bönecke E, Meurer K, Prays N, and Witting F 2015 Optimizer - Description of Usage. Available on http://www.ufz.de/index.php?de=13152.

Parton WJ, Hartman M, Ojima D, and Schimel DS 1998 DAYCENT and its land surface submodel: description and testing *Global Planet. Change* **19** 35 - 48.

Parton WJ, Holland EA, Del Grosso SJ, Hartman MD, Martin RE, Mosier AR, Ojima DS, and Schimel DS 2001 Generalized model for NO_x and N_2O emissions from soils *J. Geophys. Res.* **106** (D15) 17403.

Parton WJ, Mosier AR, Ojima DS, Valentine DW, Schimel DS, Weier K, and Kulmala AE 1996 Generalized model for N_2 and N_2O production from nitrification and denitrification *Global Biogeochem. Cy.* **10** (3) 401-412.

Press WH, Teukolsky SA, Vetterling WT, and Flannery BP 1992 Downhill simplex method in multidimensions. Numerical recipes in C: the art of scientific computing. Cambridge University Press, Cambridge.

Scheffler R, Neill C, Krusche AV, and Elsenbeer H 2011 Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier *Agr. Ecosyst. Environ.* **144** (1) 281-289.

Smith J and Smith P 2007 Environmental Modelling - An introduction. Oxford University Press, New York.

Smith P, Smith JU, Powlson DS, McGill WB, Arah JRM, Chertov OG, Coleman K, Franko U, Frolking S, Jenkinson DS, Jensen LS, Kelly RH, Klein-Gunnewiek H, Komarov AS, Li C, Molina JAE, Mueller T, Parton WJ, Thornley JHM, and Whitmore AP 1997 A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments *Geoderma* **81** 153 - 225.

Strey S, Boy J, Strey R, Weber O, and Guggenberger G 2016 Response of soil organic carbon to land-use change in central Brazil: A large-scale comparison of Ferralsols and Acrisols. *Plant Soil*.

Whitmore AP 1991 A method for assessing the goodness of computer simulations of soil processes *J. Soil Sci.* **42** 289 - 299.

Yuan F, Meixner T, Fenn ME, and Šimůnek J 2011 Impact of transient soil water simulation to estimated nitrogen leaching and emission at high- and low-deposition forest sites in Southern California. *J. Geophys. Res.* **116** G03040.

Zhang Y, Li C, Zhou X, Moore III B 2002 A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture *Ecol. Model.* **151** 75 - 108.

Zimmermann B, Elsenbeer H, and Moraes JM de 2006 The influence of land-use changes on soil hydraulic properties: Implications for runoff generation *Forest Ecol.Manag.* **222** (1-3) 29-38.

4. Future scenarios of land use and land cover change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils

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Abstract

The calculation of robust estimates of future greenhouse gas emissions from agriculture is essential to support the framing of the Brazilian climate mitigation policy. Prerequisite is 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. The spatially explicit land use model LandSHIFT was applied to calculate a set of high resolution land use scenarios for Southern Amazonia. Time frame of the analysis was the year 2030. Based on the generated maps, emission factors were applied to calculate N_2O, CH_4, and CO_2 emissions from agricultural soils. The results indicate that future land use pattern and the resulting greenhouse gas emissions in Southern Amazonia will be strongly determined by global and regional demands for agricultural commodities but also from the level of intensification of agriculture and the implementation of nature protection policies.

Keywords: Land use and land cover change, Southern Amazonia, scenarios, agriculture, greenhouse gas emissions

1. Introduction

Throughout the last decades, Southern Amazonia was characterized by the conversion of large areas of forest and Cerrado ecosystems (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 Brazils' largest contributors to greenhouse gas emissions (e.g. Lapola et al. 2014). Main drivers of these land use and land cover changes were an accelerated population growth together with an ongoing trend of urbanization and the expansion of cropland and grazing land due to an increased global demand for fodder and energy crops, meat and timber (Godfray et al. 2010). The subsequent agricultural land use currently contributes ~35 % to Brazil's greenhouse gas emissions (CAIT 2014) mainly in form of CO_2 but also N_2O and CH_4.

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. 2015a; Nepstad et al. 2014) and (2) the decrease of world market prices for soybean (Nepstad et al. 2009; Hecht 2011) in combination with a further intensification of agricultural systems (Cohn et al. 2014; Macedo et al. 2012). But it is likely that deforestation and expansion of agricultural land will increase again as soon as Brazil´s Soy Moratorium ends in May 2016 (Gibbs et al. 2015a), the cattle agreement runs out in 2019 (Gibbs et al. 2015b), and world market prices for soy and cotton eventually rise again. Therefore, the analysis of future land use and land cover change (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 models in combination with scenario techniques are suitable tools to systematically explore future LULCC trajectories (Lambin 2000), because they can capture the interplay between multiple drivers such as agricultural intensification, regional governance and linkages between regional and global markets (Veldkamp & Lambin 2001; Mietzner & Reger 2005). In the last couple of years different land use models were used to study deforestation processes (Soares-Filho et al. 2004, 2006; Walker et al. 2004; Aguiar 2007; Arvor et al. 2013), 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.

Nevertheless, in their review article Dalla-Nora et al. (2014) stress the need for improved modelling techniques and for new scenarios which portray the interplay between regional and global drivers in a more detailed manner as a prerequisite for generating information that is useful to inform and to support regional policy makers. Dalla-Nora et al. (2014) especially stress the need of an integration of both intra-regional and global drivers into the modeling step of land demand calculation. Land demand calculation based on international economic growth or population growth alone fails to capture intra-regional dynamics, while land demand calculation based on regional drivers of change neglects pressure due to international trade or productivity factors. Furthermore, Dalla-Nora et al. (2014) plead against an oversimplification of model assumptions. For instance, the integration of regional policies (e.g. Soy Moratorium, Cattle Agreement, and New Forest Code) in the form of land use constraints and management practices (e.g. multi-cropping) could lead to improved modeling results. Moreover, most of the existing studies of land-use related greenhouse gas emissions concentrate on the effects of land conversion, in particular biomass burning (e.g. Fearnside et al. 2009; Galford et al. 2010).

The objectives of our study are twofold. First is to develop a new set of consistent land use scenarios for Southern Amazonia. These scenarios integrate international (e.g. crop yield development due to technological change (IMPACT), international trade (IBGE)) as well as regional drivers (regional policies (New Forest Code), pasture intensification) of LULCC. For this purpose we apply the spatially explicit land use model LandSHIFT (Schaldach et al. 2011) to translate the scenario storylines that were developed within the Carbiocial project, in a set of land use maps. Second objective is to calculate the resulting greenhouse gas emissions (CO_2, N_2O, and CH_4) from agricultural soils in order to provide first insights into the potential role of future agricultural development in Brazil for climate mitigation.

2. Material and Methods

2.1 Study Area

The study focusses on the two federal states Mato Grosso and Pará in Brazil containing 36 municipalities being blacklisted as so called “priority municipalities” in terms of monitoring and repressing deforestation through an optimized monitoring system and stricter environmental law enforcement respectively. These constitute only 6.6 % of the area of all municipalities within the Amazon biome but accounted for almost 45 % of deforestation within the Amazon. Hotspots of deforestation can be found especially around the development corridors (BR-070, BR-158, BR-163). The study area comprises 1,253,165 km^2 in Pará and 906,807 km^2 in Mato Grosso.

Mato Grosso has a population of 3.2 million people (IBGE 2014), 69807 km² of land is used for soybean cultivation (IBGE 2013) and 1149 km² were deforested in 2013 which constitutes an increase of 52 % in comparison to 2012 (INPE 2014b). Another dominant land use sector is cattle ranching with a total herd size of 28.4 million animals (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), mainly located in the Cerrado biome.

Pará has a population of 8 million people (IBGE 2014). Only 11,969 km² of the land is used for soybean cultivation (IBGE 2013). In 2013, 2,379 km² were deforested which is an increase of 37 % in comparison to 2012 (INPE 2014b). The dominant land use sector is cattle ranching with a total herd size of 19.2 million animals (IBGE 2013). The natural vegetation is dominated by dense rainforest (Vieira et al. 2008). A hot spot of LULCC is along the Cuiabá-Santarem highway (BR-163), the most recent of the development corridors which are used to acquire the agriculturally rather underdeveloped northern parts of Brazil for crop cultivation and cattle farming (Coy & Klingler 2008).

2.2 Land use change modeling

2.1.1 Model description

Land suitability and land-use change were 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. 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 900 x 900 m that covers the territories of the federal states of Mato Grosso and Pará.

The model consists of sub-modules that represent three different land use types: settlement (URBAN), cropland (AGRO) and pasture (GRAZE). An additional module (BIOPROD) provides information on potential rain-fed yields of 14 crop types (wheat, maize etc.) as well as on NPP for grasslands. This data serves as input to the AGRO and GRAZE sub-modules where it is used for calculating land suitability and to define the amount of crop production and livestock that can be allocated to each cell (Figure 4.1).

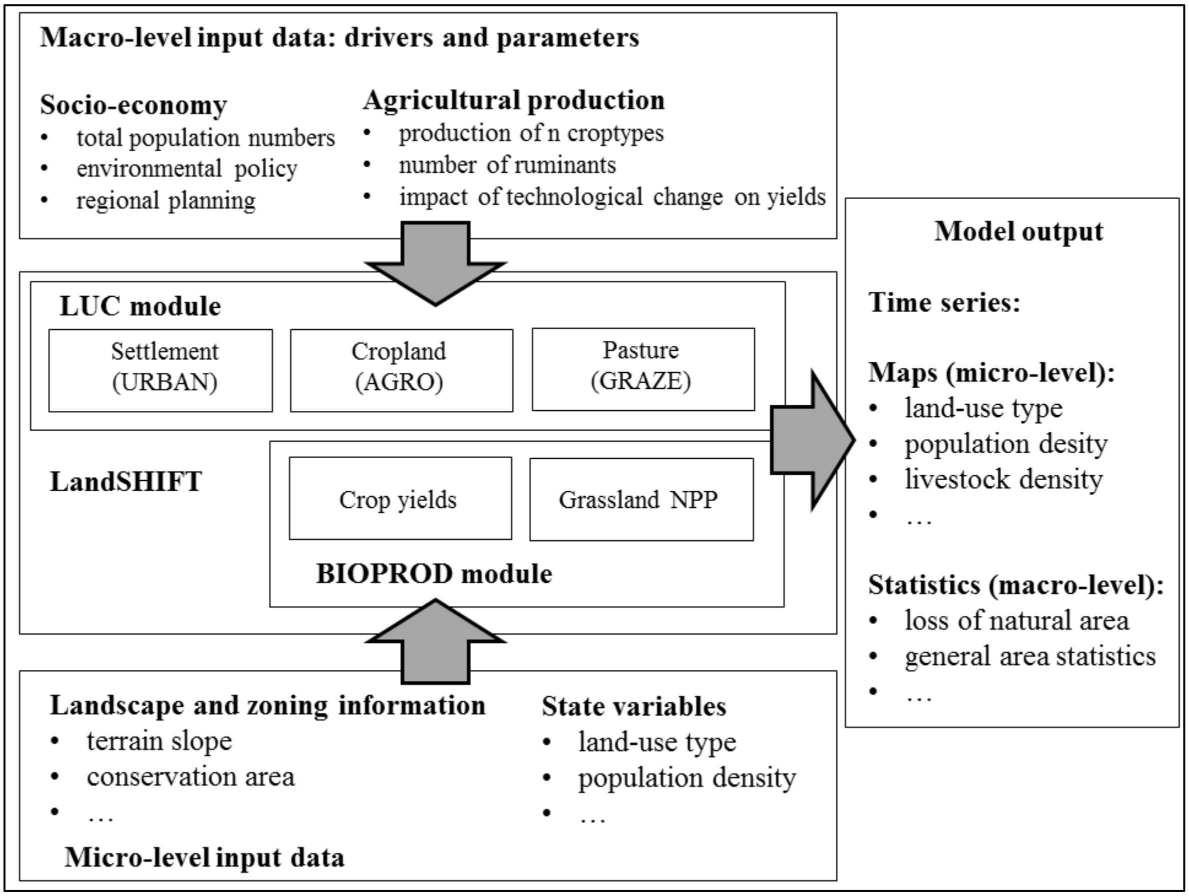

Figure 4.1: Structure of the LandSHIFT model (adapted from Schaldach et al. 2010).

LandSHIFT simulates the spatiotemporal dynamics of the three land use types by regionalizing their state-level drivers to the raster level in 5-year time steps. For this purpose, each land use type implements two process steps. First the preference of each grid cell for the respective land-use type is determined using a multi-criteria analysis according to the following equation 4.1:

$$\psi_k = \underbrace{\sum_{i=1}^{n} w_i \, p_{i,k}}_{suitability} \times \underbrace{\prod_{j=1}^{m} c_{j,k}}_{constraints}, \qquad \text{(Eq. 4.1)}$$

with $\sum_i w_i = 1$ and $p_{i,k}, c_{j,k} \in [0,1]$.

The factors p_i reflect the most important geographical and biophysical drivers that affect suitability for a particular land use type. The factor-weights w_i describe the importance of each factor at grid cell k (e.g. high potential crop yields, moderate slope and no soil constraints would be favorable conditions for cropland), while c_j determine constraints that restrict particular land use changes (e.g. the exclusion of nature conservation areas from agriculture). Both p_i and c_j are normalized by value functions transforming the factor values to a co-domain from 0 to 1. Each land use activity implements its own evaluation scheme.

The second process step is the allocation of land use changes. Firstly, URBAN determines the change of settlement area. Then, the allocation algorithm of AGRO regionalizes the state-level crop production to the cells with the highest preference values for each crop type. It calculates a “quasi-optimum” spatial crop distribution using the multi objective land allocation heuristic introduced by Eastman et al. (1996). The crop production of a given grid cell k is defined as the potential crop yield at k (as calculated by LPJmL) corrected by the influence of TC and multiplied by the area in k that is not covered by settlement. Finally, the allocation of rangeland by GRAZE relies on the potential grassland NPP in the grid cells, based on livestock-forage supply-demand logic. Forage supply is calculated by summing up the grass production of every rangeland cell multiplied by the fraction of biomass utilizable by livestock (grazing efficiency of 30 %, according to Stéphenne and Lambin (2001)). Total forage demand is determined with the multiplication of the total ruminant herd size by the average forage consumption per livestock unit (4.6 Mg yr^{-1}). The share of forage demand fulfilled by rangeland is specified for each country individually by analyzing the available grassland forage in the base land use map and is kept constant during the simulation. If forage demand is higher than the supply, then new rangeland cells are allocated, starting from grid cells with the highest suitability until the demand is fulfilled.

2.2.2 Model modifications

For the calculation of land use scenarios in Southern Amazonia a regional version of the model has been developed. Important elements of the scenario storylines (section 2.6) are related to land use policies and agricultural intensification. In order to reflect these assumptions more accurately, the LandSHIFT model 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 the compliance with the new Brazilian forest code (Soares-Filho et al. 2014). For this purpose a new mosaic land use type was implemented. This land use type consists of 20 % cropland or rangeland and 80 % forests. This adaptation reflects the partial conservation of forest land cover from conversion into agricultural land as is presumed in the case of the Legal Intensification scenario and described in more detail in section 2.6.2.

In order to represent the intensification of pasture management described in some of the scenarios the model includes the new variables *intensification rate* and *maximum intensity*. The intensification rate specifies the increase of biomass productivity of each pasture cell per time step until the defined maximum is reached. 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 past pasture intensification rates in Brazil. The stocking density of pastures in Brazil has been continuously rising from 1990 to 2010 (Lapola et al. 2014, Robinson et al. 2007). The increase amounted to 45 % over the respective period.

2.2.3 Model input data

LandSHIFT is initialized with a gridded historic land use map representing the year 2001 which combines MODIS land-cover data (Friedl et al. 2002) and statistical information on the spatial distribution of crop types. The size of the grid cells is 900 x 900 m. Human population density for each cell was derived from the population density data set published by Salvatore (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 and 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-Economico da Rodovia*

BR-163 and the *Ministério do Meio Ambiente*, respectively. Crop yields and biomass productivity of pasture were calculated by the LPJmL model (Bondeau et al. 2007) for current climate conditions, defined by the reference period 1971-2000 using the CRU TS 2.1 dataset for monthly precipitation, air temperature, cloud cover, and frequency of wet days (Mitchell and Jones 2005). Additional datasets (soil texture, soil moisture, tree cover, and atmospheric CO_2 concentration) were applied according to Sitch et al. (2003). LPJmL modeling results are typically available in a spatial resolution of 0.5° and had to be adapted to the resolution used for modeling LULCC with LandSHIFT of 900 x 900 m. For this purpose we simply disaggregated the 0.5° cell to 900x900 m cells. We assumed the yield value of the lower resolution cell to be valid for each 900 x 900 m cell that is an element of this 0.5° cell.

On the municipality level, data on crop production, human population number, and number of grazing animals (converted into livestock units (LU)) was taken from the municipal livestock and agricultural production survey for the years 2000, 2005 and 2010 available at the IBGE database (IBGE 2013). Information on agricultural area for both of the Federal States was also derived from the IBGE database but used only for the step of base-map generation. These model drivers were aggregated to the state level (i.e. for Mato Grosso and Pará) and serve as input for the URBAN, AGRO and GRAZE modules. Table C.1 summarizes the data used to initialize and operate the model.

2.3 Calculation of N_2O and CH_4 fluxes from agricultural soils

We used the average N_2O emissions reported in the review of Meurer et al. (2016) for different land use types in Brazil (Table C.2). The authors of that study 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. In this study we considered pastures in 2010 to be older than 10 years, but included the age and the corresponding average emissions of the pastures established after 2010 for estimation of total 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. Furthermore, this assessment of N_2O and CH_4 emissions focusses on emissions after clearing (persisting land use) and does not consider emissions that originate from the conversion process.

2.4 Calculation of CO_2 fluxes from agricultural soils

CO_2-emissions and uptake from agricultural soils were derived from changes in soil organic carbon (SOC) stocks under different land use regimes. Here we rely on field trials conducted within the Carbiocial project where 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 the analysis concentrated on Ferralsols and Acrisols. Additionally it was distinguish between old (> 10 years) and young (≤ 10 years) forms of pasture and cropland in order to capture the specific potentials to absorb or emit CO_2. Result of the analysis was a set of emission values (Table C.3) that was be applied to determine carbon fluxes for the different land use scenarios.

2.5 Effects of climate change and technological improvements 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, Oliveira 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. (submitted).

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. These limits are 35 t ha^{-1} for maize and 12.5 t ha^{-1} 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^{-1}, while soybean yields in famer competitions reached 7.6 t ha^{-1} (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.

2.6 Construction of land use scenarios

2.6.1 The scenario building process

A central aspect of the Carbiocial project was the construction of scenarios that describe plausible future development pathways of Southern Amazonia until the year 2030. The main intention was to provide an instrument for informed stakeholder dialogues and as a framework for designing a multi-level decision support tool that can help to identify potential environmental risks associated with specific regional development trajectories. Four scenarios were developed each consisting of a storyline and related quantitative information that describe the main drivers of LULCC such as agricultural production, technological change, population, infrastructure and governance. These drivers were used as input for the LandSHIFT model to conduct simulation runs. In the following we give an overview of the main characteristics of the storylines and their translation into drivers of LULCC.

2.6.2 From storylines to drivers of LULCC

Each scenario consists of a storyline which is a short narrative of the respective future world. On this level the most important small-scale factors and agents such as farmers and institutions are considered. On the basis of the outcome of a scenario workshop, a panel of experts was established. This expert panel has then begun to translate the findings of several stakeholder workshops and extensive stakeholder and expert interviews, which were conducted throughout 2012 in the project region, into qualitative information needed to further define these scenarios. Four narrative storylines outlining the *Trend* scenario and three further scenarios have been deduced. The next step was the quantification of the qualitative information deviated from these storylines so that scenarios can be designed to ultimately facilitate a simulation-based scenario analysis. For this purpose, land use drivers were classified into three categories (human population, agricultural development, and land use policy). For each of these categories the main statements have been extracted from the storylines and interpreted into assumptions that can be translated into numerical drivers of LULCC according to Tables C.4 – C.7.

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 numerical land use drivers between 2010 and 2030 (crop production and population) were derived by linear extrapolation of historical trends from 1973 - 2000 employing the method of least squares (Rao et al. 1999) and in case of crop yield increases due to technological change from a global scenario analysis with the economic trade model IMPACT (Rosegrant 2012) conducted in context of food security research (Vervoort et al. 2013). In this storyline, in Pará crop production (in kg) will increase by 108.5 % and in Mato Grosso by 64.5 %. Crop yields will augment by 50.1 % in Pará and by 48.9 % in Mato Grosso, and livestock numbers will grow by 217 % in Pará and by 157 % in Mato Grosso. In both states population is projected to rise by 35%. The model settings for protected areas and infrastructure development are presented in Table C.8.

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. As a result crop production is projected to increase by 120.7 % in Pará and by 69.6 % in Mato Grosso, while livestock numbers will increase by 284 % in Pará and by 211 % in Mato Grosso. Crop yields increases are similar to the *Trend* scenario. Additionally the scenarios presume the intensification of cattle ranching as described in section 2.2.2. The two scenarios differ in respect of the assumed enforcement of environmental law (Table C.8). Under *Legal Intensification* the conversion of protected areas of any kind is not allowed. In addition we assume compliance with the New Forest Code which implies that cropland and pasture expansion is realized as the new mosaic land use type (section 2.2.2), 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 only military and indigenous areas are protected while areas under ecological protection status are de facto available for agricultural use. Also the compliance with the New 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; WHO 2014) we find a strong decrease of livestock numbers and a significant increase of 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.

Accordingly, crop production will increase by 629.6 % in Pará (considering massive growth rates of beans and soybean due to low historic production) and by 192.2 % in Mato Grosso. Due to the strong focus on crop production, crop yields are assumed to have a stronger increase than in the other scenarios (+ 95.1 % in Pará and + 93.6 % in Mato Grosso). Livestock numbers are estimated to decrease by 75 % in Pará and by 50 % in Mato Grosso while human population was calculated to increase by 32 % and by 29 % respectively.

2.7 Modeling protocol

Using these scenario drivers as input 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 the 12 crop types into the land use class cropland, the 5 forest types into the class rainforest, and the 2 savannah vegetation types into the class savannah (Cerrado) according to Table C.9. 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 to the Ferrasol and Acrisol soil type. Then the 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 values described in sections 2.3 and 2.4.

3. Results

3.1 Model output

The LandSHIFT simulation results for all scenarios are summarized in the supporting materials, (Tables C.10 – C.12). Calculated N_2O and CH_4 emissions are shown in Table C.11 while the calculated CO_2 emissions are summarized in Table C.12. Figure 4.2 shows the simulated land use maps for the base year 2010 and the scenarios in 2030. Figure 4.3 shows the land use and land cover change for each of the applied scenarios between 2010 and 2030. Figure 4.4 depicts the expected changes of GHG emissions according to the calculated LULCC for each of the scenarios. Figure 4.5 presents total global warming potential (GWP) [CO_2-eq] for the greenhouse gases CO_2, N_2O, and CH_4 in 2030 for each of the calculated scenarios. In the following sections the main characteristics of the scenarios are described.

3.2 Trend Scenario

3.2.1 LULCC

In Pará the loss of tropical rainforests amounts to 113,370 km^2 (-11.5 %) while 12,879 km^2 of the Cerrado biome is converted into urban and agricultural land. The majority of deforestation can be found in close proximity to the newly established development corridors (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 compared to 2010. Cropland expands by 16.4 % from 147,960 to 172,190 km^2 despite the assumed yield improvements due to technological change (e.g. 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 forest 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 nature protection area. Pasture area expands from 168,198 km^2 to 252,786 km^2 (+ 50.3 %). Cropland decreases by 8.3 %.

3.2.2 N_2O, CH_4, and CO_2 emissions from agricultural soils

In Pará, N_2O fluxes more than double due to the expansion of pasture area and cropland. In Mato Grosso, total 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 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 factor assumed accounts for CH_4 fluxes from the soil to the atmosphere.

In Pará net CO_2 emissions from agricultural soils increase from 70 Mt in 2010 to 216Mt in 2030. During the same period, in Mato Grosso CO_2 emissions rise from 38 Mt to 224 Mt. Main contributor in both states is old cropland (> 10 years) followed by old pasture. Uptake by young cropland in 2030 amounts to approximately 1 Mt in Pará and 4 Mt in Mato Grosso, respectively.

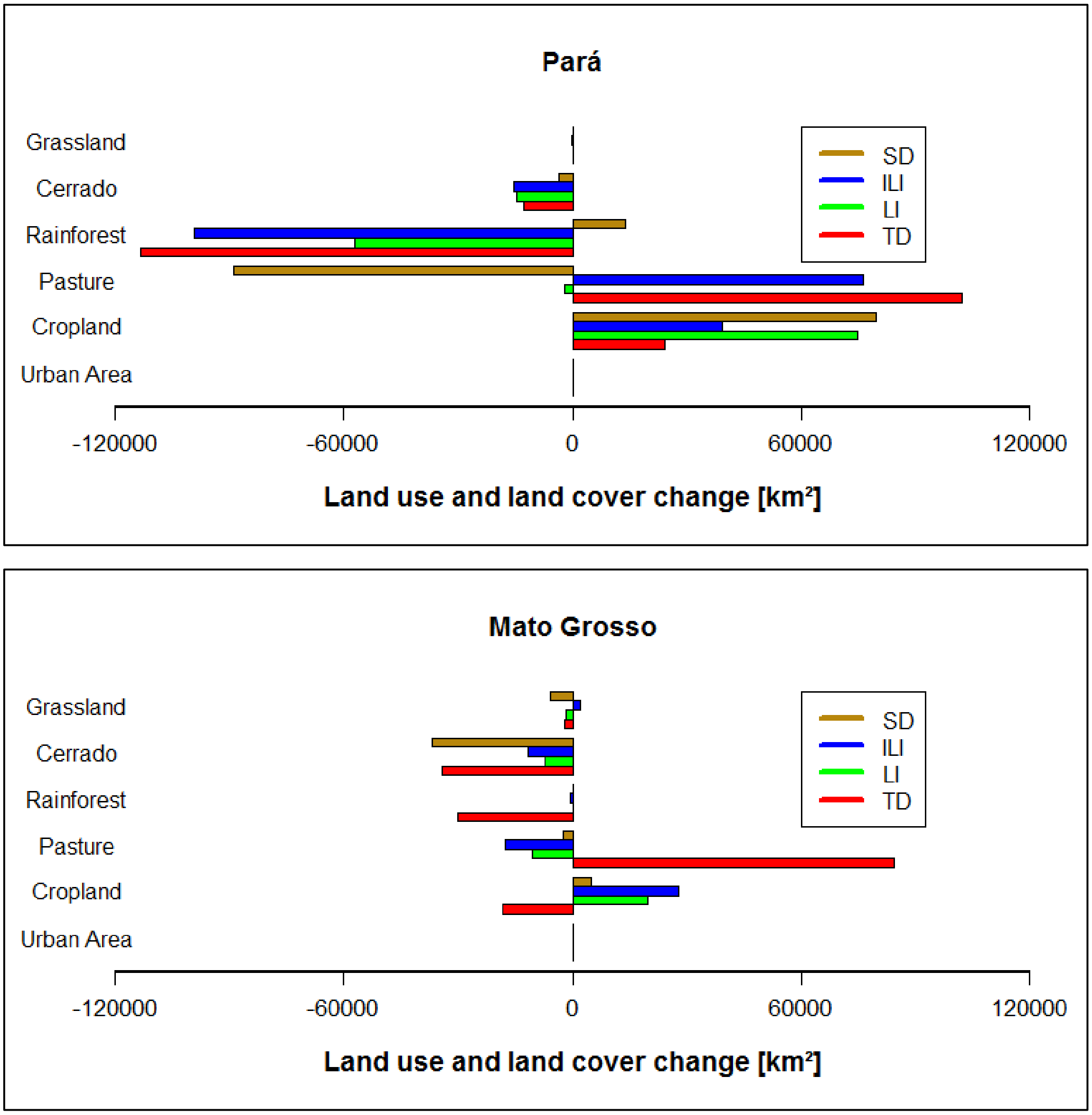

Figure 4.2: Land use and land cover changes [km²] in Pará and Mato Grosso between 2010 and 2030. SD = Sustainable Development, ILI = Illegal Intensification, LI = Legal Intensification, TD = Trend.

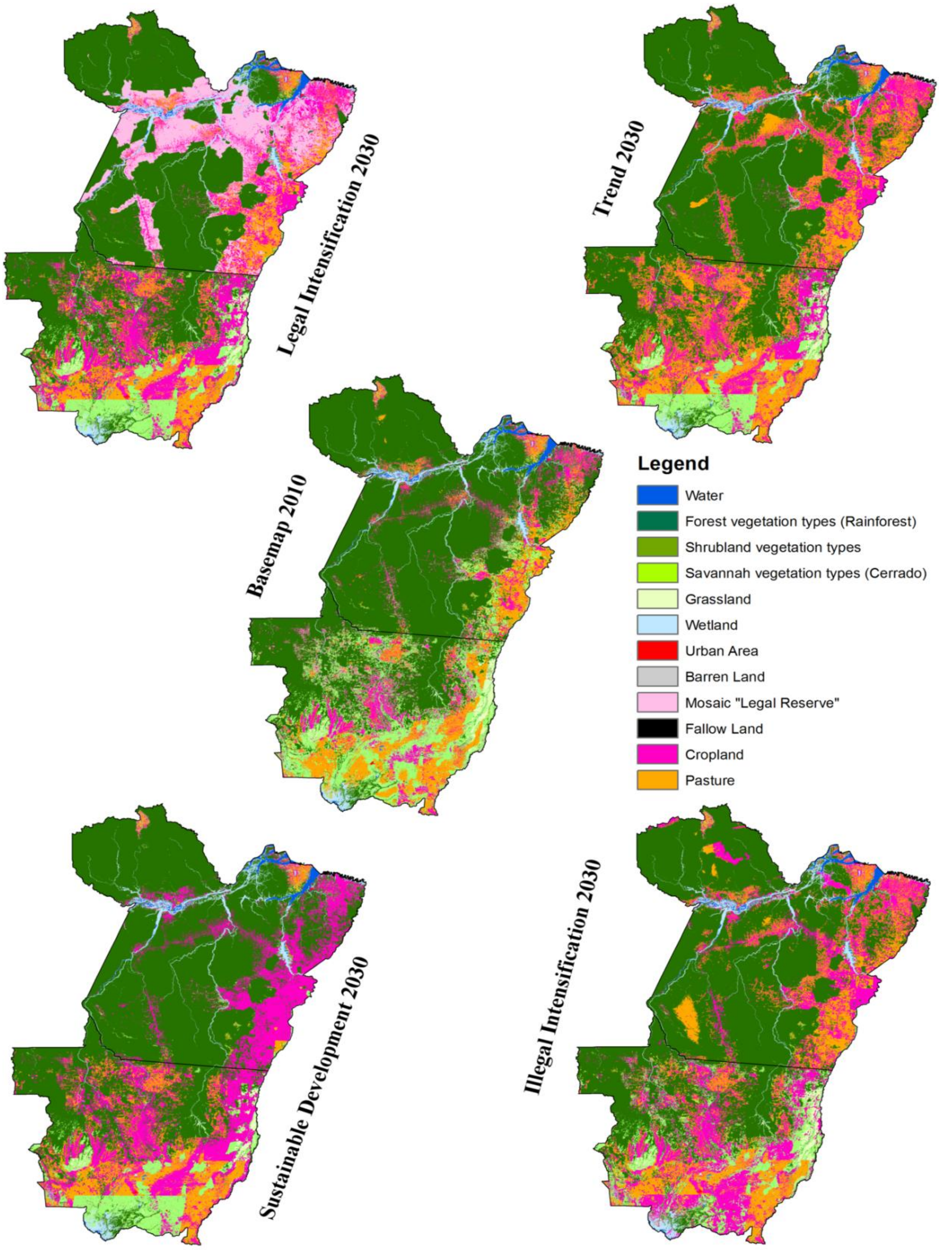

Figure 4.3: Land use and land cover changes in Pará and Mato Grosso between 2010 and 2030 for the four Carbiocial scenarios as simulated by the LandSHIFT model.

3.3 Legal Intensification scenario

3.3.1 LULCC

In Pará 57,339 km^2 of rainforest (-5.8 %) and 14,721 km² of Cerrado vegetation (-59.7 %) are converted. Urban area increases by 6.2 % from 599 km² to 636 km^2. Cropland increases by 50.5 % from 134,641 km² to 222,677 km². 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 km² to 240,987 km^2 (+ 8.9 %) while pasture decreases from 168,198 km² to 157,536 km^2 (- 6.3 %).

In both states the decrease of pasture can be attributed to the intensification of grazing management 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 the resulting land use pattern has a very different characteristic from the trend scenario. As we have previously described, the newly allocated cropland cells have a mosaic land-cover consisting of 20 % cropland and 80 % of the original natural land-cover type. This might have positive effects for example on biodiversity compared to larger agricultural entities 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.

3.3.2 N_2O, CH_4, and CO_2 emissions from agricultural soils

Total N_2O fluxes slightly increase in Pará and Mato Grosso mainly due to an expansion of cropland. In Mato Grosso, young pastures exist, but they only amount for 0.9 % of the total emissions in 2030. N_2O fluxes from pastures are slightly lower (~ 5 %) in 2030 as compared to 2010. At the same time the soils uptake of atmospheric CH_4 increases in both states also because of an expansion of cropland.

In Pará net CO_2 emissions from agricultural soils increase from 70 Mt in 2010 to 244 Mt in 2030. In Mato Grosso we find an increase to 242 Mt. Similar to the trend scenario old cropland and old pasture are the main sources. CO_2-uptake by young cropland amounts to 0.24 Mt in Pará and 5 Mt in Mato Grosso.

3.4 Illegal Intensification scenario

3.4.1 LULCC

In Pará 99,377 km^2 of tropical rainforest is converted. Cerrado decreases by 62.2 % from 24,648 km² to 9327 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 protection (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 between Baía do Vieira Grande and Baía 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 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 forest cover only slightly decreases by 0.2 %. The largest share of land conversion is at the expanse of Cerrado vegetation that 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 rangeland area decreases by 10.5 %. Due to expansion of pasture taking place mainly in central southern Mato Grosso, large areas of rain forest 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 precious zones from destruction.

3.4.2 N_2O, CH_4, and CO_2 emissions from agricultural soils

In Pará, total 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 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 CH_4 emissions to the atmosphere and an increasing CH_4 uptake.

CO_2-emissions from agricultural soils increase to 227 Mt in Pará and to 240 Mt in Mato Grosso. Main sources are old cropland and old pasture. As a consequence of the increasing pasture area in Pará, emissions from young pasture also play a significant role (10 Mt). Again, young pastures act as a carbon sink in both states with an uptake of 1 Mt CO_2 in Pará and of 4 Mt CO_2 in Mato Grosso.

3.5 Sustainability scenario

3.5.1 LULCC

In Pará 3,766 km^2 of natural vegetation cover are converted into croplands. As forest is fully protected the majority of the converted area (98.5 %) is Cerrado vegetation. Caused by the lower meat consumption, pasture areas considerably decrease until 2030. In total, 89,038 km2 (-86.7 %) of the original pasture (2010) can be released. In contrast cropland increases by 53.9 % from 134,641 km² to 227,636 km². Thus, most of the newly established cropland area is found in areas that were formerly used for grazing 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 corridors (BR-163, BR-230) and around the shores of the Amazonas in western Pará (close to Santarém). Most of the new cropland is allocated on former pasture characterized by relatively high crop yields.

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, forest area is protected 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 %). Also triggered by the shift in diets, pasture area is slightly decreasing.

3.5.2 N_2O, CH_4, and CO_2 emissions from agricultural soils

In total, 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 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 N_2O emission increase of 10 %. The total uptake of atmospheric methane increases by 0.022 Mt in Pará and by 0.006 Mt in Mato Grosso. Main driver in Pará is the reduced pasture area which leads to 0.01 Mt less CH_4 fluxes to the atmosphere. The decrease of 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. CO_2-uptake amounts to 30 Mt in Pará and 225 Mt in Mato Grosso, respectively. Nevertheless in Pará net emissions increase to 197 Mt and in Mato Grosso to 225 Mt in 2030. 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.

3.6 Impact of climate change and technological change on crop yields

The simulation results from the MONICA model for Pará show a 21 % decrease of average soybean yields from 2.4 t ha^{-1} in 2000 – 2005 under current climate to 1.9 t ha^{-1} 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^{-1} to 4.2 t ha^{-1} 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^{-1} in 2000 – 2005 to 1.9 t ha^{-1} 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^{-1}. 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.

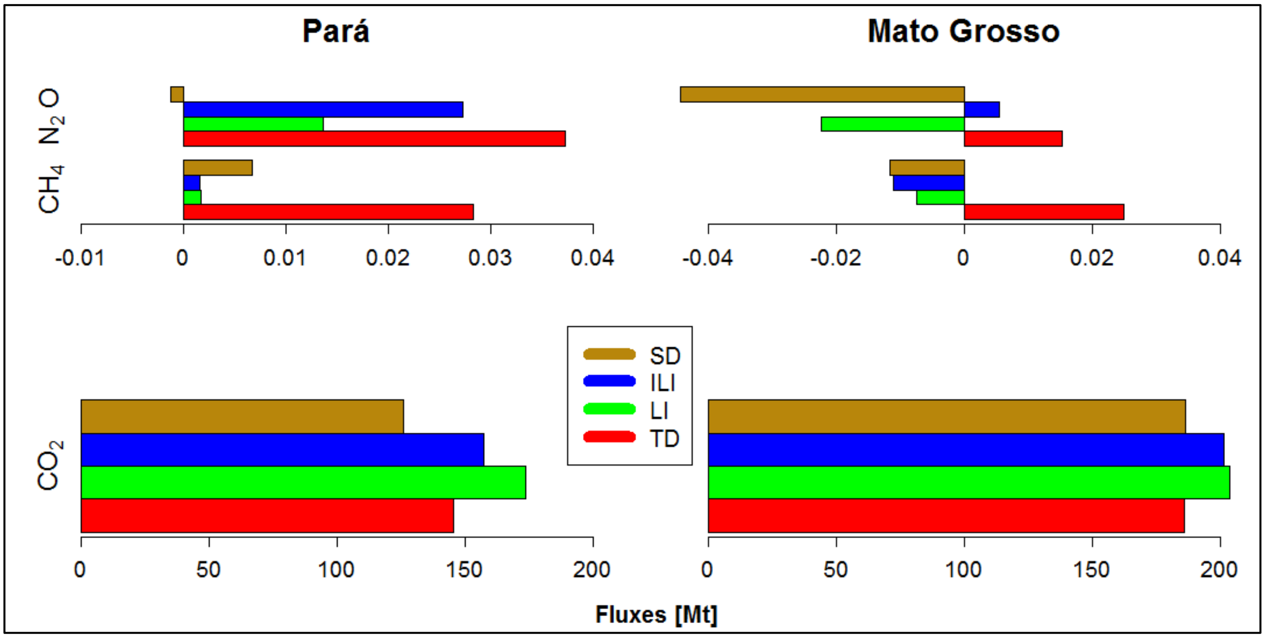

Figure 4.4: Changes of GHG emissions (N_2O, CH_4, and CO_2) [Mt] in Pará and Mato Grosso between 2010 and 2030. SD = Sustainable Development, ILI = Illegal Intensification, LI = Legal Intensification, TD = Trend.

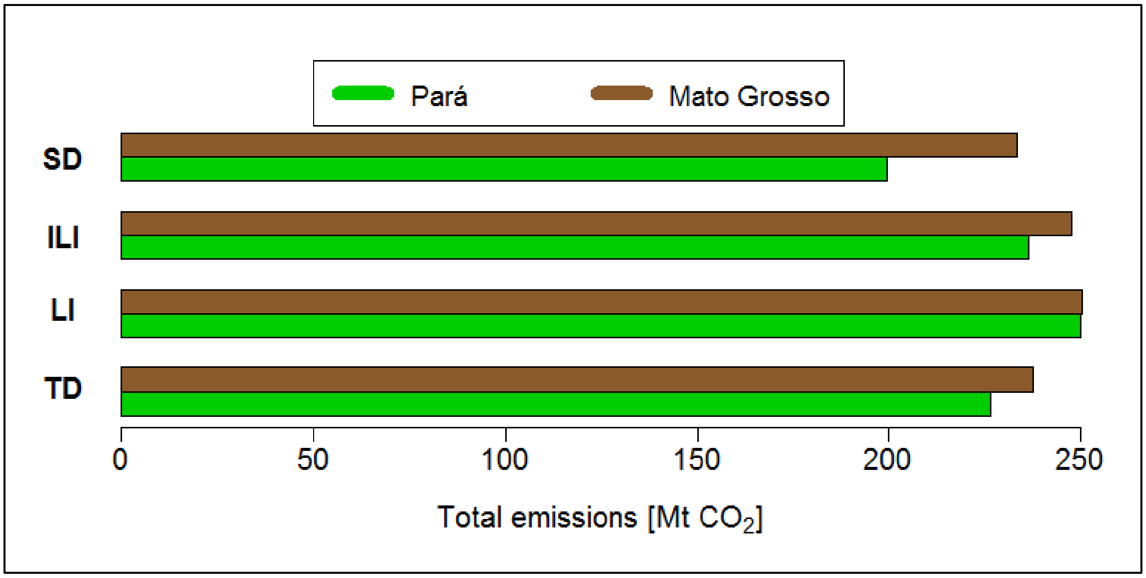

Figure 4.5: Emissions of CO_2, N_2O, and CH_4 [Mt CO_2] from Pará and Mato Grosso in based on the land use distribution in the year 2030.

4. Discussion

The main objective of this modeling exercise is to support scenario developers and decision makers to better interpret the storyline assumptions and to evaluate potential impacts of changes in politics, society, and economy on the resulting environmental consequences. In this context our models can provide a test-bed for the effectiveness of strategies aiming at a more sustainable land-management and can help to identify potential hot spots of future LULCC.

4.1 Discussion of LULCC scenario results

The largest reduction of rainforest was simulated for the *Trend* scenario. 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 lowered in the Legal Intensification scenario (compliance with the New Forest Code), indicating that, especially in Pará, effective governance and protection of natural habitats play an important role for reducing deforestation (Arima et al. 2014). These results are reinforced by Soares-Filho (2010) who arguments that 37 % of deforestation could be halted by the establishment of new protected areas. The compliance with protection policies leads to a reduction of deforestation by 35 % in the case of the Legal Intensification scenario in comparison with the *Illegal Intensification* scenario. 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 New Forest Code imposes a high risk of habitat fragmentation resulting in lower species abundance (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 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 alone by further area expansion.

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 vegetarian diet. Parts of this additional demand are fulfilled by crops (e.g. soybean) formerly used as livestock fodder. 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 rangeland in Pará could be achieved for the *Sustainable Developm*ent 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 simultaneously fulfilling the growing demand for agricultural commodities as has been emphasized by Soares-Filho (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 *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 mean of habitat protection as has been discussed by Galford et al. (2013). This result is supported by Cardoso et al. (2016) who compared the results of 5 different intensification scenarios with each scenario representing a higher degree of pasture intensification. Cardoso et al. (2016) found that the introduction of a forage legume on Brazilian pastures, thus increasing the digestible biomass productivity on pastures, led to a reduction of pasture area by 36 % in Brazil. 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 pasture farming.

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

In our scenarios we investigate three main mechanisms that can be part of such strategies: land protection policies, agricultural intensification and changing human consumption patterns.

The outstanding role of land protection policies becomes obvious in all scenarios as suggested by Arima et al. (2014). As biophysical conditions of natural ecosystems in Southern Amazonia are often very suitable for agriculture, without effective protection measures in our simulation runs these are being converted into cropland and pasture when agricultural production cannot be compensated by intensification. In the scenarios land protection is realized either as a land use mosaic under the New Forest Code or by the strict protection of specific regions. A detailed analysis of the resulting effects of both approaches on biodiversity was beyond the scope of this paper.

In section 4.1 we elaborated that the intensification of pasture management 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 as has been proposed by Galford et al. (2013). In the case of Pará, intensification measures were less relevant for reducing pasture expansion. Here, the compliance with the public policies (e.g. New Forest Code) and the protection of natural habitats in combination with a shift of human consumption patterns towards a more crop-based diet had the strongest impact in terms of a reduction of pasture expansion and forest 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 2012). However, if we assume further increase of crop production, e.g. in the *Legal* and *Illegal Intensification* scenarios, this effect is cancelled out.

These 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 for avoiding further LULCC.

4.3 Agriculture and greenhouse gas emissions

In contrast to the comprehensive study by Galford et al. (2010) on the effect of alternative deforestation futures on greenhouse gas emissions in Mato Grosso, in this study we focus on cropland and pasture and their role as respective sources or sinks for CO_2, N_2O, and CH_4. As our scenario analysis shows (Figure 4.4 c), the *Sustainable Development* scenario and thus, a considerable change in terms of anthropogenic consumption pattern, produces the lowest GHG emissions compared to the other scenarios. 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 CO_2-eq according to Myhre et al. (2013) in relation to a time horizon of twenty years ($GWP_{CH4} = 86$, $GWP_{N2O} = 268$) .

As expected, in Pará the largest reduction of N_2O and CH_4 emissions from pasture is achieved for the *Sustainable Development* scenario. In contrast, in Mato Grosso the reduction of non-CO_2 greenhouse gases from pasture is largest under the *Illegal Intensification* scenario. Here pasture expands into protected areas (mainly the Pantanal) that are characterized by higher biomass productivity thus reducing the net area demand. The highest increase of N_2O and CH_4 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 mean of pasture intensification.

The highest increase of CH_4 uptake by cropland in Pará could be achieved for the *Sustainable Development* scenario. A decrease of N_2O emissions from cropland is only calculated for the *Trend* scenario in Mato Grosso due to the reduction of cropland area.

For both states a substantial increase of 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 for CO_2 emissions.

In Mato Grosso the *Illegal Intensification* scenario shows the lowest amount of CO_2 emissions from pasture as it is characterized by the lowest extend of pasture area of all scenarios due to the strong intensification of grazing management. Interestingly, compared to the base year, we find decreasing 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 3 times more CO_2 than older pastures (Table C.12). Consequently it would be a good measure to reactivate older degraded pastures instead of transforming natural vegetation in order to reduce CO_2.

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

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

4.4 Climate change and crop productivity

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. At the same time studies such as Lapola et al. (2011) point out that climate change might have negative effects on crop yields in Amazonia. The simulation runs with the MONICA model indicate that negative climate effects under an A1B 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 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. Rosenzweig et al. 2014).

4.5 Limitations and uncertainties of the study

Our scenario projections of agricultural production and population growth combine the extrapolation of historic trends and relatively simple assumptions regarding future changes in demands for agricultural commodities due to international trade and changing consumer behavior. Therefore, in contrast to studies based on economic modeling (e.g. Chaudhury et al. 2013) they do not give a comprehensive picture of future changes in global economy and trade. Nevertheless, comparison of the production data of the *Trend* scenario with the USDA baseline projection for Brazil (Westcott and Hansen, 2015) indicates that that our assumptions are in a reasonable order of magnitude.

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 over the period from 2000 to 2012 was illegal (Lawson 2014). This illegally cleared area was used mainly for crop production or cattle ranching. The production quantity produced on these illegally cleared areas and the areas themselves are not included in the IBGE agricultural survey, thus IBGE data on crop production and cropland area underestimates agricultural production and agricultural used area in Brazil. Yet MODIS satellite images capture all agricultural area. 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 following process. In the step of base-map generation, 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 forest 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) in each year. The inclusion of these processes into our land use model will play an important part in upcoming studies.

Furthermore, as described earlier (Section 2.3) our estimates of CO_2, N_2O, and CH_4 only consider emissions caused after clearing due to persisting land use. Information on emissions caused by biomas burning or changes in biomass carbon content were neglected. So far, nothing is known about what happens during the conversion process – here, further research is needed. In order to holistically compare the CO_2, N_2O, and CH_4 emissions caused due to LULCC for each of the scenarios in the study region, these aspects need to be integrated.

5. Conclusion

In the light of these limitations, our model-based scenario analysis should not be misunderstood as a method to predict concrete future events. It rather 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 and social consequences. In this sense it can help to test potential impacts of political and social exertions as well as environmental influences (e.g. climate change) on changing land use pattern and to assess their effects in relation to social, economic and environmental goals that have been set as policy targets.

References

Aguiar APD, Câmara G, and Escada MIS 2007 Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: Exploring intra-regional heterogeneity *Ecol. Model.* **209** (2) 169-188.

Arima EY, Barreto P, Araújo E, and Soares-Filho B 2014 Public policies can reduce tropical deforestation: Lessons and challenges from Brazil *Land Use Policy* **41** 465-473.

Arvor D, Dubreuil V, Simões M, and Bégué A 2013 Mapping and spatial analysis of the soybean agricultural frontier in Mato Grosso, Brazil, using remote sensing data *GeoJournal* **78** (5), 833-850.

Arvor D, Meirelles M, Dubreuil V, Begue A, and Shimabukuro YE 2012 Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices *Appl. Geogr.* **32** (2) 702-713.

Assunção J, Gandour CC, and Rocha R 2012 Deforestation slowdown in the Legal Amazon: prices or policies. Climate Policy Initiative Working Paper.

Barona E, Ramankutty N, Hyman G, and Coomes OT 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon *Environ. Res. Lett.* **5** (2) 024002.

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, and Smith B 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Global Change Biol.* **13** (3) 679-706.

Bringezu S, O'Brien M, and Schütz H 2012 Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources *Land Use Policy* **29** (1) 224-232.

CAIT Climate Data Explorer. 2015. Washington, DC: World Resources Institute. Available online at: http://cait.wri.org. Please Note: CAIT data are derived from several sources. Any use of the Land-Use Change and Forestry or Agriculture indicator should be cited as FAO 2014, FAOSTAT Emissions Database. Any use of CO2 emissions from fuel combustion data should be cited as CO_2 Emissions from Fuel Combustion, ©OECD/IEA, 2014.

Carmo JB, do Neto ER, de Sousa, Duarte-Neto PJ, Ometto JPHB, and Martinelli LA 2012 Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions *Agr. Ecosyst. Environ.* **148** 37 – 43

Carvalho JLN, Raucci GS, Frazao LA, Cerri CEP, Bernoux M, and Cerri CC 2014 Crop-pasture rotation: A strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado *Agr. Ecosyst. Environ.* **183** 167 – 175, doi: 10.1016/j.agee.2013.11.014

CESB (2015). "Desafio Nacional de Máxima Produtividade da Soja." from http://www.cesbrasil.org.br/Sobre.aspx.

Chaplin-Kramer R, Sharp RP, Mandle L, Sim S, Johnson J, Butnar I, Canals LMi, Eichelberger BA, Ramler I, Mueller C, McLachlan N, Yousefin A, King H, and Kareiva PM 2015 Spatial patterns of agricultural expansion determine impacts on biodiversity and carbon storage *P. Natl. Acad. Sci. USA* **112** (24) 7402-7407.

Chaudhury MJ, Vervoort P, Kristjanson P, Ericksen P, and Ainslie A (2013) Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Reg. Environ. Change* **13** 389-398.

Cohn AS, Mosnier A, Havlík P, Valin H, Herrero M, Schmid E, O'Hare M, and Obersteiner M 2014 Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation *P. Natl. Acad. Sci. USA* **111** (20) 7236-7241.

Coy M 2001 Globalisierung in Brasilien: Raumwirksamkeit und Reaktionen. Beispiele aus städtischen und ländlichen Regionen. In: Latenamerika im Umbruch. Geistige Strömungen im Globalisierungsstress. Borsdorf A, G Krömer, C Parnreiter (eds.) Innsbrucker Geographische Studien 32, pp 19 – 33, Innsbruck.

Coy M and Klingler M 2008 Pionierfronten im brasilianischen Amazonien zwischen alten Problemen und neuen Dynamiken. Das Beispiel des „Entwicklungskorridors "Cuiabá (Mato Grosso)–Santarém (Pará). Innsbrucker Geographische Gesellschaft (Hg.): Jahresbericht 2010 109-129.

Dalla-Nora EL, de Aguiar APD, Lapola DM, and Woltjer G 2014 Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade? *Land Use Policy* **39** 403-411.

Eastman JR, Jin W, Kyem PK, and Toledano J 1995 Raster procedures for multi-criteria/multi-objective decisions. *Photogramm. Eng. Rem. S.* **61** 539–47.

Ellert BH and Bettany JR 1995 Calculation of organic matter and nutrients stored in soils under contrasting management regimes *Can. J. Soil Sci.* **75** (4) 529-538.

Embrapa 2014 "Ensaio Nacional de Cultivares de Milho." Retrieved 15 July 2015. Available at: http://www.cnpms.embrapa.br/ensaio/.

Farr TG and Kobrick M 2000 Shuttle Radar Topography Mission produces a wealth of data *Eos* **81** (48) 583-585.

Fearnside PM, Righi CA, de Alencastro Graça PML, Keizer EW, Cerri CC, Nogueira EM, and Barbosa RI 2009 Biomass and greenhouse-gas emissions from land-use change in Brazil's Amazonian "arc of deforestation": The states of Mato Grosso and Rondônia *Forest Ecol. Manag.* **258** (9) 1968-1978.

Fernandes SAP, Bernoux M, Cerri CC, Feigl BJ, and Piccolo MC 2002 Seasonal variation of soil chemical properties and CO_2 and CH_4 fluxes in unfertilized and P-fertilized pastures in an Ultisol of the Brazilian Amazon *Geoderma* **107** 227 – 241.

Friedl MA, Sulla-Menashe D, Tan B, Schneider A, Ramankutty N, Sibley A, and Huang X 2010 MODIS Collection 5 global land cover: Algorithms and characterization of new datasets *Remote Sens. Environ.* **115** 168-182.

Galford GL, Melillo JM, Kicklighter DW, Cronin TW, Cerri CE, Mustard JF, and Cerri CC 2010 Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon *P. Natl. Acad. Sci. USA* **107** (46) 19649-19654.

Galford GL, Soares-Filho B, and Cerri CE 2013 Prospects for land-use sustainability on the agricultural frontier of the Brazilian Amazon *Philos. T. R. Soc. B.: Biological Sciences* **368** (1619) 20120171.

Gibbs HK, Rausch L, Munger J, Schelly I, Morton DC, Noojipady P, Soares-Filho B, Barreto P, Micol L, and Walker NF 2015a Brazil's Soy Moratorium *Science* **347** (6220) 337 – 378, doi: 10.1126/science.aaa0181.

Gibbs HK, Munger J, L'Roe J, Barreto P, Pereira R, Christie M, Amaral T, and Walker NF 2015b Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? *Conserv. Lett.* **9** (1) 32 – 42, doi: 10.1111/conl.12175.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, and Toulmin C 2010 Food security: the challenge of feeding 9 billion people. *Science* **327**(5967) 812-818, doi: 10.1126/science.1185383.

Godfray HCJ, Crute IR, Haddad L, Lawrence D, Muir JF, Nisbett N, Pretty J, Robinson S, Toulmin C, and Whiteley R 2010 The future of the global food system *Philos. T. R. Soc. B.: Biological Sciences* **365** (1554) 2769-2777, doi: 10.1098/rstb.2010.0180.

Gollnow F and Lakes T 2014 Policy change, land use, and agriculture: The case of soy production and cattle ranching in Brazil, 2001–2012 *Appl. Geogr.* **55** 203-211.

Greenpeace-Brazil 2009 Amazon Cattle Footprint. Mato Grosso: State of Destruction p 15. Available at: www.greenpeace.org/international/press/reports/amazon-cattle-footprint-mato.

Hecht SB 2011 From eco-catastrophe to zero deforestation? Interdisciplinarities, politics, environmentalism and reduced clearing in Amazonia *Environ. Conserv.* **39** (1) 4-19.

IBGE/EMBRAPA (2011). O novo mapa de solos do Brasil. Rio de Janeiro. https://www.embrapa.br/busca-de-publicacoes/-/publicacao/920267/o-novo-mapa-de-solos-do-brasil-legenda-atualizada

Indicadores IBGE. Estatística da Produção Agrícola. August, 2015. Available at: ftp://ftp.ibge.gov.br/Producao_Agricola/Fasciculo_Indicadores_IBGE/estProdAgr_201508.pdf.

INPE (Instituto Nacional de Pesquisas Especiais), 2013: Amazonia – Deforestation 2000 – 2013. FUNCATE, 23.

IUSS World Reference Base 2014 World Reference Base for Soil Resources 2014. International soil classification system for naming and creating legends for soil maps. World Soil Resources Reports No- 106. FAO, Rome, Italy.

Jasinski E, Morton D, DeFries R, Shimabukuro Y, Anderson L, and Hansen M 2005 Physical landscape correlates of the expansion of mechanized agriculture in Mato Grosso, Brazil *Earth Interact.* **9** (16) 1-18.

Justino F, Oliveira EC, Rodrigues R de Avila, Goncalves PHL, Souza PJOP, Stordal F, Marengo J, Silva TG da Silva, Delgado RC, Lindemann D da Silva, and Costa LC 2013 Mean and Interannual Variability of Maite and Soybean in Brazil under Global Warming Conditions *Am. J. Climate Change* **2** 237 - 253, doi: 10.4236/ajcc.2013.24024

Kohlhepp G 2002 Regionalentwicklung im Amazonasgebiet Brasiliens. Institut Martius-Staden: Jahrbuch 49 2001-2002 182 – 216. São Paulo (erweiterte Fassung von Nr. 236).

Krogh L, Noergaard A, Hermansen M, Greve M, Balstroem T, and Breuning-Madsen H 2003 Preliminary estimates of contemporary soil organic carbon stocks in Denmark using multiple datasets and four scaling-up methods. *Agr. Ecosyst. Environ.* **96** 19 – 28.

Lambin EF, Rounsevell MDA, and Geist HJ 2000 Are agricultural land-use models able to predict changes in land-use intensity? *Agr. Ecosyst. Environ.* **82** (1) 321-331.

Lapola DM, Martinelli LA, Peres CA, Ometto JP, Ferreira ME, Nobre CA, Aguiar APD, Bustamante MMC, Cardoso MF, Costa MH, Joly CA, Leite CC, Moutinho P, Sampaio G, Strassburg BBN, and Vieira ICG 2014 Pervasive transition of the Brazilian land-use system *Nat. Clim. Change* **4** (1) 27-35.

Lapola DM, Schaldach R, Alcamo J, Bondeau A, Msangi S, Priess JA, Silvestrini R, Soares-Filho BS 2011 Impacts of climate change and the end of deforestation on land use in the Brazilian Amazon *Earth Interact.* **15** 1-29.

Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA 2010 Indirect land-use changes can overcome carbon savings from biofuels in Brazil *P. Natl. Acad. Sci. USA* **107** (8) 3388-3393.

Lawson S, Blundell A, Cabarle B, Basik N, Jenkins M, and Canby K 2014 Consumer Goods and Deforestation: An Analysis of the Extent and Nature of Illegality in Forest Conversion for Agriculture and Timber Plantations *Forest Trend Report Series – Forest Trade and Finance*. Available at: http://www.forest-trends.org/documents/files/doc_4718.pdf.

Macedo MN, DeFries RS, Morton DC, Stickler CM, Galford GL, and Shimabukuro YE 2012 Decoupling of deforestation and soy production in the southern Amazon during the late 2000s *P. Natl. Acad. Sci. USA* **109** (4) 1341-1346.

Marengo JA, Chou SC, Kay G, Alves LM, Pesquero JF, Soares WR, Santos DC, Lyra AA, Sueiro G, Betts R, Chagas DJ, Gomes JL, Bustamante JF, and Tavares P 2012 Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins *Clim. Dynam.* **38** (9-10) 1829-1848.

Martinelli LA, Naylor R, Vitousek PM, and Moutinho P 2010 Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future *Curr. Opin. Env. Sust.* **2** (5) 431-438.

Metay A, Oliver R, Scopel E, Douzet J.-M, Moreira JAA, Maraux F, Feigl BJ, and Feller C (2007) N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiania (Cerrados, Brazil). *Geoderma* **141** 78 – 88, doi: 10.1016/j.geoderma.2007.05.010

Meurer KHE, Franko U, Stange CF, Rosa JD, Madari BE, and Jungkunst HF 2016 Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil - a critical review *Environ. Res. Lett.* 11 (2016) 023001, doi: 10.1088/1748-8326/11/2/023001.

Mietzner D and Reger G 2005 Advantages and disadvantages of scenario approaches for strategic foresight *International Journal Technology Intelligence and Planning* **1** (2) 220-239.

Mitchell TD and Jones PD 2005 An improved method of constructing a database of monthly climate observations and associated high-resolution grids *Int. J. Climatol.* **25** (6) 693-712.

MMA, Ministério do Meio Ambiente 2001 Causas e dinamica do desmatamento na Amazonia *MMA* 436.

Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, and Zhang H 2013 Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker TF, D Qin, GK Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, and PM Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nendel C, Berg M, Kersebaum KC, Mirschel W, Specka X, Wegehenkel M, Wenkel KO, and Wieland R 2011 The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics *Ecol. Model.* **222** (9) 1614-1625.

Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, Seroa R da Motta, Armijo E, Castello L, Brando P, Hansen MC, McGrath-Horn M, Carvalho O, and Hess L 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains *Science* **344** (6188) 1118-1123.

Nepstad D, Soares-Filho BS, Merry F, Lima A, Moutinho P, Carter J, and Stella O 2009 The End of deforestation in the Brazilian Amazon *Science* **326** (5958) 1350-1351.

Neto MS, Piccolo M, de Cassia Junior CC, Cerri CC, and Bernoux M 2011 Emissao de gases do efeito estufa em diferentes usos da terra no bioma cerrado *R. Bras. Ci. Solo* **35** 63 – 76

Österle H, Gerstengarbe FW, and Werner PC 2003 Homogenisierung und Aktualisierung des Klimadatensatzes der Climate Research Unit der Universität of East Anglia, Norwich *Terra Nostra* **6** (6).

Pacheco P 2012 Actor and frontier types in the Brazilian Amazon: Assessing interactions and outcomes associated with frontier expansion *Geoforum* **43** (4) 864-874.

Piva JT, Dieckow J, Bayer C, Zanatta JA, Moraes A de, Tomazi M, Pauletti V, Barth G, and Piccolo M de Cassia (2014) Soil gaseous N_2O and CH_4 emissions and carbon pool due to integrated crop-livestock in a subtropical Ferralsol *Agr. Ecosyst. Environ.* **190** 87 – 93, doi: 10.1016/j.agee.2013.09.008

Poeplau C and Don A 2013 Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe *Geoderma* **192** 189 - 201.

Quesada CA, Lloyd J, Anderson LO, Fyllas NM, Schwarz M, Czimczik CI 2011 Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* **8** 1415–1440, doi:10.5194/bg-8-1415-2011.

Rao CR and Toutenburg H 1999 Linear Models: Least Squares and Alternatives. 2nd edition, pp 427, Springer Series in Statistics.

Rosegrant MW 2012 International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. IFPRI, Washington, DC.

Rosenzweig C, Elliott J, Deryng D, Ruane AC, Müller C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh TAM, Schmid E, Stehfest E, Yang H, and Jones JW 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *P. Natl. Acad. Sci. USA* **111** (9) 3268-3273.

Schaldach R, Alcamo J, Koch J, Kölking C, Lapola DM, Schüngel J, and Priess JA 2011 An integrated approach to modelling land-use change on continental and global scales *Environ. Modell. Softw.* **26** (8) 1041-1051.

Schmidt MWI, Torn, MS, Abiven S, Dittmar T, Guggenberger G, Janssens I A, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, Nannupieri P, Rasse DP, Weiner S, and Trumbore SE 2011 Persistence of soil organic matter as an ecosystem property *Nature* **478** 49 – 56.

Silver WL, Thompson AW, McGroddy ME, Varner RK, Dias JD, Silva H, Crill PM, and Keller M 2005 Fine root dynamics and trace gas fluxes in two lowland tropical forest soils *Global Change Biol*. **11** 290 – 306, doi: 10.1111/j.1365-2486.2005.00903.x.

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, and Venevsky S 2003 Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model *Global Change Biol.* **9** (2) 161-185.

Soares-Filho B, Alencar A, Nepstad D, Cerqueira G, Diaz V, del Carmen M, Rivero S, Solórzano L, and Voll E 2004 Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarém–Cuiabá corridor *Global Change Biol.* **10** (5) 745-764.

Soares-Filho B, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA, and Schlesinger P 2006 Modelling conservation in the Amazon basin *Nature* **440** (7083) 520-523.

Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Coe M, Rodriguez H, and Alencar A 2014 Cracking Brazil's forest code *Science* **344** (6182) 363-364.

Specht JE, Hume DJ, and Kumudini SV 1999 Soybean yield potential - A genetic and physiological perspective *Crop Sci.* **39** (6) 1560-1570.

Srinivasan CS, Irz X, and Shankar B 2006 An assessment of the potential consumption impacts of WHO dietary norms in OECD countries *Food Policy*, **31** (1) 53-77.

Stehfest E, Bouwman L, van Vuuren DP, den Elzen, MG, Eickhout B, Kabat P 2009 Climate benefits of changing diet *Climatic Change* **95** (1-2) 83-102.

Steudler PA, Melillo JM, Feigl BJ, Neill C, Piccolo MC, and Cerri CC 1996 Consequences of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon Basin *J. Geophys. Res.* **101** (D13) 18,547 – 18,554.

Turner BL, Lambin EF, and Reenberg A 2007 The emergence of land change science for global environmental change and sustainability *P. Natl. Acad. Sci. USA* **104** (52) 20666-20671.

Vasconcelos SS, Zarin DJ, Capanu M, Littell R, Davidson EA, Ishida FY, Santos EB, Araujo MM, Aragao DV, Rangel-Vasconcelos LGT, Oliveira F. de Assis, McDowell WH, and Carvalho CJR de 2004 Moisture and substrate availability constrain soil trace gas fluxes in an eastern Amazonian regrowth forest *Global Biogeochem. Cy.* **18** GB2009, doi: 10.1029/2003GB002210

Veldkamp A and Lambin EF 2001 Predicting land-use change. *Agr. Ecosyst. Environ.* **85** (1) 1-6, doi: 10.1016/S0167-8809(01)00199-2.

Verchot LV, Davidson EA, Cattanio JH, Ackerman IL, Erickson HE, and Keller M 1999 Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia *Global Biogeochem. Cy.* **13** (1) 31 – 46, doi: 10.1029/1998GB900019.

Zoneamento Ecológico-Econômico da Influencia da Rodovia BR-163 (ZEE) 2009 Available at: http://www.mma.gov.br/port/conama/processos/606CC34C/ApresZEEBr163_49aCTAJ_19aCTGTB_18fev091.pdf.

5. A multi-scale modelling framework for the analysis of societal and environmental processes in Southern Amazonian land systems: Lessons learned from the Carbiocial project

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Abstract

In Southern Amazonia, the expansion of agricultural land during the last decades led to a massive conversion of natural ecosystems degrading biodiversity and environmental processes. Building on the land-systems approach a modelling framework has been developed as an important part of the Carbiocial project, in order to gain new insights into human-environment relationships within this region. On different scale levels it combines land-use models with different types of environmental models. The article describes the structure of the framework and how it was applied in simulation experiments for answering critical questions regarding the future development of land-use change in Southern Amazonia and the resulting environmental impacts. A central aspect in this context was the development and analysis of scenarios for the year 2030. The main findings from the simulation experiments that are presented in various articles of this special issue are summarized, contextualized and discussed. Based on these outcomes the authors reflect on which lessons could be learned from the model development process itself as well as for the design and implementation of future research projects.

Keywords: Modelling framework, land systems, Southern Amazonia, human-environment interaction

1. Introduction

Brazil is a global player in terms of food and biofuel production, with major influence on world markets (Hertel 2015; FAO 2015). In addition to agricultural products, Brazil’s environmental resources (e.g. clean water, CO_2 sink, biodiversity) are of global importance. In particular the Amazon rainforest is considered as a crucial tipping element of the global climate system whose destruction may have significant impacts on the functioning of that system (Lenton et al. 2008, Nepstad et al. 2008). Locally, however, these resources are valued quite differently, and Amazonia’s resources for timber, employment and large-scale agricultural production out-compete all efforts to protect the pristine ecosystem.

In Southern Amazonia, the expansion of agricultural land during the last decades led to a massive conversion of natural ecosystems (mainly rainforest and cerrado) degrading biodiversity and environmental processes. Although the rate of land conversion could be significantly reduced in the past decade, e.g. by agricultural intensification and environmental protection policies, it is uncertain whether this trend will prevail or if increasing global demands for food, bioenergy and biomaterials in combination with weak law enforcement will trigger enhanced deforestation again.

In order to gain a better scientific understanding of possible future development trajectories of the region it is essential to overcome the boundaries between social and environmental sciences and to develop integrative research tools. The land-system approach (Turner et al. 2007) provides a consistent framework for describing and analyzing human-environment relationships and dynamics, based on two coupled sub-systems of social and environmental processes. Human activities such as land-use affect the structure and the functioning of ecosystems and consequently the provisioning of ecosystem goods and services (e.g. freshwater availability). These changes intended or unintended may in turn have positive and negative effects on human well-being. The human system responds for example by adapting to or by trying to mitigate negative environmental changes.

Simulation models have proven suitable tools for investigating the dynamics of human-environment interactions within land systems (van Ittersum et al. 2004; Ewert et al. 2011; van Wijk 2014, An et al. 2014) and particularly in the Brazilian Amazon (Soares-Filho et al. 2006; Richards et al. 2014; Lapola et al. 2011). A recent review by Dalla-Nora et al. (2014) has shown that the existing modelled scenarios substantially deviate from the observed land-use change in the Brazilian Amazon. Consequently the authors highlight the need for the integration e.g. of economic and environmental models models to explore plausible trajectories of future land-use change and the resulting effects on society and environment.

The main objective of the Carbiocial project operating from 2011 – 2016 was to investigate viable, carbon-optimized land management strategies for Southern Amazonia (Gerold et al. in review). The project followed an interdisciplinary and multiscale research approach, using scenario techniques and life histories as well as field experiments, remote sensing and dynamic simulation modelling. Consequently, models from different scientific disciplines were combined to investigate human-environment interactions in Southern Amazonia land systems across spatial scale levels. The objectives of the modelling exercises were to gain a better scientific understanding of the processes within these land systems but also to develop new ideas of plausible future regional development pathways. In this context our article focuses on three main research questions which were formulated within the project. (1) How do trends of global change affect land-use change in Southern Amazonia in the coming decades? (2) How does the changing land-use pattern affect carbon stocks, greenhouse gas emissions, the water cycle and soil erosion? (3) How does climate change together with technological change affect crop yields within the region?

The article first describes how different simulation models were adapted to the case study region and then linked to each other. In the second step, the main results from the modelling exercises regarding the aforementioned research questions are reviewed. It is then discussed how these results contribute to an improved scientific understanding of the social and environmental processes within the investigated land-use systems. Finally it is investigated which lessons could be learned for the design and implementation of forthcoming research projects.

2. Materials and Methods

2.1 Study region

The study region stretches along the BR-163 highway from Cuiabá in the state of Mato Grosso to Novo Progresso in the state of Pará, at the southern fringe of the Brazilian rainforest. Along its route the highway passes through 3 agroscapes which represent a historical land-use gradient

(Gerold et al. in review). Today, Central Mato Grosso is characterized by a highly industrialized agriculture, with large-scale soybean, cotton and maize production, whereas in Pará smaller-scale farming and cattle ranching still dominate. As this frontier is still dynamic, the majority of deforestation is located in Pará. Overall, the highway is an excellent example for the pioneer front development in the Amazon (Galford et al. 2010), integrating boviculture, agriculture, and agroindustrial practices into what is still the world's largest untouched forest ecosystem. The land-use gradient nearly parallels a climatological gradient, which is manifested in the biomes from the Cerrado (savannah and forest) of the semi humid tropics to the evergreen rainforest of the humid tropics in Pará.

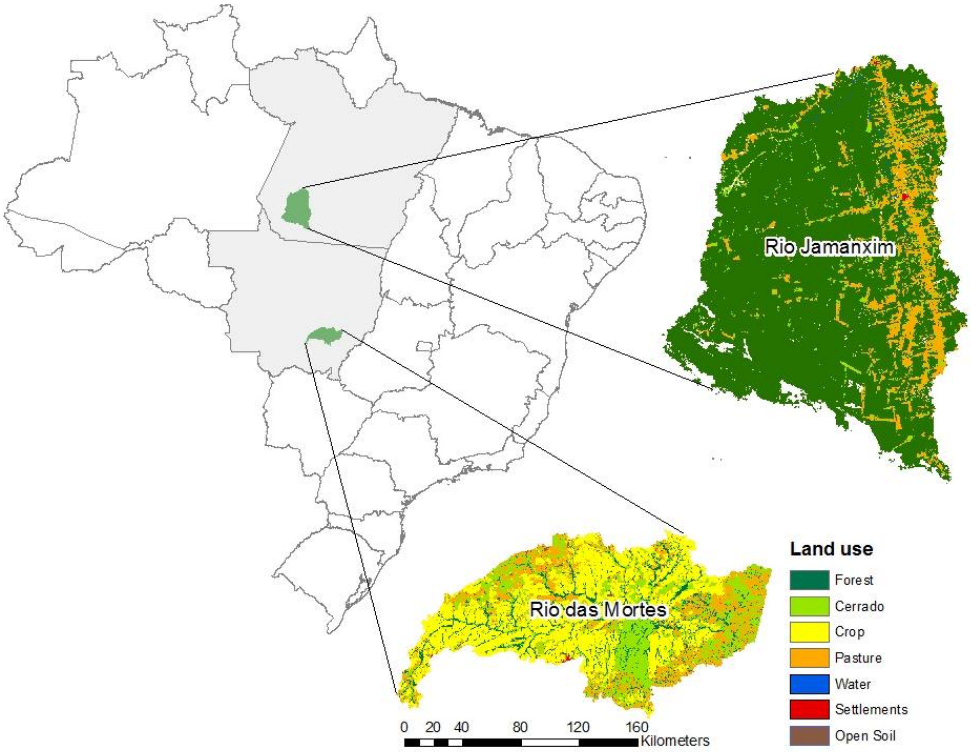

Figure 5.1: Overview of the Carbiocial study region. The map shows the regional level with the Federal States of Mato Grosso and Pará, and the land use within the two investigated watersheds.

Modelling exercises were undertaken on different spatial scales: local, watershed, landscape and regional level (Figure 5.1). The local level comprises selected farms in Mato Grosso. The watershed level includes the 2 macro-catchments "Rio das Mortes" and "Rio Jamanxim". A tributary of the Tapajós river in Pará, the "Rio Jamanxim" catchment (37,400 km²) is still largely covered by primary rainforest, but the pioneer front of human-induced land-use change is evident along its course. Contrasting, the "Rio das Mortes" catchment (17,500 km²) in Mato Grosso, east of Cuiabá, has seen most of the primary forest being cut more than 30 years ago and turned into cropland. The catchment characteristics are described in detail in Lamparter et al. (in review). The landscape level focuses on the deforestation frontier region along the BR-163. Finally the regional level includes the whole territories of both states with an area of almost 2.5 million km².

2.2 Modelling Framework

Figure 5.2 shows the linkages between the simulation models that were used to describe and to analyse societal and environmental processes within Southern Amazonian land systems. The individual models are introduced in the following subchapters. Societal aspects of land-use change and land management were simulated on farm level with the agent-based MPMAS model, on the landscape-scale using alucR and on the regional level with the LandSHIFT model. Environmental aspects of the land systems were calculated with different empirical and process-based modelling approaches. The impacts of climate change and technological change on crop productivity were calculated for the whole study region with the MONICA model. The calculated crop yields were used to inform both MPMAS and LandSHIFT. On the watershed level the SWAT model was applied to simulate the effects of land-use change (as provided by LandSHIFT) on the water balance whereas the effects on water soil erosion were investigated with the EROSION 3D model. Additionally on the regional level greenhouse gas emissions (GHG) and changes in soil organic carbon (SOC) stocks related to land-use changes were assessed with a set of empirical models (emission values).

Drivers of global change used by MPMAS, alucR and LandSHIFT such as agricultural production, market prices for crop commodities, and population development were provided in form of scenarios that include both qualitative aspects in form of verbal descriptions (storylines) and quantitative information on the future development of these drivers (see 2.3).

A potential climate change in the study region was assessed utilizing simulations of three different models: i) The global IPCC climate model ECHAM5/MPI-OM (Roeckner et al. 2003), ii) the regional climate model WRF driven by ECHAM/5/MPI_OM data, and iii) the Statistical Regional Model STAR (Orlowsky et al. 2010) using ERA-interim input interpolated to a 900x900m grid. As the focus of the model-based analyses is on the socio-economic scenarios and due to the short time frame of the study until 2030, only the A1B scenario (Forster et al. 2007) was used.

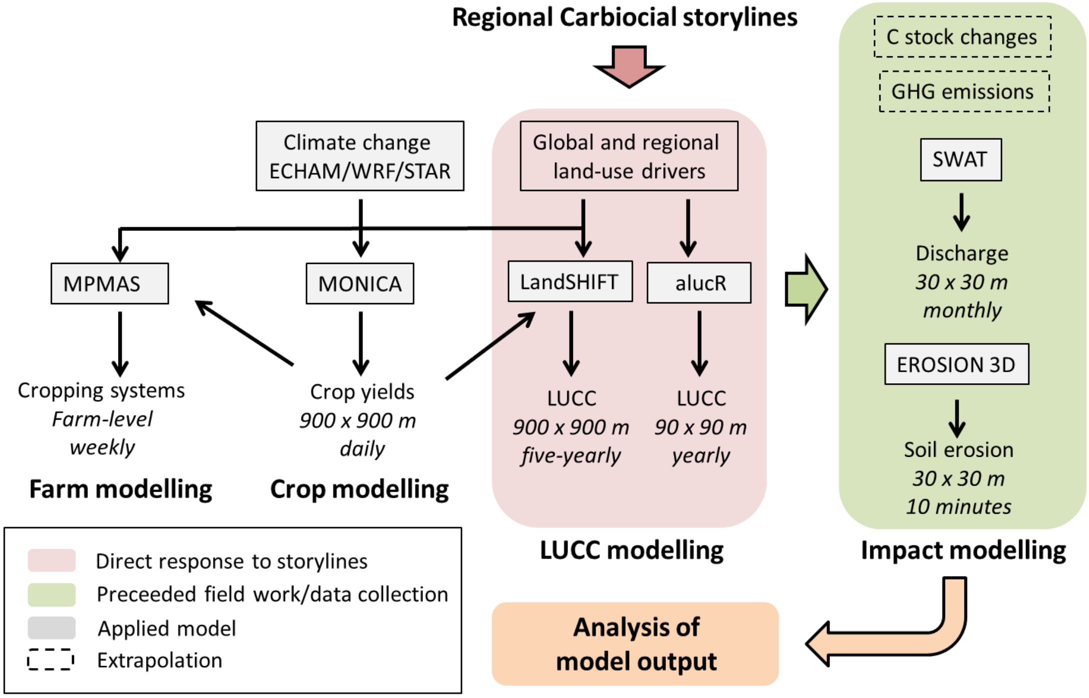

Figure 5.2: Model framework and linkages between the models.

2.3 Scenarios

The analytical framework for the simulation exercises is defined by a set of four scenarios which portray the societal development of the study region until the year 2030 (Schönenberg et al. in review). Each scenario consists of a storyline that verbally describes the situation in 2030 and a set of quantitative drivers that is used as model input for LandSHIFT (Goepel et al. in review), alucR (Gollnow et al. in review) and MPMAS (Moraes et al. 2016).

The Trend storyline is based on a forward projection of growing demands for agricultural products, a continuation of the conversion of natural ecosystems, the technical and social consolidation of highway BR-163 and local populations, as well as the further intensification of agricultural production.

Legal Intensification assumes a growing demand for agricultural products, but with an effective law enforcement preventing the illegal conversion of natural ecosystems. The technical and social consolidation of highway BR-163 and its populations will include a high intensification of agricultural production with regard to increased production as well as productivity and law enforcement of social and environmental law will be effective even as climate change continues. The Illegal Intensification storyline includes similar assumptions as “Legal Intensification”, but with only very sporadic law enforcement which will lead to the further conversion of natural ecosystems.

Finally, within the storyline of the “Sustainable Development” scenario Amazonian society will enjoy a social model with participation, citizenship and the enforcement of existing laws. Knowledge and technical resources will be available to most of the people, and there will be a growing demand for global finance mechanisms for sustainable economics and for certified agricultural goods. The latter are increasingly plant-based, as a shift to a low-meat diet assumes a general reduction of global meat consumption and, consequently, a reduction of Brazilian meat production by almost 70 %. Furthermore, land rights in the region will be clarified and licensed.

Based on the storylines for each scenario, a set of land-use drivers was identified to quantitatively describe the evolution of key variables until 2030. They include 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 (Goepel et al. in review; Gollnow et al. in review).

2.4 Modelling land-use change on fram level

MPMAS (Schreinemachers and Berger 2011) is a simulation package for dynamic modelling of agricultural systems at farm-level. It integrates an agent-based decision module representing the activities of land users with a cellular module representing the geographical landscape. MPMAS employs mathematical programming to simulate the investment, production, and consumption decisions of computational agents that represent real-world farm holdings. Agents in MPMAS maximize expected income by choosing the optimal land use and resource allocation while accounting for individual risk aversion. The software simulates the multi-period dynamics of agricultural systems by implementing the temporal carry-over of farm agent resources and updating of agent expectations. In addition, MPMAS is designed such that it allows coupling with external software packages, for example the crop-growth simulator MONICA. MPMAS can then be run for thousands of farm holdings simultaneously and thereby simulate the emergent policy response at aggregate level. Results for simulating the impacts of the Brazilian program for low-carbon agriculture (Programa ABC) are presented in Moraes et al. (in review).

2.5 Modelling of land-use change on landscape level

The alucR model was developed and applied for the empirical analysis and modelling of land use change specifically in the Brazilian Amazon within the Carbiocial project (Gollnow et al. in review). The model includes a non-spatial macro level that allows for integrating globally and regionally determined demands of land use change for possible future trajectories and a spatially explicit micro level dimension that allows for allocating the simulated future land use change on a raster-level of 90 x 90 m on a yearly basis. To develop locally adapted land use change processes the model "learns from historical developments" by applying a regression analysis in a first step to analyse the specific local drivers and determinants of change that was observed in past years in TerraClass data. From these findings the likelihood of change is derived and combined with a rule-based definition of possible transitions and dynamics of change. Modelling results are the identified statistically significant drivers and spatial determinants of land use change observed in the past and the simulated scenarios of future land use change on raster cells of 90 x 90 m on a yearly basis for the landscape-level along the BR-163.

2.6 Modelling of regional land-use change

The LandSHIFT model is used to calculate spatial and temporal land-use change due to the cultivation of food and energy crops, grazing, and urbanization (Schaldach 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 was simulated on a raster with the spatial resolution of 900 x 900 m. Each cell is assigned to a state (regional level). Model drivers are specified separately for each state (see 2.3). Cell-level information comprises land-use type, human population density, and a set of parameters that describe the landscape characteristics (e.g. terrain slope, potential yields, road infrastructure) and land-use restrictions (e.g. protected areas). During the simulation, LandSHIFT translates the regional model drivers into spatial land-use patterns. At the beginning of every time step the suitability of each raster cell for the different land-use types is determined based on cell-level information. Thereafter, the model uses region-level data to determine and allocate the land needed for each crop type, pasture and settlement in the most suitable cells. Model results are raster maps that depict the spatial and temporal patterns of land-use change until 2030.

2.7 Land-use change impacts on GHG fluxes, SOC stock changes, and carbon losses

GHG fluxes

The calculation of greenhouse gas emissions on the regional scale level was done using land use-specific average emissions of N_2O (Meurer et al. 2016 a) and CH_4 (Goepel et al. in review) which were extrapolated on the basis of the predicted land-use expansion or reduction, respectively. Since N_2O fluxes from cattle pastures were reported to increase noticeably for a certain period after the clear-cut (e.g. Melillo et al. 2001) and then decline to a level considerably below forest emissions (e.g. Neill et al. 2005, Meurer et al. 2016 a), average emission values of N_2O differed between young (≤ 10 years) and old (> 10 years) pastures. Results for the land-use types rainforest, cerrado, pasture, and cropland were converted into CO_2-equivalents considering the global warming potentials (GWP) of the two gases ($N_2O = 298$, $CH_4 = 25$, Forster et al. 2007).

SOC stock changes and carbon losses from forest conversion

SOC stock changes and carbon loss (as direct CO_2 emissions) resulting from forest conversion and biomass removal were likewise calculated. For the latter, we considered an average above-ground biomass for rainforest (222.3 Mg ha^{-1}, Lima et al. 2012) and above-ground C stocks for cerrado areas (37.4 Mg C ha^{-1}, de Miranda et al. 2014), as reported by Fearnside (2016). These values were applied to the converted rainforest and cerrado areas. SOC stock changes were calculated for the land-use types pasture and cropland based on measured data (> 950 samples) from the two reference soil groups Ferralsol and Acrisol (Strey et al. 2016). Samples were taken to a depth of 100 cm (n = 9 (plot level), n = 29 (regional level)). C stocks were calculated using an on-plot bulk density measurement and subsequently corrected for their soil mass according to Ellert and Bettany (1995) and Poeplau and Don (2013).

2.8 Modelling the effects of land-use change on water balance

For two macro-catchments a SWAT-model (Arnold et al. 2012) was setup with the implementation of gradual land use change for the periods with the most intensive deforestation: 1977-1986 for “Rio das Mortes” (cerrado biome), 2000-2009 for “Rio Jamanxim” (rainforest biome). The scenario application in both catchments was set to the decade 2026-2035. The better performance of the SWAT model with gradual land-use change compared to a classic setup with steady state land use distribution was demonstrated with the good calibration and validation statistics (Lamparter et al., in review). For the parametrization of the hydrological model alongside an extensive literature review and data mining with eco-physiological and hydrological studies of the region (vegetation parameter) and statistical analysis of the RADAM soil profile data base (ESALQ 2015), own research results on soil hydrological properties in different scales were used with: spatial variability of key soil physical properties in five micro-catchments (with main land use types and cerrado and rainforest as reference) with texture, bulk-density, porosity, C-content, hydraulic conductivity (Guzha et al. 2014). Also land use-dependent differences in pedo-hydrological conditions for the main soil types in the macro-catchment “Rio das Mortes” were used (Wolf 2016) which allows a better estimation of sensitive land use and soil parameters for each soil and land use type combination separately.

2.9 Modelling the effect of land-use change on soil erosion

The process-based soil erosion model EROSION 3D (Schmidt 1991) simulates soil loss, sediment transport and deposition for single events or sequences. It has been applied to numerous catchments (e.g. Defersha and Melesse 2012; Starkloff and Stolte 2014). EROSION 3D enables simulations of a wide range of processes including erosion by sheet and channel flow. Simulation of infiltration is based on the Green-Ampt approach (Green and Ampt, 1911) whereas particle detachment and transport are calculated using the momentum flux approach (Schmidt 1991). Model parameters were identified as functions of land use, soil characteristics and simulation date using an extensive data base deducted from numerous rainfall experiment simulation on test plots between 2012 and 2013 within the two watersheds. Experiments were conducted on the most common regional soil, land use and tillage types. The consequences on climate change and land-use change for soil loss by erosion were simulated for the four scenarios.

2.10 Impacts of climate change and technological change and crop yields

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 as described in section 2.2.

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^{-1} for maize and 12.5 t ha^{-1} 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^{-1}, while soybean yields in famer competitions reached 7.6 t ha^{-1} (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.

3. Results

3.1 The effect of global change on land-use change in Southern Amazonia

Land-use change on the farm level

Moraes et al. (in review) conducted simulation experiments to quantify the impacts of preferential credit programs on the adoption of low-carbon agricultural systems in the federal state of Mato Grosso. Starting in 2010, the Brazilian government launched the so-called ABC Program that offers subsidized credit for integrated crop, livestock and forestry systems (Gil et al. 2014). By providing this incentive, the government intends to relieve land-use pressure on the agricultural frontier and fulfil its pledge at COP15 of reducing its greenhouse gas emissions substantially. The impacts of this program, however, are still unclear, and MPMAS together with MONICA was employed to quantify them with the help of computer simulation.

The simulation results suggest that the ABC Program indeed contributed to the adoption of integrated systems in Mato Grosso. Without these preferential credit lines, the adoption of integrated systems would be rather modest at about 11 % of agricultural land use. With the introduction of the ABC program the area under integrated systems more than doubled in Mato Grosso. Furthermore, without the ABC Program, almost the entire area of integrated systems would be made up of crop-livestock integration only. With the ABC Program, the simulations suggest an increase in more deeply integrated crop-livestock-forestry and crop-forestry systems.

Still, impact and cost-effectiveness of the ABC Program vary significantly across Mato Grosso. Given the heterogeneity of farming conditions, it appears ineffective to apply the ABC Program under identical conditions in the entire state. Tailoring financing conditions to smaller geographical units could decrease the implementation costs of this program and increase its effectiveness. Explorative simulations concerning the possible introduction of high-value timber markets suggest that enabling more farmers to engage in commercial teak production could further increase the state's area of integrated systems with ABC credit.

Land-use change on the landscape level

The simulation results are described in detail by Gollnow et al. (in review). While on the regional level (see below) pasture area decreased and croplands expanded under *Sustainable Development*, these dynamics were less pronounced along the BR-163 where pasture area remained the dominant land use in 2030. In contrast, the Trend scenario depicts a strong expansion of pasture and an increase of cropland and settlements. The model outcome on the landscape level thereby reflects the dynamics of processes such as intensification (conversion of pastures to croplands) and migration which have shaped recent decades of the BR-163 region (Rudorff et al. 2011, Richards 2012). Results also highlight that pasture expansion was rather determined by infrastructure availability or accessibility while it was more indifferent on biophysical determinates. In this rational, an effective implementation of the cattle moratorium, the implementation of a property cadastre, combined with efforts on intensification may be an important policy to curb deforestation within the region, next to the soy moratorium and strategies implemented within the PPCDAm.

Land-use change on the regional level

The model output from LandSHIFT is described in Goepel et al. (in review) and summarized in Figure 5.3. The largest reduction of rainforest was simulated for the *Trend* scenario, mainly driven by the expansion of rangeland. In contrast, the loss of rainforest was considerably lower in the *Legal Intensification* scenario, indicating that, especially in Pará, effective governance and protection of natural habitats play an important role for reducing deforestation. The highest loss of Cerrado was simulated for the *Trend* scenario while the lowest loss did occur under *Legal Intensification*.

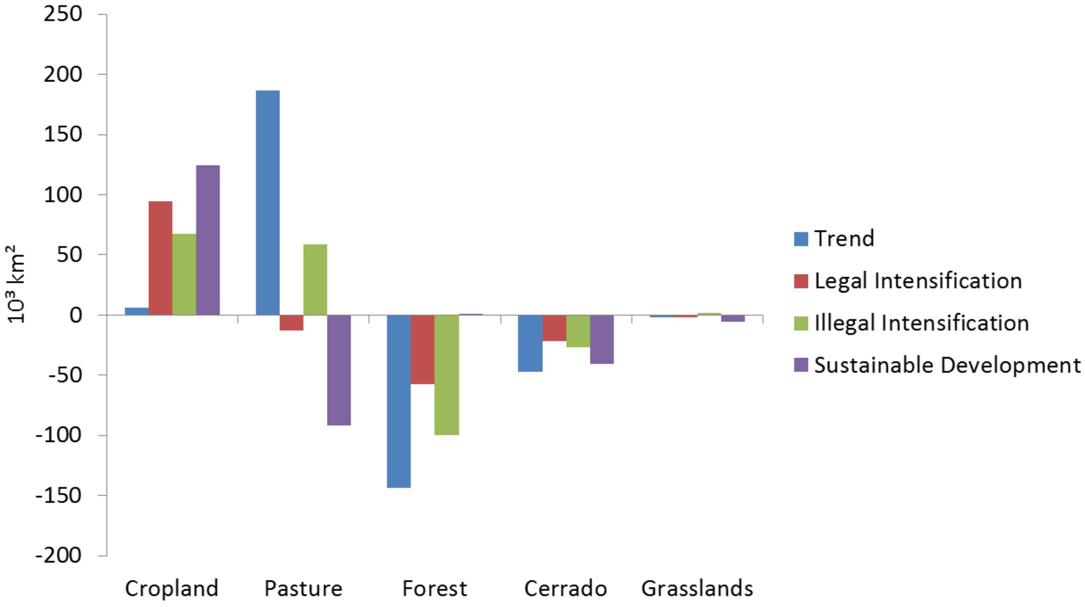

Figure 5.3: Projected land-use change in Mato Grosso and Pará under the 4 scenarios.

The highest increase of cropland area was projected for the *Sustainable Development* scenario which can be explained by the soaring demands for crop products due to a shift towards a vegetarian diet. Parts of this additional demand was fulfilled by crops (e.g. soybean) formerly used as livestock fodder. A substantial share of the newly acquired cropland was located on former pasture. Both intensification scenarios were characterized by cropland expansion which could only partly be compensated by increasing crop yields.

The highest increase of pasture area was found in the *Trend* scenario, which assumes a strong increase of meat demand, but no concurrent intensification of pasture management.

Consequently, the additional cattle feed demand was satisfied by area expansion alone. Pasture expansion under the intensification scenarios was significantly lower as a more intensive pasture management outweighs the effect of increasing livestock numbers. In contrast, pasture area strongly declined under the *Sustainable Development* scenario due to the lower demand for meat products.

3.2 Land-use change impacts on GHG fluxes and SOC stock changes

Greenhouse gas emissions on the regional level

Table 5.1 summarizes the calculated GHG emission, expressed as CO_2-equivalents, for the different land use scenarios in the year 2030.

Table 5.1: Calculated median emission of N_2O and CH_4 [CO_2-eq] from soils for scenario-based land distribution (including natural and agricultural areas) in the year 2030.

Scenario	GHG emission [CO_2-eq, 10^6 Mg]	
	Pará	**Mato Grosso**
Trend	68.00	34.78
Legal Intensification	67.66	32.54
Illegal Intensification	67.30	32.45
Sustainable Development	69.75	33.36

Median emissions from soils did not vary a lot between the scenarios, but differed between the states Pará and Mato Grosso. Emissions in Pará were almost twice as high as in Mato Grosso because of the larger forest area in Pará, compared to Mato Grosso. Main drivers between the scenarios were the conversion of rainforest areas and the establishment of new pastures. The *Sustainable Development* scenario does not account for further forest conversion and the uptake of CH_4 from rainforest soils does not compensate the high N_2O fluxes in the overall budget ($69.75 \cdot 10^6$ Mg CO_2-eq). Since young pastures (≤ 10 years) were found to emit even larger amount of N_2O than forest areas, they play an important role in estimating GHG emissions. In the Trend scenario, 19 % and 17 % of all pastures in Pará and Mato Grosso were younger than 10 years in 2030 (Goepel et al., in review). This proportion accounted for 39,534 and 43,706 km², respectively, and explains the high GHG emissions, especially in Mato Grosso.

Carbon losses from forest conversion and SOC stock changes

The carbon loss from biomass removal for the different land-use scenarios are depicted in Table 5.2. It becomes clear that the area of converted rainforest and cerrado is directly reflected in the resulting CO_2 emissions.

Table 5.2: Estimated carbon loss as CO_2 from biomass in the states Pará and Mato Grosso resulting from biomass loss between 2010 and 2030.

Scenario	**CO_2 emissions[10^9 Mg]**						
	Pará			**Mato Grosso**			**Total**
	Rainforest	**Cerrado**	**Total**	**Rainforest**	**Cerrado**	**Total**	
Trend	4.44	0.18	4.62	1.18	0.47	1.65	6.27
Legal Intensification	2.78	0.20	2.98	0	0.10	0.10	3.08
Illegal Intensification	3.89	0.21	4.10	0.03	0.16	0.19	4.29
Sustainable Development	0	0.52	0.52	0	0.50	0.50	1.02

The response of SOC stocks to land-use changes under the four scenarios differs greatly between Acrisols and Ferralsols (Table 5.3). Compared to the native forest or cerrado vegetation, Acrisols showed an increase of SOC stocks in the first meter of soil depth when converted into pastures but a SOC decrease if used as cropland. SOC stocks in Ferralsols reacted oppositely, with a loss of SOC if converted to pastures and a gain of SOC if transferred to cropland. Therefore, in scenarios with extensive conversion to pasture, Acrisols will appear as C sinks where at the same time Ferralsols will act as SOC sources. In summary, the Trend scenario appeared as the worst case scenario with respect to SOC storage, since this scenario predicted the biggest and unpropitious conversion area, particular in Pará. However, the coefficient of variation of SOC changes varies between 61 and 358 % (Table 5.3), indicating the level of uncertainty and that at a larger scale the effects of SOC losses and gains might compensate each other (Strey et al. 2016).

Table 5.3: SOC stock changes in Acrisols and Ferralsols (0 - 100 cm) for pastures and cropland in Pará and Mato Grosso. SOC stock changes were calculated for areas that were converted from native vegetation to pasture or pasture to cropland between 2010 and 2030. TD = Trend, LI = Legal Intensification, ILI = Illegal Intensification, SD = Sustainable Development.

Scenario	**Pará**					**Mato Grosso**					**Total**
	Converted area $[10^9\ km^2]$		**SOC stock changes $[Mg\ 10^{12}\ km^{-2}]$**			**Converted area $[10^9\ km^2]$**		**SOC stock changes $[Mg\ 10^{12}\ km^{-2}]$**			
	Pasture	**Cropland**	**Pasture[1]**	**Cropland[2]**	**Total**	**Pasture**	**Cropland**	**Pasture**	**Cropland**	**Total**	
						Acrisol					
TD	43.73	2.96	23.66	−3.83	19.83	26.52	28.22	14.35	−36.51	−22.17	-2.34
LI	8.51	2.26	4.60	−2.92	1.68	8.12	33.91	4.40	−43.88	−39.48	-37.80
ILI	41.90	9.85	22.67	−12.75	9.92	4.43	38.38	2.39	−49.67	−47.28	-37.36
SD	−31.52	−4.07	-[3]	-[3]	-[3]	9.67	34.11	5.23	−44.14	−38.91	-38.91
						Ferralsol					
TD	97.79	25.64	−51.73	32.56	−19.17	66.38	19.00	−35.11	24.14	−10.98	-30.15
LI	2.61	21.14	−1.38	26.85	25.47	19.08	42.29	−10.09	53.71	43.62	69.09
ILI	30.47	26.17	−16.12	33.23	17.12	13.03	34.27	−6.89	43.52	36.63	53.75
SD	−25.33	11.29	-[3]	14.34	14.34	23.14	41.40	−12.24	52.57	40.33	54.67

[1] mean SOC accumulations = 6.2 % (Acrisol) and 4.8 % (Ferralsol); CV = 156 % (Acrisol) and 348 % (Ferralsol), considering only the variation of SOC not the variation of the converted area

[2] mean SOC losses = 20.1% (Acrisol) and 9.6 % (Ferralsol); CV = 103 % (Acrisol) and 61 % (Ferralsol), considering only the variation of SOC not the variation of the converted area

[3] no calculated data since the area of this land-use type decreased from 2010-2030 and it is not clear which is the new land-use

3.3 Land-use change impacts on the water balance

As land-use change is accompanied by soil compaction processes with lower hydraulic conductivity (k_{sat}) for cropland and pasture it has a clear effect on discharge (Q) in both catchments. For both catchments model results show an increase of Q with continuing deforestation. A reduction of cerrado of 5 % and an increase of pasture of 12 % resulted in a 3.4 % increase of annual Q (comparison *Sustainable Development* and *Trend* scenario in 2030). In the “Rio Jamanxim” catchment 24 % more deforestation increases Q by 2 % (compare *Sustainable Development* to *Illegal Intensification*) (see Figures 3 a and b in Lamparter et al., in review). In the “Rio das Mortes” catchment only the Trend scenario with the highest increase of pasture area shows higher Q due to lower evapotranspiration and ksat reduction. Higher evapotranspiration (ET) for the *Sustainable Development* scenario (no further deforestation, 88 % forest cover remains) and therefore lowest the Q within the scenarios was calculated for the “Rio Jamanxim” catchment. The strongest effects of land-use change on hydrology were visible during the rainy season. In the cerrado catchment only gradual differences in the water balance components exist between the scenarios, because main land-use change was completed after 1990 (Table 1 in Lamparter et al., in review). Moreover the simulations reveal a clear seasonality of the changes to the water balance components. Q shows the strongest land use change effects at the beginning of the rainy season. The seasonal pattern seems characteristic for hydrological effects of land-use change in areas with pronounced wet and dry periods.

3.4 Land-use change impacts on soil erosion on watershed level

In both catchments soil erosion and sediment transport are a function of climate, land use and soil types. Most endangered areas are croplands, pastures and deforested area. Since the vulnerability of the catchments depends on distribution of resilient soil types, the “Rio Jamanxim” catchment with its widespread little-resilient Acrisols suffers the most from land use changes.

In the “Rio das Mortes catchment” compared to the status quo (3.2 t ha^{-1} a^{-1}) all scenarios reveal more than a tripling of soil losses, which is a result of an increased rainfall intensities of the WRF climate scenario rather than of land use changes. The highest soil losses were calculated for the Trend scenario which can be explained by the large expansion of erosion-prone pastures in the east part of the catchment. All others scenarios reveal quite similar results around 11 t ha^{-1} a^{-1} soil loss and 0.5 t ha^{-1} a^{-1} deposition.

Simulations of the “Rio Jamanxim” catchment indicate that under the Trend scenario annual mean soil losses of 28 t ha^{-1} a^{-1} seem possible, which corresponds to an increase by factor 3.3 compared to the current situation (8.48 t ha^{-1} a^{-1}). Under Illegal Intensification simulated erosion even increased by the factor 5.6, which is due to the high rate of land forest conversion into pasture in the western part of the catchment. A legal intensification of land use would lead to a decrease of 25 % in soil erosion compared to the actual situation. In contrast, a Sustainable Development of land use in the catchment would lead to an annual soil loss of only 4 t ha^{-1} a^{-1}, which means a decrease of more than 50 % compared to the status quo.

3.5 Effects of climate change and technological change on crop yields

The simulation results from the MONICA model for Pará show a 21 % decrease of average soybean yields from 2.4 t ha^{-1} in 2000–2005 under current climate to 1.9 t ha^{-1} 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^{-1} to 4.2 t ha^{-1} 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^{-1} in 2000 – 2005 to 1.9 t ha^{-1} 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^{-1}. 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 202 5– 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.

4. Discussion and conclusion

We illustrated the application of various combined simulation models to answer the three research questions posed in the introduction that were central to the Carbiocial project:

How do trends of global change affect land-use change in Southern Amazonia in the coming decades?

We found that the development of global demands for agricultural commodities led to a further increase of crop and livestock production within the region, and in tendency a growing demand for land resources. In the scenarios this pressure could partly be compensated by further intensification of agricultural systems gaining higher per ha biomass productivity. It also became clear that the loss of natural ecosystems is strongly determined by the successful enforcement of conservation laws either in form of the new forest code or by a strict definition of protected areas (e.g. Soares-Filho et al. 2010). Results from the Sustainable Development scenario highlighted that changes in human lifestyle and consumption patterns together with strong law enforcement has a high potential for further reducing the loss of natural ecosystems (e.g. Stehfest et al. 2006) .

How does the changing land-use pattern affect SOC, GHG emissions, the water cycle, and soil erosion?

Based on the output from the land-use models environmental impacts were assessed. SOC stock changes and direct GHG emissions from soils vary significantly between the scenarios and were mainly driven by the underlying soil type and the area of converted natural vegetation, respectively. Assuming a steady rate in forest conversion over the time from 2010 to 2030, the annual CO_2 emissions from biomass removal ranges from 0 to 60·106 Mg C for rainforest and from 5 to 30·106 Mg C for cerrado. Especially the numbers for cerrado are considerably higher than the results from Fearnside et al. (2009) for 2006/2007, which can be explained by the higher conversion rates of cerrado within all Carbiocial scenarios. Impacts on hydrological processes (discharge) and water erosion were investigated on the watershed level. By feeding SWAT and EROSION 3D with output from the regional land-use model a direct link between global and regional drivers of land-use change and their effects on these processes was achieved. Also in these analyses the scenarios with the highest transformation of forest cover to pasture and cropland had the strongest effects.

How does climate change together with technological change affect crop yields?

Our simulation experiments indicated that climate change in tendency has negative effects on crop yields in both states. Only second-season maize may profit from the changing conditions. Against this background, major efforts to improve crop yields e.g. by the introduction of new crop varieties or an optimization of crop management practices are necessary in order to achieve the assumed crop yield increases within the scenarios (see also Moraes et al., 2016).

Lessons learned from model building and the combination of models

Addressing the goals of the project required advancements in the modelling techniques. Innovations of land-use models for example included the development of a high-resolution models for the whole region and along the BR-163, and the ability to simulate the interplay of the different drivers of land-use change in a more explicit manner as in recent studies with focus on deforestation alone (e.g. Soares-Filho et al. 2006; Gilford et al. 2010). For agricultural yield simulations, only a very few simulation models are available that have been successfully tested for tropical regions and are capable of simulating crop rotations. A tailor-made solution was required by adapting the MONICA model for tropical regions which required significant efforts for example in the representation of soil properties.

Independent of the modelling scale, experimental data was mandatory for model building, calibration and evaluation (Jakeman et al. 2006). Especially regarding the calibration of the hydrological and erosion models we found the necessity for more differentiated information of soil and land use types. New scientific insights could be gained from the field measurements that formed the foundation especially of the model-based analysis of environmental impacts. The calculation of GHG emissions and SOC stock changes were based on field measurements for obtaining the emission factors. Emissions of N_2O and CH_4 from Brazilian soil were found to be low across the country (Meurer et al. 2016 a; Goepel et al. in review) and CH_4 was rather absorbed by most of the soils, except for cattle pastures. Measurements in the states of Mato Grosso and Pará did not show any recognizable dynamics (Meurer et al. submitted) and detailed mechanistic model applications in daily time steps was found to be too sophisticated for regional approaches (Meurer et al. 2016 b). The same applies to soil organic carbon (SOC) stocks, which were hardly affected by a change in land-use system, but noticeable by the soil type itself. Table 5.4 gives an overview of new scientific knowledge gained by these field experiments.

In became clear that only by combination of the different models a comprehensive analysis of processes of the investigated land systems was possible. Although the models were not fully integrated (e.g. Hamilton et al. 2015), our modelling framework ensured that they were using consistent data sets and scenario assumptions for their experiments whenever possible. It also facilitated the analysis of linkages between different spatial scale levels. For example it was possible to investigate how hydrological and erosion processes were influenced by land-use change which is mainly driven by regional and global drivers.

Table 5.4: Hypotheses (based on current knowledge), approaches, gained scientific understanding, and application of field data within the modelling framework.

Research topic	Hypotheses	Approach	Understanding gained	Application within the modelling framework	Reference
N_2O and CH_4 fluxes from soils	High and dynamic fluxes from Brazilian agricultural soils (especially during rainy season)	Field measurements (daily measurements)	Low emissions of N2O and CH4 and negligible short-term dynamics	Extrapolation of emission values for different land use types gained by an extensive literature review (Meurer et al. 2016 a)	Meurer et al. (2016 b) Meurer et al. (submitted)
	Models as prediction tools for determination of meaningful measurement period for hot moments of N_2O	Model application (CANDY, DNDC, and DDC)	Process-based models were too sensitive; overestimations likely due to simulated expected “hot moments”		Meurer et al. (2016 b)
Hydrological modelling, water balance	Deforestation with land-use change and climate change increase discharge variability and leads to more discharge peaks. ET is mainly changed by land-use change.	Field measurements with long-term hydrological and hydro-chemical monitoring in micro-catchments. Model application with SWAT	Mainly pasture expansion increases discharge and its variability, due to changes of pedohyrological parameters. Climate change further increases discharge changes by land-use change.	Measured field data allows better model parameterisation for land-use change scenarios in macro-catchments	Guzha et al. (2013) Guzha et al. (2014) Lamparter et al. (in review)

Lessons learned for the design and implementation of future research projects

As illustrated by Turner et al. (2016) interdisciplinary research is needed to efficiently bring together analyses of land-use change with the analyses of impacts on ecosystems and the human system. Here the Carbiocial modelling framework is a first step for knowledge integration which can be transferred to future research projects. An important prerequisite is a clear definition of interfaces for the exchange of information not only between models but also between the responsible scientists in order to adequately portray the interplay between societal and environmental aspects (see Schönenberg et al., in review). This includes the willingness from scientists to reflect benefits but also shortcoming of each one of the specific models and – most importantly – the time (and funding) to develop and implement an operating modelling framework.

With our model experiments we could illustrate that scale needs to be accounted for in the respective studies by addressing the inherent multi-scale processes in a transparent manner. Particularly for land-use change, processes on different scales and interactions between scales and places have to be accounted for (e.g. Meyfroidt et al. 2013).

Last but not least communication and the translation of scientific findings from comprehensive model experiments and projects into policy and stakeholder-relevant information is a decisive step that has to be accounted for by using generalizations but at the same time transparent interpretation of the simulation results. In this regard, scenarios together with spatially explicit model outcome in form of maps may allow for stimulating and structuring discussion of possible future pathways of land-use change in the Brazilian Amazon. The coupled model system MPMAS-MONICA, for example, has a graphical user interface (GUI) containing soil maps and historical climate data from local meteorological stations. Also, it is synchronized with Google Maps® and can display terrain and road maps from Google Maps®. The GUI was originally developed by Wenkel et al. (2013) and was adapted for the Carbiocial study area to include the results of farm performance simulated by MPMAS. The GUI has been designed to support the decisions of local land users. Through the interface, its users can apply MPMAS and MONICA for the improvement of farm planning. The user selects the location and the size of the farm, for which he or she wants to perform simulations, and the interface displays the results of respective model computations. The GUI provides visualized information on simulated optimal land use, crop yields, per hectare gross margins of different land use activities and total profit of the farms (Latynskiy et al. 2014)

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References

An l, Zvoleff A, Liu JG, and Axinn W 2014 Agent-based modeling in coupled human and natural systems (chans): lessons from a comparative analysis *Ann. Assoc. Am. Geogr.* **104** (4) 723-745.

Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, van Griensven A, Van Liew MW, and Kannan N 2012 SWAT: Model use, calibration, and validation. *T. ASABE* **55** (4) 1491-1508.

CESB 2015 Desafio Nacional de Máxima Produtividade da Soja. http://www.cesbrasil.org.br/Sobre.aspx. Accessed June 2015.

Dalla-Nora EL, de Aguiar APD, Lapola DM, and Woltjer G 2014 Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade? *Land Use Policy* **39** 403-411, doi: 10.1016/j.landusepol.2014.02.004.

Defersha MB and Melesse AM 2012 Field-scale investigation of the effect of land use on sediment yield and runoff using runoff plot data and models in the Mara River basin, Kenya *Catena* **89** (1) 54–64, doi: 10.1016/j.catena.2011.07.010.

Ellert BH and Bettany JR 1995 Calculation of organic matter and nutrients stored in soils under contrasting management regimes *Can. J. Soil Sci.* **75** (4) 529-538, doi: 10.4141/cjss95-075.

Embrapa 2014 Ensaio Nacional de Cultivares de Milho. http://www.cnpms.embrapa.br/ensaio/. Accessed 15 July 2015.

Ewert F, van Ittersum MK, Heckelei T, Therond O, Bezlepkina I, and Andersen E 2011 Scale changes and model linking methods for integrated assessment of agri-environmental systems *Agric. Ecosyst. Environ.* **142** 6-17.

FAO 2015 Food Outlook – Biannual report on global food markets. FAO, Rome.

Fearnside PM, Righi CA, de Alencastro Graça, PML, Keizer EWH, Cerri CC, Nogueira EM, and Barbosa RI 2009 Biomass and greenhouse-gas emissions from land-use change in Brazil's Amazonia "arc of deforestation": The states of Mato Grosso and Rondonia *Forest Ecol. Manage.* **258** 1968 – 1978, doi:10.1016/j.foreco.2009.07.042.

Fearnside PM 2016 Brazil's Amazonian forest carbon: The key to Southern Amazonia's significance for global climate. *Reg. Environ. Change* (2016) 1 - 15, doi: 10.1007/s10113-016-1007-2.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywoos J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, and Can Dorland R 2007 Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (ed) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Galford GL, Melillo JM, Mustard JF, Cerri CEP, and Cerri CC 2010 The Amazon frontier of land-use change: croplands and consequences for greenhouse gas emissions *Earth Interact.* **14** 1–24, doi: http://dx.doi.org/10.1175/2010EI327.1.

Gerold G, Jungkunst HF, Guimarães Couto E, Madaric B, Silva Santos Amorim R, Hohnwald S, Klingler M, de Almeida Machadoc PLO, and Nendel C Introduction to the special issue: Impacts of carbon-optimised land use management in Southern Amazonia – multi-disciplinary perspectives *Reg. Environ. Change* (in review).

Gil J, Siebold M, and Berger T 2014 Adoption and development of integrated crop–livestock–forestry systems in Mato Grosso, Brazil *Agr. Ecosyst. Environ.* **199** 394-406.

Goepel J, Schüngel J, Schaldach R, Meurer KHE, Jungkunst HF, Franko U, Boy J, Strey R, Strey S, Guggenberger G, Hampf AC, and Parker PS Future scenarios of land-use change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils *Reg. Environ. Change* (in review).

Gollnow F, Goepel J, Lakes T, and Schaldach R Future development paths of local land use changes within a globally changing world - A Multi-Scale Land Use Modelling approach for the Brazilian Amazon *Reg. Environ. Change* (in review).

Green WH and Ampt GA 1911 Studies on soil physics I. The flow of air and water through soils. *J. Agr. Sci.* **4** 1–24. doi: 10.1017/S0021859600001441.

Guzha A, Nóbrega RLB, Kovacs K, Amorim RSS, and Gerold G 2013 Quantifying impacts of agro-industrial expansion in Mato Grosso, Brazil, on hydrological fluxes and water related ecosystem service provision using the Soil and Water Assessment Tool (SWAT) model. 20th International Congress on Modelling and Simulation, Adelaide, Australia.

Guzha A, Nóbrega RLB, Kovacs K, Rebola-Lichtenberg J, Amorim RSS, and Gerold G 2014 Characterizing rainfall runoff signatures from micro catchments with contrasting land cover characteristics in Southern Amazonia. *Hydrol. Process.* **29** (4) 508 - 521, doi: 10.1002/hyp.10161.

Hamilton SH, El Sawah S, Guillaume JHA, Jakeman, AJ, and Pierce SA 2015 Integrated assessment and modelling: Overview and synthesis of salient dimensions *Environ. Modell. Softw.* **64** 215–229.

Hampf AC, Moraes MCMM, Latynski E, Libera AAD, Monteiro A, Sentelhas PC, Berger T, and Nendel C (in preparation) Decomposing the yield gap in Southern Amazon into its proximate and underlying factors – a bio-economic modelling approach.

Hertel TW 2015 The challenges of sustainably feeding a growing planet *Food Secur.* **7** (2) 185–198, doi: 10.1007/s12571-015-0440-2.

Jakeman AJ, Letcher, RA, and Norton, JP 2006 Ten iterative steps in development and evaluation of environmental models *Environ. Modell. Softw.* **21** (5) 602-614.

Lamparter G, Nóbrega RLB, Kovacs K, Amorim RS, and Gerold G Gradual land use change in hydrological modelling: Towards an improved prediction of water balance components applied to land use scenarios for two macro-catchments in Southern Amazonia *Reg. Environ. Change* (in review).

Lapola DM, Schaldach R, and Alcamo J 2011 Impacts of climate change and the end of deforestation on land use in the Brazilian Legal Amazon *Earth Interact.* **1** 2–29.

Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, and Priess J A 2010 Indirect land-use changes can overcome carbon savings from biofuels in Brazil *P. Natl. Acad. Sci.* **107** (8) 3388-3393.

Latynskiy E, Berger T, and Troost C 2014 Assessment of policies forlow-carbon agriculture by means of multi-agent simulation. Proceedings -7th International Congress on Environmental Modelling and Software: Bold Visions for Environmental Modeling *iEMSs 2014* **4** 1881-1888.

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, and Schellnhuber HJ 2008 Tipping elements in the Earth's climate system *Proc Natl Acad Sci USA* **105** (6) 1786–1793, doi: 10.1073/pnas.0705414105.

Lima AJN, Suwa R, Ribeiro GHPM, Kajimoto T, dos Santos J, da Silva RP, de Souza, CAS, de Barros, PC, Noguchi H, Ishizuka M, and Higuchi N 2012 Allometric models for estimating above- and below-ground biomass in Amazonian forests at São Gabriel da Cachoeira in the upper Rio Negro, Brazil *Forest Ecol. Manage.* **277** 163–172, doi:10.1016/j.foreco.2012.04.028.

Miranda SC, Bustamante M, Palace M, Hagen S, Keller M, and Ferreira LG 2014 Regional variations in biomass distribution in Brazilian savanna woodland *Biotropica* **46** (2) 125–138, doi: 10.1111/btp.12095.

Melillo JM, Steudler PA, Feigl BJ, Neill C, Garcia D, Piccolo MC, Tian H 2001 Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon *J. Geophys. Res.* **106** (D24): 34179-34188.

Meurer KHE, Franko U, Stange CF, Dalla Rosa J, Madari BE, and Jungkunst HF 2016 a Direct nitrous oxide (N2O) fluxes from soils under different land use in Brazil – a critical review. *Environ. Res. Lett.* **11** 02001, doi: 10.1088/1748-9326/11/2/023001

Meurer KHE, Franko U, Spott O, Stange, CF, Jungkunst HF 2016 b Model testing for nitrous oxide (N_2O) fluxes from Amazonian cattle pastures. *Atmos. Environ.* **143** (2016) 67 – 78, doi: 10.1016/j.atmosenv.2016.08.047.

Meurer HKE, Franko W, Spott O, Schützenmeister K, Niehaus E, Strange CF, and Jungkunst HF Missing hot moments of greenhouse gases in Southern Amazonia. *Erdkunde* (submitted).

Meyfroidt P, Lambin EF, Erb, KH, and Hertel TW 2013 Globalization of land use: distant drivers of land change and geographic displacement of land use *Curr. Opin. Env. Sust.* **5** (5) 438-444.

Moraes MCMM, Libera AAD, Latynskiy E, Hampf A, Silveira JMFJ, and Berger T 2016 Integrated assessment of novel two-season production systems in Mato Grosso, Brazil. In: Sauvage, S., Sánchez-Pérez, J.M., Rizzoli, A. (Eds.), Proceedings of the 8th International Congress on Environmental Modelling and Software, Toulouse, France, http://www.iemss.org/ society/index.php/iemss-2016-proceedings.

Müller H, Rufin P, Griffiths P; Barros Siqueira AJ, and Hostert P 2015 Mining dense Landsat time series for separating cropland and pasture in a heterogeneous Brazilian savanna landscape *Remote Sens. Environ.* **156** 490–499, doi: 10.1016/j.rse.2014.10.014.

Neill C, Steudler PA, Garcia-Montiel DC, Melillo JM, Feigl, BJ, Piccolo MC, and Cerri CC 2005 Rates and controls of nitrous oxide and nitric oxide emissions following conversion of forest to pasture in Rondonia *Nutr. Cycl. Agroecosys.* **71** 1 – 15, doi: 10.1007/s10705-004-0378-9.

Nendel C, Berg M, Kersebaum KC, Mirschel W, Specka X, Wegehenkel M, Wenkel KO, and Wieland R 2011 The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics *Ecol. Model.* **222** (9) 1614–1625, doi:10.1016/j.ecolmodel.2011.02.018.

Nepstad DC, Stickler CM, Filho BS, and Merry F 2008 Interactions among amazon land use, forests and climate: prospects for a near-term forest tipping point *Philos. T. Roy. Soc. B* **363** (1498) 1737–1746, doi:10.1098/rstb.2007.0036.

Orlowsky B, Bothe O, Fraedrich K, Gerstengarbe FW, and Zhu X 2010 Future climates from bias-bootstrapped weather analogs: an application to the Yangtze River Basin *J. Climate* **23** (13) 3509-3524.

Parker PS, Hampf AC, Bender FD, Monteiro LA, Berg M, and Nendel C (in preparation) Simulated future yields in soybean–maize rotations throughout Mato Grosso and Pará, Brazil.

Poeplau C and Don A 2013 Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe *Geoderma* **192** 189 - 201.

Richards, Peter D., Robert T. Walker, and Eugenio Y. Arima Spatially complex land change: The Indirect effect of Brazil's agricultural sector on land use in Amazonia *Global Environmental Change* **29** (2014) 1-9.

Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kirchner I, Kornblueh L, Manzini E, Rhodin A, Schlese U, Schulzweida U, and Tompkins A 2003 The atmospheric general circulation model ECHAM 5. PART I: Model description.

Rudorff BFT, Adami M, Aguiar DA, Moreira MA, Mello MP, Fabiani L, Amaral DF, and Pires BM 2011 The Soy Moratorium in the Amazon Biome Monitored by Remote Sensing Images *Remote Sensing* **3** (12) 185–202, doi: 10.3390/rs3010185.

Schaldach R, Alcamo J, Koch J, Kölking C, Lapola DM, Schüngel J, and Priess, JA 2011)An integrated approach to modelling land-use change on continental and global scales *Environ. Modell. Softw.* **26** (8) 1041-1051.

Schmidt J 1991 A mathematical model to simulate rainfall erosion. In: Bork HR, de Ploey J, Schick AP (eds): Erosion, transport and deposition processes - theories and models *Catena Supplement* **19** 101–109.

Schönenberg R, Lakes T, and Schaldach R Inter- and transdisciplinary scenario construction to explore future land use options in Southern Amazonia *Ecol Soc.* (in review).

Schönenberg R, Hartberger K, Schumann C, Guggenberger G, Siebold M, Boy J, Lakes T, Lamparter G, Schindewolf M, Nendel C, Hohnwald S, Meurer KHE, Gerold G, Klingler M Methods of inter- and transdisciplinary research – a trajectory of knowledge integration *Reg. Environ. Change* (in review).

Schreinemachers P and Berger T 2011 An agent-based simulation model of human environment interactions in agricultural systems *Environ. Modell. Softw.* **26** 845-859.

Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA,Voll E, McDonald A, Lefebvre P, and Schlesinger P 2006 Modelling conservation in the Amazon basin *Nature* **440** 520–523.

Soares-Filho B, Moutinho P, Nepstad D, Anderson A, Rodrigues H, Garcia R, and Silvestrini R (2010) Role of Brazilian Amazon protected areas in climate change mitigation *P. Nat. Acad. Sci.* **107** (24) 10821-10826, doi: 10.1073/pnas.0913048107.

Specht JE, Hume DJ, and Kumudini SV 1999 Soybean yield potential - A genetic and physiological perspective *Crop Sci* **39** (6) 1560-1570, doi:10.2135/cropsci1999.3961560x.

Starkloff T and Stolte J 2014 Applied comparison of the erosion risk models EROSION 3D and LISEM for a small catchment in Norway *Catena* **118** 154–167, doi: 10.1016/j.catena.2014.02.004.

Stehfest E, Bouwman L, van Vuuren DP, den Elzen, MG, Eickhout B, and Kabat P 2009 Climate benefits of changing diet *Climatic Change* **95** (1-2) 83-102, doi: 10.1007/s10584-008-9534-6.

Turner BL, Lambin EF, and Reenberg A 2007 The emergence of land change science for global environmental change and sustainability *P. Nat. Acad. Sci.* **104** (52) 20666-20671.

Turner BL, Geoghegan J, Lawrence D, Radel C, Schmook B, Vance C, and Vester H 2016 Land system science and the social–environmental system: the case of Southern Yucatán Peninsular Region (SYPR) project *Curr. Opin. Env. Sust.* **19** 18-29.

van Ittersum M, Roetter R, Van Keulen H, De Ridder N, Hoanh C, Laborte A, Aggarwal P, Ismail A, and Tawang A 2004 A systems network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia *Land Use Policy* **21** 101-113.

van Wijk 2014 From global economic modelling to household level analyses of food security and sustainability: How big is the gap and can we bridge it? *Food Policy* **49** 378-388, doi: 10.1016/j.foodpol.2014.10.003.

Wenkel KO, Berg M, Mirschel W, Wieland R, Nendel C, and Köstner B 2013 LandCaRe DSS - An interactive decision support system for climate change impact assessment and the analysis of potential agricultural land use adaptation strategies *J. Environ. Manage.* **127** 168–183.

Wolf R. 2016 Process-based hydrological modeling of the Rio das Mortes catchment based on field and laboratory experiments M.Sc. thesis TU München 87 p.

6. Synopsis

The aim of the present study was to investigate the effect of changing land use on GHG emissions from Brazilian soils. Starting on the plot scale, as presented in *chapters 2* (data collection) and *3* (measurements and modeling), this thesis follows a bottom-up approach ending up at the regional scale by providing scenario-based estimates on emission development from agricultural soils (*chapter 4*) and suggestions for further political attempts in terms of carbon sequestration and GHG mitigation strategies (*chapter 5*). The latter study combines the results of specific research areas within the Carbiocial project, resulting in outcomes on changes in soil C stocks, GHG emissions from soil and as a consequence of biomass removal, and C loss from soil erosion. Following the objectives of the presented thesis, the concluding synopsis will just focus on the development of soil-derived GHG fluxes. Additional outcomes can be looked up in *chapter 5*.

In contrast to the assumption of high emissions from Brazilian soils, the results of the literature research (*chapter 2*) showed that N_2O emissions were generally low compared with fluxes reported from Europe (Jungkunst et al. 2004), Australia (Breuer et al. 2000), and North America (Roelandt et al. 2005). However, emission levels varied with the land use type in the order: Young Pastures > Amazon Rainforest > Old Pastures > Atlantic Rainforest > Cropland > Cerrado. According to short-term studies and experiments on agriculturally used lands, not even application of nitrogen fertilization did have a strong impact on emissions, since reactions were rather moderate or even neglectable. Only few studies allowed for comparison with the emission factor (EF) suggested by the IPCC (1 %), and thus an assessment of this approach to agricultural soils in Brazil is not possible. A rather undynamic behavior of N_2O fluxes was also found during the measurements on cattle pastures in Pará and emission peaks following precipitation events were not observed.

Soil texture and structure are generally highly relevant driving factors for N_2O emissions, and finer textures soils are likely to emit higher amounts of N_2O than sandy soils, due to their higher N availability (Matson et al. 1990). In this study, clay content turned out to be a poor predictor for N_2O emissions, which can be related to the formation of micro-aggregates and the change in the hydraulic behavior of the soil. According to Tomasella et al. (2000), the water content decreases very rapidly between saturation and -100 kPa in Brazilian soils, which gives them the hydraulic properties of coarse-textured soils. Following this, increasing clay content does not

necessarily lead to an increasing water holding capacity. On the contrary, the higher drainage capacity prevents the formation of anaerobic areas within the soil which makes N_2O fluxes very likely to result from nitrification rather than denitrification. This assumption is supported by the missing effect of the soil chemical properties pH and C_{org}. Although they are known to influence denitrification (Knowles 1982), they seem to be of secondary importance for N_2O emissions from Brazilian soils. Summarized: Neither soil nor management properties served as indicators for N_2O fluxes. Oddly enough, N_2O itself was found to point out the degradation stage of cattle pastures, the decreasing N availability, and nitrification and denitrification, respectively.
Another output of the literature research was the identification of concrete regions that have been ignored so far (e.g. the biomes Caatinga and Pantanal). At the same time, the study clearly shows that the time expenditure and measurement frequency found in the studies are not adequat, especially with respect to national budgeting. Obviously, both spatially expanded and highly temporal resolved measurements are usually restricted to automated measurements. Since the areas of interest are often rather remote and not easily accessible, manual measurements will be the only way to achieve an adequate spatial measurement distribution across a nation such as Brazil. At the same time, the high event-based emission peaks have to be captured and included into national estimates. As already suggested by Groffman et al. (2009), mathematical models can be used for the evaluation of external environmental changes. With regard to the strong development and improvement of mechanistic models in recent years, it can be assumed that their application might help in determining important time periods for detection of hot moments.

This approach turned out to be suitable for data collection in the study areas of the Carbiocial project (*chapter 3*). Three process-oriented models were run in a pre-measurement manner for a cattle pasture under grazing and by using historical climate data. The prediction of the models followed the current knowledge of biogeochemical processes in the soil, according to which seasonal patterns can lead to emission peaks (e.g. Brumme et al. 1999). Following the model predictions, measurements on three cattle pastures of different ages were performed in Southern Pará during the early wet season (December 2012 + January 2013 and November + December 2013, respectively). Although these time periods were characterized by days without rain, as well as subsequent intense and constant rains, predicted emission peaks were not observed in the field. Subsequent emission dynamics in the course of the rainy season were rather moderate. These first results follow the findings of the literature research and thus highlight the need for further investigation of underlying processes.

Nevertheless, the fluxes measured on the cattle pastures supported the assumption of a relationship between pasture age and N availability and hence N_2O levels, as higher fluxes were observed from the oldest and lower emissions from the youngest pasture. This relation could not be reproduced by the models: since the oldest pasture was used for model calibration, the retaining of adapted emission parameters for the CANDY and DDC model led to underestimations of observed fluxes from the younger validation pastures. The DNDC model was found to be unsuitable for Brazilian conditions, as its strong sensitivity to precipitation events led to overestimations of N_2O fluxes. Consequently, the model followed the current process understanding but was not able to reproduce field observations. However, the choice of the perennial grassland as vegetation led to a steady increase of soil nitrogen during the spin-up (5 years). Consequently, the annual N_2O emissions were higher each year.

For all models correct description of easy-to-measure underlying processes (here soil moisture and C_{org} content) led to a better adaptation to observed N_2O fluxes. This shows that the linkages between the different soil compartments are satisfyingly respected and implemented in the models. Nevertheless, the CANDY and DNDC model struggled when it came to heavy precipitation events and simulated soil moisture strongly overestimated observations. While increasing the hydraulic conductivity led to considerable improvements in the DNDC model, measurements from a depth of 0 – 10 cm turned out to be inappropriate for calibrating the CANDY model. The consideration of puddle water and inclusion into the first soil horizon led to simulated soil moistures that exceeded the soil pore space. As this shallow depth is known to be decisive for N_2O production, a further refinement of the first soil layer might improve the adaptation.

All-season fluxes simulated with the calibrated models indicated that the time periods chosen for the field campaigns were within the most dynamic and thus adequately chosen. However, the CANDY model suggested the first precipitation events at the end of the dry season as most active for N_2O peaks and rather moderate dynamics during the subsequent rainy season. This might be another explanation for the missing emission peaks, and if this is the case, future measurement campaigns have to capture the immediate beginning of the rainy season - this needs further investigation. Nevertheless, mechanistic models – and ideally a combination of models – proved to be immensely helpful for planning field campaigns in remote areas as presented in this study. However, since observed emissions seemed to be unaffected by external short-term events, process-oriented modeling in daily time steps – as it has been made in this study – seems too sophisticated in relation to the value. In particular with regard to regionalization, simpler approaches, such as extrapolation of emission values, likely cause less uncertainties compared with comparatively elaborate modeling.

Such an extrapolation approach was performed within two studies, which aimed to asses the impact of scenario-based land use changes on GHG emissions in the two Federal States Mato Grosso and Pará (*chapters 4* and *5*). Four new land use maps for the year 2030 were created using the land use model LandSHIFT based on the alternative future scenarios established by Schönenberg et al. (submitted) (*Trend*, *Legal Intensification*, *Illegal Intensification*, and *Sustainable Development*). Aiming to investigate strategies towards a more sustainable use of land resources in Southern Amazonia, three mechanisms were identified: land protection policies, agricultural intensification, and changing human consumption patterns. Especially the first two aspects were found to play an important role for CO_2 and non-CO_2 (N_2O and CH_4) emission development, since in this case main drivers between the scenarios were the conversion of rainforest areas and the establishment of new pastures. While forest soils are sources for CO_2 and N_2O, they act as a sink for atmospheric CH_4. In contrast to this, pasture soils are sources for both gases and although nothing is known about a relationship between pasture age and CH_4 emissions, especially young pastures emit large amounts of CO_2 and N_2O. Largest reduction of forest and cerrado vegetation and subsequent expansion of pasture area was simulated for the *Trend* scenario in both states. This is still the typical procedure in this region of Brazil, since deforested areas are mainly used as cattle pastures first and after several years converted into cropland (e.g. Coy & Klingler 2011).

Although the GHG emissions mentioned above relate to the already existing land use in 2030 and do not include emissions from the conversion process itself, the comparison of the scenarios allows conclusions about the development following the specific alternative futures. Considering solely the non-CO_2 fluxes shows that the “business-as-usual” (*Trend*) scenario and the shift towards a vegetarian diet (*Sustainable Development*) are not the ideal futures in terms of GHG mitigation; mainly because of the ongoing deforestation and pasture expansion. The combination of New Forest code and pasture intensification is only considered in the *Legal Intensification* scenario. Intensive usage of established pastures is also integrated in the *Illegal Intensification* scenario and here the reductions of both CO_2 and non-CO_2 emissions are highest because of the pasture expansion to protected (and high biomass producing) areas, such as the Pantanal.

These results follow the general findings of Galford et al. (2010), who highlight that avoided deforestation is the best strategy for minimizing future GHG emissions. Although Galford et al. (2010) just focussed on Mato Grosso, this suggestion applies even more for Pará, which still contains large areas of untouched rainforest.

Generally, the results of the presented studies clearly indicate that, despite the loss of natural ecosystems, the way how agriculture will develop in Southern Amazonia strongly affects the amount of land-use specific GHG. Intensification of agriculturally used land is crucial in reducing the conversion of areas under natural vegetation and might become a key driver for GHG mitigation strategies. Thus, these results must make entry into political attempts and strategies.

References

Breuer L, Papen H, and Butterbach-Bahl K 2000. N_2O emission from tropical forest soils of Australia *J. Geophys. Res.* **105** (D21) 26,353 – 26,367.

Brumme R, Borken W, and Finke S 1999 Hierachical control on nitrous oxide emission in forest ecosystems *Global Biogeochem. Cy.* **13** (4) 1137 – 1148.

Coy M and Klingler M 2011 Pionierfronten im brasilianischen Amazonien zwischen alten Problemen und neuen Dynamiken. Das Beispiel des „Entwicklungskorridors" Cuiabá (Mato Grosso) – Santarém (Pará). In: *Innsbrucker Jahresbericht 2008 – 2010* [Coy, M. and J. Stötter (eds.)]. Innbrucker Geographische Gesellschaft, pp 288.

Galford G L, Melillo J M, Kicklighter DW, Cronin TW, Cerri CEP, Mustard JF, and Cerri CC 2010 Greenhouse gas emissions from alternative futures of deforestation and agricultureal management in the southern Amazon *P. Natl. Acad. Sci. USA* 107 (46) 19649 – 19654, doi: 10.1073/pnas.1000780107.

Groffman PM, Butterbach-Bahl K, Fulweiler RW, Gold AJ, Morse JL, Stander EK, Tague C, Tonitto C, and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* 93 49 – 77.

Jungkunst HF, Fiedler S, and Stahr K 2004 N_2O emissions of a mature Norway spruce (Picea abies) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern *Geophys. Res.* **109** DO7302.

Knowles R 1982 Denitrification *Microbiol. Rev.* **46** 43 – 70.

Matson PA, Vitousek PM, Livingston GP, and Swanberg NA 1990 Sources of variation in nitrous oxide flux from Amazonian ecosystems *J. Geophys. Res.* **95** 6789 – 6798.

Roelandt C, van Wesemael B, and Rounsevell M 2005 Estimating annual N_2O emissions from agricultural soils in temperate climates *Global Change Biol.* **11** 1701 – 1711.

Tomasella J, Hodnett MG, and Rossato L 2000 Pedotransfer Functions for the Estimation of Soil Water Retention in Brazilian Soils *Soil Sci. Soc. Am. J.* **64** 327 – 338.

7. Outlook

This study offers a comprehensive overview on the influences of land conversion on soil-derived GHG emissions – mainly nitrous oxide (N_2O), but also CO_2 and CH_4 – in Southern Amazonia. It has been shown that the underlying processes of low N_2O emissions from Brazilian soils are not yet fully understood and have to be further investigated, inter alia, with more frequent and long-term measurements. In addition to that, nothing is known about the emission behavior of any GHG during the conversion process of natural vegetation. Since it can be expected that large amounts of GHG are released during these processes, research during these phases is needed in order to close this knowledge gap.

Implementation of the thereby gained knowledge into process-oriented models will result in a better adaptation to Amazonian conditions and will enable more precise calculations of expected emissions from land conversion, e.g. direct forest-to-cropland conversion. In the frame of ongoing deforestation, this might be a fundamental step towards sound national budgets on the one hand and further mitigation strategies and political attempts on the other hand.

Appendices

Appendix A

Chapter 2: Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – a critical review

Table A.1: Geographical location, climatic condition, soil type and properties of studies with N_2O-N flux measurements in Brazil.

Site No.	Reference	Geographical location [°]		MAT [°C]	MAP [mm]	Soil type WRB	Clay content [%]	C_{org} [g kg^{-1}]
		south	west					
1	Vasconcelos *et al* (2004)	1.31	47.95	25.5	2539	Ferralsol	20	2.20
2	Verchot *et al* (1999)	2.98	47.51		1850	Ferralsol		2.47 – 3.02
3	Verchot *et al* (2008)	1.11	47.78	26	2500	Leptosol		
4	Keller *et al* (2005)	3.03	54.95	25	2000	Ferralsol Acrisol	80 38	2.50
5	Davidson *et al* (2004)	2.88	54.95		2000	Ferralsol	60 - 80	
6	Silver *et al* (2005)	2.64	54.59	25	2000	Ferralsol Acrisol	60 18	
7	Varner *et al* (2003)	2.64	54.59	25	2000	Ferralsol Acrisol	80 38	
8	Livingston *et al* (1988)	3.0	60.0	26	1770	Ferralsol Acrisol		
9	Luizão *et al* (1989)	3.0	60.0		2200	Ferralsol		
10	Melillo *et al* (2001)	10.16	62.81	25.6	2200	Acrisol	19 - 29	
11	Steudler *et al* (2002)	10.16	62.81	25.5	2200	Nitisol	23 - 29	
12	Garcia-Montiel *et al* (2001)	10.5	62.5	18.8 - 25.6	2270	Acrisol	< 30	
13	Garcia-Montiel *et al* (2003)	10.5	62.5	18.8 - 25.6	2270	Acrisol	20 - 30	
14	Neill *et al* (2005)	10.5	62.5	25.6	2200	Acrisol	13 - 76	
15	Carmo *et al* (2005)	10.5	62.5		2270	Ferralsol		
16	Passianoto *et al* (2003)	10.5	62.5	25.5	2200	Acrisol		
17	Carvalho *et al* (2009)	12.48	60.0	23.1	2170	Ferralsol	73	1.71 – 2.77
18	Neto *et al* (2011)	17.78	51.91	23.3	1550	Ferralsol	54 - 68	1.85 – 2.90
19	Carvalho *et al* (2014)	17.36	51.48	23	1500 - 1800	Ferralsol	56 - 60	2.09 – 2.89
20	Metay *et al* (2007)	16.48	49.28	22.5	1500	Ferralsol	40	
21	Lessa *et al* (2014)	16.48	49.28			Ferralsol	43	
22	Santos *et al* (2008)	16.48	49.28	22.5	1460	Ferralsol		
23	Varella *et al* (2004)	15.65	47.75		1500	Ferralsol	57 - 74	2.41 4.74
24	Cruvinel *et al* (2011)	16.3 16.25	47.5 47.61			Ferralsol Ferralsol	49 – 72 68 - 76	
25a	Carmo *et al* (2013)	22.25	48.56	21	1390	Lixisol	11	
25b		22.68	48.55			Ferralsol	29	
26	Barneze *et al* (2014)	22.7	47.61			Nitisol		3.03

continued

27	Neto *et al* (2011)	23.56 23.4	45.08 45.18		3050 2300		35 21	4.59 – 9.15
28	Carmo *et al* (2012)	23.31 23.4	45.08 45.25	19.1 - 25.5	2500	Acrisol	23	
29	Coutinho *et al* (2010)	22.73	44.95	20	1500	Ferralsol	30 - 36	
30	Morais *et al* (2013)	22.76	43.68	24	1300	Acrisol	45	
31	Maddock *et al* (2001)	22.75 a)	43.08 a)	21	1500 - 2250	Ferralsol	27 - 29	2.01 2.03
32	Piva *et al* (2012)	24.78	49.95		1400	Ferralsol	44	2.87 3.05
33	Piva *et al* (2014)	24.78	49.95		1400	Ferralsol	44	2.87 2.93
34	Sordi *et al* (2014)	25.38	49.11		1400	Cambisol	44	2.50
35	Jantalia *et al* (2008)	28.25	52.4		1430	Ferralsol	63	
36	Giacomini *et al* (2006)	29.75	53.7			Luvisol		
37	Gomes *et al* (2009)	30.1	51.7	19.4	1440	Acrisol	22	

MAT: Mean annual temperature.
MAP: mean annual precipitation.
a) coordinates from MMA/IBAMA (2006)

Appendix B

Chapter 3: Model-guided measurements of nitrous oxide (N_2O) fluxes from Amazonian cattle pastures

Table B.1: Input data for the pre-simulations with CANDY, DNDC, and DDC.

Climate (daily data)	
Weather station	Alta Floresta
Latitude/Longitude	-9.87°N / -56.10°E
Time frame	2007 - 2011
Parameters	temperature mean: CANDY minimum and maximum: DNDC, DDC precipitation (all) global radiation (CANDY)
Average annual mean temperature [°C]	26.95
Average annual minimum temperature [°C]	20.70
Average annual maximum temperature [°C]	32.20
Average annual precipitation sum [mm]	2,182
Soil (average values over the depth 0 – 100 cm)	
Soil texture	loam
Clay content [%]	16
Bulk density [g cm^{-3}]	1.05
Initial C_{org} [kg C kg^{-1}]	0.0181
Porosity	44 [a)]
Field capacity [Vol %]	16 [a)]
Wilting point [Vol %]	7 [a)]
Hydraulic conductivity [cm min^{-1}]	0.17 [a)]
Management	
Vegetation type	dry pasture/grassland
Harvest	year-round grazing

[a)] taken over from the database provided by DNDC for the specific soil texture

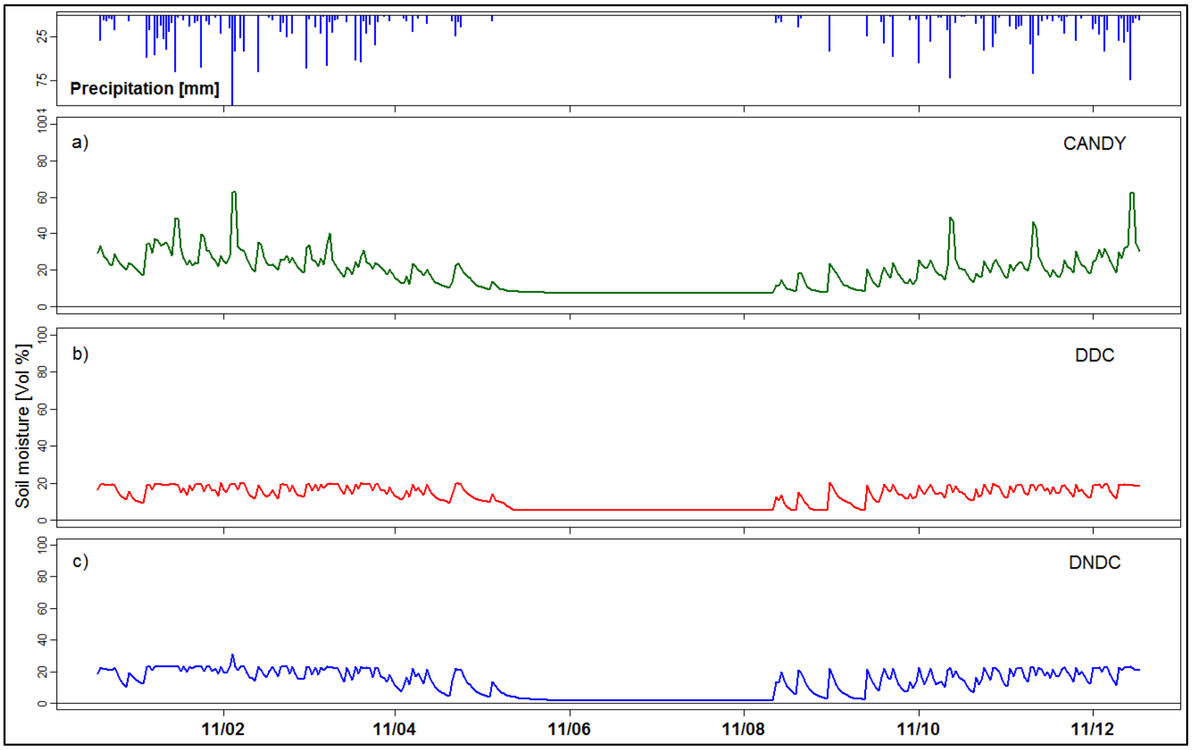

Figure B.1: Simulated soil moisture from the pre-simulations with CANDY (a), DDC (b), and DNDC (c) for the year 2011 under Amazonian conditions (see Table B.1).

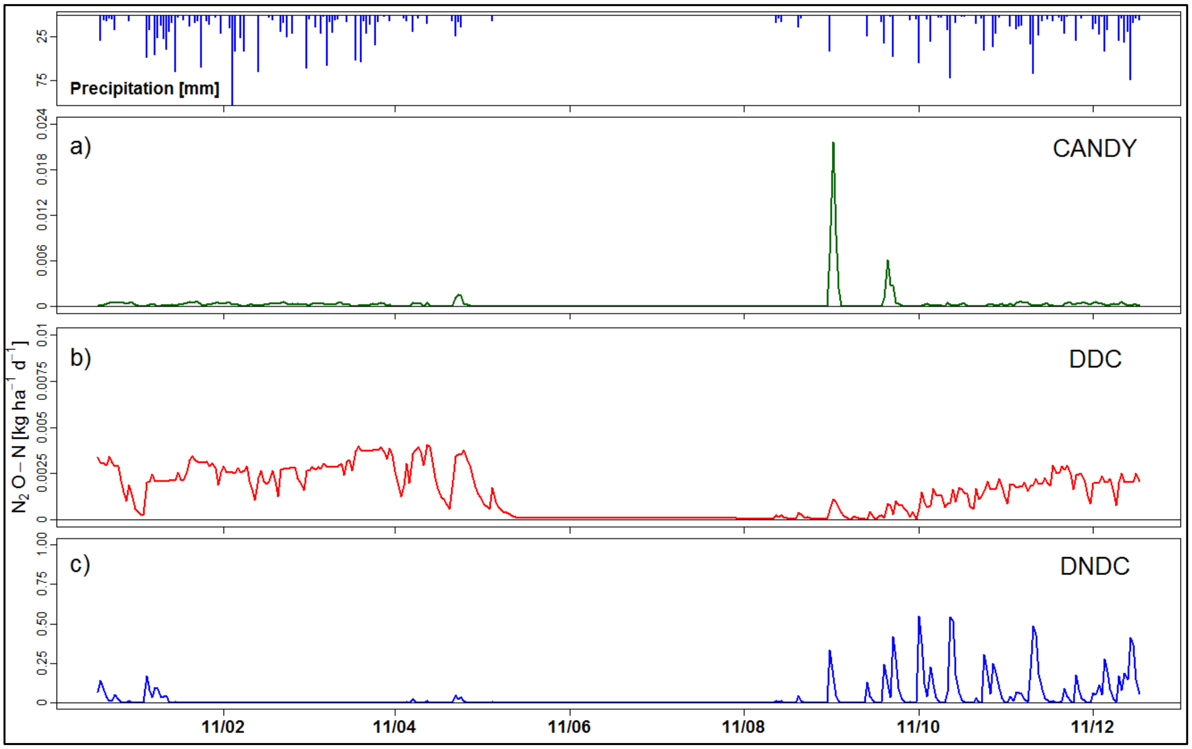

Figure B.2: Simulated N_2O-N fluxes from the pre-simulations with CANDY (a), DDC (b), and DNDC (c) for the year 2011 under Amazonian conditions (see Table B.1).

Table B.2: Optimized parameters for model adaptation to observed soil water contents, carbon contents, and N_2O-N fluxes.

Parameter and site	CANDY	DNDC	DDC
Soil water content			
Field capacity [Vol %]	0 – 10 cm		
old	36	44	39
medium	40	43	39
young	34	37	32
Permanent wilting point [Vol %]	0 – 10 cm		
old	20	16	12
medium	16	26	10
young	20	17	16
Hydraulic conductivity [m hr^{-1}]	0 – 10 cm		
old	4.5 x 10^{-2}	7.7 x 10^{-3}	4.7 x 10^{-2}
medium	6.0 x 10^{-2}	2.6 x 10^{-1}	1.7 x 10^{-2}
young	4.8 x 10^{-2}	8.9 x 10^{-1}	2.1 x 10^{-2}
Carbon content			
Initial carbon content	M% (0 – 10 / 10 – 30 cm)	kg C kg^{-1} (0 – 5 cm) a)	
old	5.80 / 0.74	0.0220	
medium	3.95 / 1.66	0.0240	
young	1.82 / 1.17	0.0185	
Carbon decrease rate			
old		4.0	
medium		1.5	
young		2.5	
Decomposition rates			DEC5(1) / (2)
old			0.130 / 0.104
medium			0.185 / 0.148
young			0.248 / 0.198
Maximum C:N ratio of material entering SOM pools			VARAT11 / 12 10 / 9
old b)			VARAT21 / 22 10 / 20 VARAT3 10
Cultivation factor for decomposition			CLTEFF(1 - 3)
old b)			2
N_2O-N fluxes			
Factor controlling denitrification rate			
old b)	1.75 x 10^{-5}		
Fraction of nitrified N lost as N_2O			
old b)			0.2

a) assuming a depth of 10 cm with uniform SOC content
b) values were kept during validation

Appendix C

Chapter 4: Future scenarios of land use and land cover change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils

C.1. Model input and scenario assumptions

Table C.1: Datasets used for land use modeling.

Spatial scale	Input variable	Temporal coverage	Purpose	Comment	Source
Federal state	crop production	2000-2010 dynamic	base map	production of major crops per federal state	IBGE 2013
	livestock numbers	2000-2010 dynamic		number of livestock (cattle, goat, sheep) per federal state	IBGE 2013
	crop area	2000		crop area of major crops per federal state	IBGE 2013
	Population	2000-2010 dynamic		total population number per federal state	IBGE 2013
Grid, 30 arc-minutes cell	crop yields/ grassland NPP	2000-2030 dynamic	biomass productivity; preference ranking	yield distribution of major crops	Bondeau et al. 2007
Grid, 30 arc-minutes cell	livestock density	2000	initial state	livestock distribution	Wint & Robinson 2007
Grid, 900 x 900m cell	land cover	2001	initial state	map of agricultural area and natural land cover types	Friedl et al. 2002
	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
	road infrastructure	2000	preference ranking	Banco de Nomes Geográficos do Brasil	IBGE 2012
	travel distance	2000	preference ranking	distance to markets (major cities)	ESRI 2009
	conservation areas	2000	land use constraint	military, ecological and indigenous protected areas	military: ZEE 2009; ecological and indigenous: MMA

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[a] Zoneamento Ecológico-Econômico da Rodovia BR-163

[b] Ministério do Meio Ambiente

C.2. CH_4 and N_2O emission values

Table C.2: Land-use specific emission values of N_2O [kg N ha^{-1}] and CH_4 [kg C ha^{-1}].

Land use type	N_2O fluxes [kg ha^{-1} yr^{-1}]^a			CH_4 fluxes [kg ha^{-1} yr^{-1}]		
	Min	Median	Max	Min	Median	Max
Rainforest	0.38	2.29	16.20	-6.57	-1.31^{b-g}	-0.41
Cerrado	-0.09	0.14	1.19	-4.35	$-3.15^{g, k, l}$	-1.3
Pasture				-2.19	$1.2^{c-e, k, l}$	2.89
old	-0.27	0.9	3.62			
young	1.32	2.25	10.16			
Cropland	-0.07	0.8	4.26	-4.18	-1.24^{h-l}	1.65

a) Meurer et al. (2016), b) Vasconcelos et al. (2004), c) Steudler et al. (1996), d) Carmo et al. (2012), e) Fernandes et al. (2001), f) Silver et al. (2005), g) Verchot et al. (1999), h) Verchot et al. (2008), i) Metay et al. (2007), j) Piva et al. (2014), k) Carvalho et al. (2014), l) Neto et al. (2011)

C.3. 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 the research transect (Figure C.3).

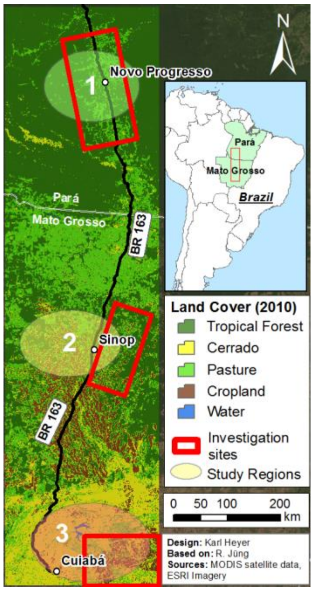

Figure C.3: Map of research area along the BR-163 with the three study regions: 1 - Novo Progresso; 2 - Sinop; 3 - Cuiaba.

The plots included three different land use types: native vegetation, pastures and crop-fields. To include the most common soil types (Quesada 2011) of the Amazon region 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 cm3 samples for 48 h by 105°C.

Land use change is mostly 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 land use change were adjusted to the corresponding soil mass on the reference plots under native vegetation (Ellert & Bettany 1995, Poeplau & Don 2013):

$$SOCSTOCK_{corr} = SOCSTOCK_i \left(\frac{SM_i + SM_{nativet}}{CV_i} \times C_{deepest} \right) \tag{C.1}$$

where $SOCSTOCK_{corr}$ is the corrected SOC stock in Mg SOC 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.

Table C.3: 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^{a}).

		SOC stocks ± SE [Mg ha^{-1}]			**SOC stock changes ± SE [Mg ha^{-1}]**		
Ferralsol	**n**	**0-30 cm**	**30-100 cm**	**0-100 cm**	**0-30 cm**	**30-100 cm**	**0-100 cm**
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	-	-	-
Pasture							
old	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	18	52.88 ± 3.68	59.92 ± 1.38	114.69 ± 4.76	-3.61 ± 3.68	-9.39 ± 1.38	-14.88 ± 4.82
Cropland							
old	32	58.39 ± 1.26	70.23 ± 1.18	131.79 ± 2.12	3.00 ± 0.81	7.65 ± 0.92	12.70 ± 1.37
young	36	47.28 ± 1.79	57.85 ± 1.91	108.21 ± 3.46	-6.42 ± 1.77	-8.30 ± 1.80	-13.28 ± 3.36
Acrisol							
Rainforest	27	34.85 ± 1.84	41.08 ± 2.37	77.68 ± 3.42	- -	- -	- -
Pasture							
old	27	39.17 ± 1.14	41.27 ± 1.62	83.38 ± 1.70	5.13 ± 1.14	0.23 ± 1.48	5.41 ± 1.62
young	9	39.64 ± 2.65	52.59 ± 1.19	93.41 ± 3.34	6.10 ± 2.65	9.46 ± 1.19	14.95 ± 3.36
Cropland							
young	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

[a] due to mass correction, the sum of topsoil SOC and subsoil SOC might not be similar to 0 – 100 cm
n = amount of individual sampling points
SE = standard error
young: ≤ 10 years
old: > 10 years

Table C.4: Translation of storyline statements into numerical LULCC drivers (*Trend* scenario).

Storyline assumption	Scenario interpretation	Quantification
Population		
population growth continues according to agricultural pioneer frontier dynamics	population growth according to past observations	trend projections (method of the least squares) until 2030
Agricultural development		
agricultural production is expanding and intensifying	agricultural production growth according to past observations	trend projections (method of the least squares) until 2030
livestock numbers continue to rise	livestock number growth according to past observations	trend projections (method of the least squares) until 2030
Land use policy		
conversion of natural ecosystems is taking place	no further constraint regarding conversion of natural ecosystems	forest and Cerrado (savannah) vegetation cover is less likely to be converted into pastures or cropland due to conversion costs
infrastructural development continues in regard to BR-163	BR-163 is going to be paved from Cuiabá to Santarem	BR-163 is integrated into database road-map layer
law enforcement in place but rather inefficient due to resource deficiency reduction of protected areas size	Mato Grosso/Pará: No further land use change in protected areas (strictly protected, sustainable use, military, indigenous).	Mato Grosso/Pará: Land use type of cells within protected areas is not changed.

Table C.5: Translation of storyline statements into numerical LULCC drivers (*Legal Intensification* scenario).

Storyline assumption	Scenario interpretation	Quantification
Population		
population dynamics and growth continue according to agricultural pioneer frontier dynamics	population growth according to past observations	trend projections until 2030
Agricultural development		
agricultural production is expanding and intensifying further accelerated due to demand from Asian countries	agricultural production growth according to past observations increased by additional demand (Asia)	trend projections until 2030 + additional growth according to population growth in Asian countries
livestock numbers continue to rise further accelerated due to demand from Asian countries	livestock number growth according to past observations increased by additional demand (Asia)	trend projection until 2030 + additional growth according to population growth in Asian countries
tendency toward intensification of cattle ranching	intensification of pasture management	Mato Grosso: livestock unit production on each grid cell is increased by 9% every time step until a maximum production increase of 50% is realized; livestock unit production on each grid cell is increased by 4.5% every time step until a maximum production increase of 30% is realized

continued

Land use policy		
conversion of natural ecosystems is taking place	conversion of natural ecosystems is taking place	conversion of natural ecosystems is taking place
infrastructural development continues in regard to BR-163	infrastructural development continues in regard to BR-163	infrastructural development continues in regard to BR-163
protected areas continue to play an important role in conservation of natural ecosystems;	protected areas continue to play an important role in conservation of natural ecosystems;	protected areas continue to play an important role in conservation of natural ecosystems;
law enforcement in place but rather inefficient due to resource deficiency	law enforcement in place but rather inefficient due to resource deficiency	law enforcement in place but rather inefficient due to resource deficiency
conversion coinciding with New Forest Code (according to Soares-Filho et al. 2014)	conversion coinciding with New Forest Code (according to Soares-Filho et al. 2014)	conversion coinciding with New Forest Code (according to Soares-Filho et al. 2014)

Table C.6: Translation of storyline statements into numerical LULCC drivers (*Illegal Intensification* scenario).

Storyline assumption	Scenario interpretation	Quantification
Population		
population dynamics and growth continue according to agricultural pioneer frontier dynamics	population growth according to past observations	trend projections until 2030
Agricultural development		
agricultural production is expanding and intensifying further accelerated due to demand from Asian countries	agricultural production growth according to past observations increased by additional demand (Asia)	trend projections until 2030 + additional growth according to population growth in Asian countries
livestock numbers continue to rise further accelerated due to demand from Asian countries	livestock number growth according to past observations increased by additional demand (Asia)	trend projections until 2030 + additional growth according to population growth in Asian countries
tendency toward intensification of cattle ranching	intensification of pastures taking place	Mato Grosso: livestock unit production on each grid cell is increased by 9% every time step until a maximum production increase of 50% is realized; livestock unit production on each grid cell is increased by 4.5% every time step until a maximum production increase of 30% is realized
Land use policy		
conversion of natural ecosystems is taking place	no constraint regarding conversion of natural ecosystems	forest and Cerrado (savannah) vegetation cover is less likely to be converted into pastures or cropland due to conversion costs
infrastructural development continues in regard to BR-163	BR-163 is going to be paved from Cuiabá to Santarem	BR-163 is integrated into database road-map layer
Road connection between Br-163 and Terra Do Meio	BR-163 corridor: road construction between Novo Progresso and Felix do Xingu	BR-163 corridor: integration of a new road layer describing subsequent construction states
protected areas are used for illegal agricultural expansion; only sporadic law enforcement	indigenous and military areas are considered as protected; strictly protected, sustainable use and riparian protected areas are not protected	no land use within military and , indigenous areas; land use change allowed in ecological strictly protected, sustainable use and riparian protected areas

Table C.7: Translation of storyline statements into numerical LULCC drivers (*Sustainable Development* scenario).

storyline assumption	scenario interpretation	Quantification
Population		
population growth stabilizing; less migration of land-less from other Brazilian regions	population growth rate decreasing (Mato Grosso: -10%; Pará: -5%)	trend projections until 2030 – growth rate correction (Mato Grosso: -10%; Pará: -5%) per time-step
Agricultural development		
agricultural production specializing on fresh products (niche market); the better the development of trade structures, the stronger smallholder and medium business production	agricultural production focusing on production of vegetarian products; focus on crops for domestic use; focus away from cash crops	trend projections until 2030 + production growth (beans, fruits, vegetables, soy); production correction of soybean (exported fraction) due to less export demand
agricultural production specializing on fresh products (niche market); worldwide trend toward vegetarian diet	livestock numbers decrease considerably; meat consumption substituted by vegetarian products	trend projections until 2030 minus 70% of total livestock numbers due to healthy and sustainable diet
high intensification regarding agricultural practices	crop yield data is further increased	crop yield growth adapted by an additional +30% of crop biomass over 30 years
Land use policy		
conversion of natural ecosystems avoided when possible	constraint regarding conversion of forest land cover; no further constraint regarding all other natural land cover	forest and Cerrado (savannah) vegetation cover is even less likely to be converted into pastures or cropland due to conversion costs and a restraining land use policy
infrastructural development continues in regard to BR-163	BR-163 is going to be paved from Cuiabá to Santarem	BR-163 is integrated into database road-map layer
protected areas continue to play an important role in conservation of natural ecosystems	protected areas (ecological, military, indigenous) are considered as protected	no land use within protected areas (exception: land use according to base-map (2000))
effective law enforcement; Soy-Moratorium continues after 2016; Cattle-Moratorium continues after 2019	Mato Grosso/Pará: no illegal transformation of natural land cover; transition of areas defined as forest not possible; conversion of Cerrado less likely	Mato Grosso/Pará: forest and Cerrado (savannah) vegetation cover is even less likely to be converted into pastures or cropland due to conversion costs and restraining land use policy

Table C.8: Overview on scenario assumptions relevant to spatial modeling.

	Variables	Trend	Legal Intensification	Illegal Intensification	Sustainable Development
Area-specific policies	New Forest Code	not considered	80 % of every forest grid cell converted into cropland/pasture retains its original natural land use type	see *Trend* scenario	see *Trend* scenario
	Nature Reserve Protection	protected[a]	see *Trend* scenario	unprotected [b] (insufficient enforcement)	see *Trend* scenario
	Military Areas	[a]	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario
	Indigenous Reserves	protected[a]	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario
Area conversions	Forest	trans: 50 % due to cost of conversion	see *Trend* scenario	see *Trend* scenario	transition probability 0%
	Shrubland/ Savannah (Cerrado)	trans: 70 % due to cost of conversion	see *Trend* scenario	see *Trend* scenario	transition probability 30%
	Grassland	trans: 100%	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario
	Fallow Land	if available: used first for conversion	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario
	Barren Land	trans: 10 % due to cost of conversion and low expected agricultural production	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario
Intensification	Pasture	not considered	Pará: 4.5 % per timestep; maximum intensity: 30 % Mato Grosso: 9 % per timestep; maximum intensity 50 %	Pará: 4.5 % per timestep; maximum intensity: 30 % Mato Grosso: 9 % per timestep; maximum intensity: 50 %	see *Trend* scenario
Infra-structure	Road Infrastructure	BR-163 considered paved from Cuiabá to Santarém	see *Trend* scenario	see *Trend* scenario	see *Trend* scenario

[a] not available for conversion
[b] available for conversion
trans. = transition probability

Table C.9: 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
pasture, rangeland	pasture

C.4 Simulated LULCC and greenhouse gas emissions

Table C.10: LULCC as comparison between land use in 2010 and 2030 regarding each scenario.

Scenario	Land use type	Pará			Mato Grosso		
		2010 [km^2]	2030 [km^2]	Change [%]	2010 [km^2]	2030 [km^2]	Change [%]
Trend	**Urban land**	599	640	+ 6.9	906	909	+ 0.3
	Cropland	147,960	172,190	+ 16.4	221,389	203,055	-8.3
	Pasture	102,675	204,946	+ 99.6	168,198	252,786	+ 50.3
	Rainforest	982,240	868,869	-11.5	360,012	329,876	-8.4
	Cerrado	24,648	11,770	-52.2	171,047	136,683	-20.1
	Grassland	341	302	-11.4	19,148	17,014	-11.2
Legal Intensification	**Urban land**	599	636	+ 6.2	906	906	0
	Cropland	147,960	222,677	+ 50.2	221,389	240,987	+ 8.9
	Pasture	102,675	100,437	-2.2	168,198	157,536	-6.3
	Rainforest	982,240	924,900	-5.8	360,012	360,016	0
	Cerrado	24,648	9,927	-59.7	171,047	163,879	-4.2
	Grassland	341	302	-11.4	19,148	17,398	-9.1
Illegal Intensification	**Urban land**	599	640	+ 6.9	906	909	+ 0.3
	Cropland	147,960	187,141	+ 26.5	221,389	249,328	+ 12.6
	Pasture	102,675	179,108	+ 74.4	168,198	150,616	-10.5
	Rainforest	982,240	882,862	-10.1	360,012	359,268	-0.2
	Cerrado	24,648	9,327	-62.2	171,047	159,401	-6.8
	Grassland	341	101	-70.4	19,148	21,038	-9.9
Sustainable Development	**Urban land**	599	631	+ 5.3	906	907	+ 0.1
	Cropland	147,960	227,636	+ 53.9	221,389	226,481	+ 2.3
	Pasture	102,675	13,636	-86.7	168,198	165,744	-1.5
	Rainforest	982,240	995,891	+1.4	360,012	360,017	0
	Cerrado	24,648	20,937	-15.1	171,047	134,316	-21.5
	Grassland	341	300	-12.0	19,148	13,387	-30.1

Table C.11: N_2O and CH_4 fluxes [Mt a^{-1}] from agricultural soils regarding each scenario.

Scenario	Land use type	Pará				Mato Grosso			
		2010		2030		2010		2030	
		N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4
Trend	**Pasture**	0.0092	0.0123	0.0249	0.0246	0.0151	0.0202	0.0298	0.0303
	old			0.0149				0.0188	
	young			0.0100				0.0110	
	Cropland	0.0108	-0.0167	0.0138	-0.0214	0.0177	-0.0275	0.0162	-0.0252
	Total	0.0200	-0.0044	0.0386	0.0032	0.0329	-0.0073	0.048	0.0052
Legal Intensification	**Pasture**	0.0092	0.0123	0.009	0.0121	0.0151	0.0202	0.0144	0.0189
	old			0.009				0.0141	
	young			0				0.0003	
	Cropland	0.0108	-0.0167	0.0178	-0.0276	0.0177	-0.0275	0.0193	-0.0299
	Total	0.0200	-0.0044	0.0269	-0.0156	0.0329	-0.0073	0.0337	-0.011
Illegal Intensification	**Pasture**	0.0092	0.0123	0.0187	0.0215	0.0151	0.0202	0.0137	0.0181
	old			0.0147				0.0135	
	young			0.0040				0.0002	
	Cropland	0.0108	-0.0167	0.015	-0.0232	0.0177	-0.0275	0.02	-0.0309
	Total	0.0200	-0.0044	0.0336	-0.0017	0.0329	-0.0073	0.0336	-0.0129
Sustainable Development	**Pasture**	0.0092	0.0123	0.0012	0.0016	0.0151	0.0202	0.0149	0.0199
	old			0.0012				0.0149	
	young			0				0	
	Cropland	0.0108	-0.0167	0.0182	-0.0282	0.0177	-0.0275	0.0213	-0.033
	Total	0.0200	-0.0044	0.0194	-0.0266	0.0329	-0.0073	0.0362	-0.0132

Table C.12: CO_2 fluxes [Mt] from Acrisol and Ferralsol regarding each scenario. Total$_{A+F}$ = CO_2 fluxes from Acrisol and Ferralsol.

Scenario	**Land use type**	**Pará**				**Mato Grosso**			
		2010		**2030**		**2010**		**2030**	
		Ferralsol	**Acrisol**	**Ferralsol**	**Acrisol**	**Ferralsol**	**Acrisol**	**Ferralsol**	**Acrisol**
Trend	**Pasture**								
	old	0	20.64	0	28.73	0	16.74	0	26.37
	young	0	12.31	0	18.98	0	16.79	0	15.23
	Cropland								
	old	63.59	28.21	96.37	72.53	77.84	30.66	131.11	55.23
	young	-37.97	-16.41	-0.40	-0.30	-74.87	-28.74	-2.49	-1.02
	Total	25.62	44.75	95.97	119.94	2.97	35.45	128.62	95.81
	Total$_{A+F}$	70.37		215.91		38.42		224.43	
Legal Intensification	**Pasture**								
	old	0	20.64	0	23.8	0	16.74	0	21.48
	young	0	12.31	0	0	0	16.79	0	0.49
	Cropland								
	old	63.59	28.21	112.34	108.27	77.84	30.66	162.54	62.13
	young	-37-97	-16.41	-0.12	-0.12	-74.87	-28.74	-3.35	-1.25
	Total	25.62	44.75	112.22	131.95	2.97	35.45	159.19	82.85
	Total$_{A+F}$	70.37		244.17		38.42		242.04	
Illegal Intensification	**Pasture**								
	old	0	20.64	0	38.88	0	16.74	0	20.98
	young	0	12.31	0	10.31	0	16.79	0	0.30
	Cropland								
	old	63.59	28.21	82.32	97.22	77.84	30.66	153.7	69.09
	young	-37.97	-16.41	-0.58	-0.67	-74.87	-28.74	-3.01	-1.32
	Total	25.62	44.75	81.74	145.74	2.97	35.45	150.69	89.05
	Total$_{A+F}$	70.37		227.48		38.42		239.74	
Sustainable Development	**Pasture**								
	old	0	20.64	0	0.6	0	16.74	0	22.55
	young	0	12.31	0	0	0	16.79	0	0
	Cropland								
	old	63.59	28.21	121.55	103.34	77.84	30.66	164.32	62.91
	young	-37.97	-16.41	-15.86	-13.13	-74.87	-28.74	-18.02	-6.90
	Total	25.62	44.75	105.69	90.81	2.97	35.45	146.3	78.56
	Total$_{A+F}$	70.37		196.5		38.42		224.86	

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation, entitled "Measurements and modeling of land-use specific greenhouse gas emissions from soils in Southern Amazonia", are my own work and effort and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. Outcomes of work done in collaboration with others have been specified in the text and the Acknowledgements.

This work is based on the following four manuscripts:

1. Meurer KHE, Franko U, Stange CF, Dalla Rosa J, Madari BE, and Jungkunst HF 2016 **Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – A critical review**. *Environ. Res. Lett.* 11 (2016) 023001, doi:10.1088/1748-9326/11/2/023001.

2. Meurer KHE, Franko U, Spott O, Stange CF, and Jungkunst HF 2016. **Model testing for nitrous oxide (N_2O) fluxes from Amazonian cattle pastures**. *Atmos. Environ.* 143 (2016) 67 – 78, doi: 10.1016/j.atmosenv2016.08.047.

3. Goepel J, Schuengel J, Schaldach R, Meurer KHE, Jungkunst HF, Franko U, Boy J, Strey R, and Strey S (in review) **Future scenarios of land use and land cover change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils**. *Reg. Environ. Change*

4. Schaldach R, Meurer KHE, Jungkunst HF, Nendel C, Lakes T, Gollnow F, Goepel J, Boy J, Guggenberger G, Strey R, Strey S, Berger T, Gerold G, Schönenberg R, Böhner J, Schindewolf M, Latynskiy E, Hampf AC, Parker PS (submitted) **A multi-scale modelling framework for the analysis of societal and environmental processes in Southern Amazonian land systems: Lessons learned from the Carbiocial project**. *Reg. Environ. Change*

Landau (Pfalz), 25 August 2016

Clarification of contribution

The thesis consists of four publications, resulting from the BMBF-funded research project Carbiocial (speaker: Prof. Dr. Gerold and Prof. Dr. Jungkunst).

I have the leading authorship in two of the manuscripts and contribute as co-author in the other two.

The first manuscript “Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – a critical review” has six authors in total: Katharina H. E. Meurer, Uwe Franko, Claus F. Stange, Beata E. Madari, Jaqueline Dalla Rosa, and Hermann F. Jungkunst. I was responsible for the literature research and data compilation. Additional literature in Portuguese was delivered by Brazilian partners. I wrote the basic framework of the manuscript, which was supported by Hermann F. Jungkunst, Uwe Franko, and Claus F. Stange.

The second manuscript “Model testing for nitrous oxide (N_2O) fluxes from Amazonian cattle pastures” is authored by Katharina H. E. Meurer, Uwe Franko, Oliver Spott, Florian Stange, and Hermann Jungkunst. The study includes model simulations, as well as results from two field campaigns in Southern Amazonia. I ran the (pre-)simulations, planned and performed the measurement campaigns, and re-calibrated the models. Uwe Franko and Oliver Spott supported the model optimization set-up and carried out the analyses of the gas samples at the gas chromatograph, respectively. The structure and thread of the manuscript were developed by Hermann F. Jungkunst, Florian Stange, and me. I did the main work in writing the manuscript; however, this was supported by all co-authors.

The author’s list of the third manuscript (“Future scenarios of land use and land cover change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils”) includes members from four subprojects of the Carbiocial project. The leading author is Jan Göpel from the CESR in Kassel, who did the main work in translating the given storylines and simulating different land use scenarios with the LandSHIFT model. My contribution was the calculation of N_2O and CH_4 emissions from agricultural soils for the different scenarios. Additionally, I worked out the distribution of different soil types, which served as template for calculation of SOC stock changes. The manuscript was mainly written by the leading author – here, my contribution was confined to the description of the methodology of my calculations, the interpretation of the results, and the integration into the total output.

The fourth manuscript, “A multi-scale modelling framework for the analysis of societal and environmental processes on Southern Amazonian land systems: Lessons learned from the Carbiocial project”, is authored by 19 Carbiocial members. Again, my task was the calculation of scenario-specific greenhouse gas emissions from soils (based on previous calculations from the third manuscript), but also estimations of CO_2 releases due to removal of natural vegetation. Here, Rüdiger Schaldach is the leading author and he did the main work in writing the manuscript – however, I supported the preparation of the synoptical tables. Additionally, my contribution included the description of the used methodology, as well as the interpretation of the results and the comparison of my approach with other studies.

Curriculum Vitae

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Education

1997 – 2006	Bischöfliches Gymnasium St. Mauritz, Münster Degree: Abitur
10/2007 – 07/2010	Studies at the TU Braunschweig Degree: Bachelor of Science
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Publications

Peer-reviewed journals

Meurer KHE, Franko U, Stange CF, Dalla Rosa J, Madari BE, and Jungkunst HF 2016
Direct nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – A critical review. *Environ. Res. Lett.* 11 (2016) 023001, doi:10.1088/1748-9326/11/2/023001.

Meurer KHE, Franko U, Spott O, Stange CF, and Jungkunst HF (submitted). **Model testing for nitrous oxide (N_2O) fluxes from Amazonian cattle pastures**. *Atmos. Environ.* 143 (2016) 67 – 78, doi: 10.1016/j.atmosenv.2016.08.047.

Schönenberg R, Hartberger K, Schumann C, Guggenberger G, Siebold M, Boy J, Lakes T, Lamparter G, Schindewolf M, Nendel C, Hohnwald S, Meurer KHE, Gerold G, and Klingler M (in review) **Methods of inter- and transdisciplinary research – a trajectory of knowledge integration**. *Reg. Environ. Change*

Goepel J, Schuengel J, Schaldach R, Meurer KHE, Jungkunst HF, Franko U, Boy J, Strey R, Strey S, Guggenberger G, Hampf AC, and Parker PS (in review) **Future scenarios of land use and land cover change in Southern Amazonia and its impacts on greenhouse gas emissions from agricultural soils**. *Reg. Environ. Change*

Schaldach R, Meurer KHE, Jungkunst HF, Nendel C, Lakes T, Gollnow F, Goepel J, Boy J, Guggenberger G, Strey R, Strey S, Berger T, Gerold G, Schönenberg R, Böhner J, Schindewolf M, Latynskiy, Hampf AC, and Parker PS, (submitted) **A multi-scale modelling framework for the analysis of societal and environmental processes in Southern Amazonian land systems: Lessons learned from the Carbiocial project**. *Reg. Environ. Change*

Meurer KHE, Franko U, Spott O, Schützenmeister K, Niehaus E, Stange CF, and Jungkunst HF (submitted) **Missing hot moments of greenhouse gases in Southern Amazonia.** *Erdkunde*

Selected conference contributions

Presentations

Meurer KHE, Franko U, Spott O, Stange CF, Madari BE, and Jungkunst HF 2015 **Nitrous oxide (N_2O) fluxes from soils under different land use in Brazil**. *EGU General Assembly 2015, 12. - 17.04.2015, Vienna, Austria*

Meurer KHE, Franko U, Spott O, Stange CF, and Jungkunst HF 2015 **N_2O-Emissionen aus Böden unterschiedlicher Landnutzung in Südamazonien – Messung und Modellierung**. *Annual Meeting of the German Soil Science Society (DBG), 07. - 09.09.2015, Munich, Germany*

Meurer KHE, Franko U, Spott O, Stange CF, and Jungkunst HF 2015 **Nitrous oxide (N_2O) fluxes from soils under different land use in Brazil – Overview, measurements, and modeling**. *AGU Fall Meeting 2015, 14. - 18.12.2015, San Francisco, USA*

Posters

Meurer KHE, Jungkunst HF, Franko U, and Stange CF **2013 Messungen und Modellierung von Treibhausgasemissionen aus Böden unterschiedlicher Landnutzung in Südamazonien**. *Annual Meeting of the German Soil Science Society (DBG), 07. – 12.09.2013, Rostock, Germany*

Meurer KHE, Jungkunst HF, Franko U, and Stange CF 2013 **Measurements and modelling of greenhouse emissions from soils under different land use in Southern Amazonia**. *Open Science Conference. Greenhouse Gas Management in European Land Use Systems,16. – 18.09.2013, Antwerp, Belgium*

Meurer KHE, Jungkunst HF, Franko U, Spott O, and Stange CF 2014 **N_2O and CH_4 fluxes from soils under land use change in Southern Amazonia – measurements and modelling**. *BIOGEOMON, 8th International Symposium on Ecosystem Behavior, 13. - 17.07.2014, Bayreuth, Germany*

Meurer KHE, Franko U, Spott O, Stange CF, and Jungkunst HF 2016 **Model-guided measurements of N_2O fluxes from cattle pastures in Southern Amazonia**. *Austin International Conference on Soil Modeling, 29.03. – 01.04.2016, Austin, Texas, USA*

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The path to greatness is along with others (B. Gracion)

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You never walk alone

Without any doubt, the biggest thank goes to my mother, who enabled my studies and therewith paved the way for this PhD project. Thanks for letting me make my way, but assisting whenever necessary ♦ My entire family was fantastic when it came to the field campaigns in Brazil and I am very grateful to my sisters Friederike and Alexandra and to my father for the support in logistics, transport, and solution finding ♦ An equally big "Thank You!" goes to my two favorite "Geiseltal" girls Inge and Julia-Pascal Ebermann – thanks a lot for always being so flexible and attending my journeys, no matter if they went to Bad Lauchstädt, to the Portuguese Embassy in Berlin or, once again, to the airport in Frankfurt! Thanks a lot for always providing a home for my horses and me ♦ I am extremely thankful to Manuela Klein, Ina Greger, and Susanne (*R.I.P.*) and Jochen Wassmuth. Thank you, dear friends, for always reminding me of my strengths when I tended to forget them and for always drawing my attention to the very positive aspects in each and every situation, no matter how unpromising it appeared to me ♦ I do not want to miss the opportunity to thank Alexandro Kirst for having been a guardian angel during the field work in Novo Progresso and the "the-Hilux-needs-maintenance" trip from Novo Progresso to Cuiabá – I would not have managed it without you ♦ Running over a Brazilian cattle pasture under burning sun or in pouring rain is one thing – writing a PhD thesis is another. For that reason, I wish to thank the very critical and merciless proof-readers, who in the end definitely improved this thesis ♦ And last but not least, I would like to thank my grandpa (*R.I.P.*) for keeping a watchful eye on me whenever I found myself in any gloomy forest or when any street turned out to be slippery. I know that it was a hard task sometimes, but you did a very good job!

Once we accept our limits, we go beyond them (A. Einstein)