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THE ROLE OF FUTURE LAND-USE CHANGE IN SOUTHERN AMAZONIA TO REACH THE AIMS OF BRAZIL'S NATIONAL CLIMATE PLAN

Rüdiger Schaldach, Jan Göpel and Michael Klingler

With 4 figures and 5 appendices
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Summary: During the 1990s and early 2000s, forestry and agriculture were the main emitters of greenhouse gases in Brazil, contributing to approximately 80 % of the total national CO_2-equivalent emissions. In Southern Amazonia, the conversion of forest and Cerrado ecosystems to pasture and cropland particularly resulted in high CO_2-emissions from soils and vegetation. Other emissions from the agricultural sector include N_2O emissions from the application of fertilisers and CH_4 emissions from livestock. Only recently was significant progress made in decoupling further increases of agricultural production from deforestation rates. Given the expected increase in global demand for food, bioenergy and biomaterials in the coming years, it is uncertain whether the established policies and available technological potentials to improve crop productivity are sufficient to prevent further expansion of agricultural area. This would be an essential prerequisite for slowing down deforestation considerably and for achieving the national climate targets of reducing the annual greenhouse gas emission by 43 % in 2030. In order to explore the future pathways of land-use change in Southern Amazonia until 2030, we developed a set of four scenarios consisting of storylines and simulated high-resolution land-use maps. The scenarios take into consideration changing agricultural production due to changing commodity demands from domestic and global markets, as well as different assumptions regarding agricultural intensification and the effectiveness of policies targeting the preservation of protected areas. Based on the generated maps, greenhouse gas emissions (N_2O, CH_4 and CO_2) were calculated. Emission reductions compared to the reference year 2010 could be achieved under the Legal Intensification (-38 %) and Sustainable Development (-79 %) scenarios. In both cases, the results indicate that further agricultural intensification together with strict conservation policies are essential requirements to slow down the loss of natural ecosystems and at the same time to reduce greenhouse gas emissions. Additionally, under Sustainable Development, a changing consumption pattern towards a more sustainable diet was identified as a suitable way to further mitigate the climate change impacts of agriculture.

Zusammenfassung: In den 1990er und frühen 2000er Jahren waren Forst- und Landwirtschaft die Hauptverursacher von Treibhausgasen (THG) in Brasilien. Umgerechnet in CO_2-Äquivalenten waren allein diese beiden Sektoren für etwa 80 % der nationalen THG-Emissionen verantwortlich. Im südlichen Amazonasgebiet führte insbesondere die Umwandlung von Wald- und Cerrado Ökosystemen in Weide- und Ackerland zur Freisetzung von CO_2 aus Böden und Vegetation in die Atmosphäre. Weiterhin ist die Landwirtschaft verantwortlich für N_2O-Emissionen aus der Anwendung von Düngemitteln und CH_4-Emissionen aus der Tierhaltung. Erst vor kurzer Zeit konnte eine Entkopplung der Erhöhung der landwirtschaftlichen Produktion von den beobachteten Entwaldungsraten erreicht werden. Angesichts einer zu erwarteten Zunahme der globalen Nachfrage nach Nahrungsmitteln, Bioenergie und Biomaterialien in den kommenden Jahren, ist es jedoch unsicher, ob die bestehenden Gesetze und technologischen Potenziale zur Steigerung von Pflanzenerträgen ausreichend sein werden, um eine weitere Ausdehnung landwirtschaftlich genutzter Flächen zu vermindern. Dies wäre eine wesentliche Voraussetzung zur Verlangsamung der Entwaldung und zur Erreichung der nationalen Klimaziele, die bis 2030 eine Reduktion der jährlichen THG-Emissionen um 43 % verlangen. Um die zukünftigen Landnutzungsänderungen im südlichen Amazonasgebiet bis zum Jahr 2030 zu untersuchen, wurde ein Satz von Szenarien, bestehend aus Narrativen und modellierten hochaufgelösten Landnutzungskarten entwickelt. Die Szenarien berücksichtigen dabei die Entwicklung der Agrarproduktion aufgrund einer sich verändernder Nachfrage nach Agrargütern durch nationale und internationale Märkte ebenso wie verschiedene Annahmen zur Intensivierung der Landwirtschaft und zur Wirksamkeit von Gesetzen zum Erhalt von Schutzgebieten. Basierend auf den generierten Karten wurden THG-Emissionen (CO_2, N_2O und CH_4) berechnet. Eine Verringerung dieser Emissionen im Vergleich zum Startjahr der Untersuchungen 2010 konnte lediglich in den Szenarien „Legale Intensivierung" (-38 %) und „Nachhaltige Entwicklung" (-79 %) erreicht werden. In beiden Fällen zeigen die Ergebnisse, dass die weitere Intensivierung der Landwirtschaft zusammen mit wirksamen strengen Schutzmaßnahmen wesentliche Voraussetzungen dafür sind, um den Verlust von natürlichen Ökosystemen und gleichzeitig die THG-Emissionen durch Landnutzungsänderungen und Landwirtschaft zu verringern. Darüber hinaus wurde im Szenario „Nachhaltige Entwicklung" ein verändertes Konsumverhalten, hin zu einer nachhaltigeren Ernährung, als ein geeigneter Weg identifiziert, um die Auswirkungen der Landwirtschaft auf den Klimawandel weiter zu mindern.

Keywords: Southern Amazonia, land-use change, greenhouse gas emissions, modelling, scenarios

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1 Introduction

During the 1990s and early 2000s, forestry and agriculture were the main emitters of greenhouse gases in Brazil (e.g., through land-use change and agricultural management), contributing to approximately 84 % of the total national CO_2-equivalent emissions (Lapola et al. 2014; SEEG 2017). This emission pattern is unique among the industrialised nations and stresses the importance of these two sectors for the national climate policy. Important drivers of land-use change include the expansion of cropland (e.g. soybean), cattle ranching and (illegal) logging in combination with weak law enforcement (Moutinho et al. 2016; Nepstad et al. 2014; Soares-Filho et al. 2014). More specifically, in Southern Amazonia, the conversion of large areas of forest and Cerrado ecosystems could be observed due to a series of political, economic and market changes (Arvor et al. 2013; Coy and Klingler 2014; Morton et al. 2006) resulting in CO_2-emissions from soils and vegetation, particularly in the phase of land clearing (Schmidt et al. 2011; Krogh et al. 2003; DeFries et al. 2008). Emissions from the agricultural sector further include N_2O-emissions from the application of fertilisers and CH_4-emissions from livestock. According to Cerri et al. (2010), in 2005 methane emissions from livestock accounted for 12 % of the total national greenhouse gas (GHG) emissions.

After 2005, the increase in crop production, especially of soybean, could be decoupled from deforestation (Macedo et al. 2012). This development can be explained by decreasing world market prices for soybean (Nepstad et al. 2009; Hecht 2011; Richards et al. 2012) going hand in hand with the further intensification of cropping systems (Cohn et al. 2014; Macedo et al. 2012; VanWey et al. 2013), successful initiatives of the Brazilian government to protect natural ecosystems (Gibbs et al. 2015; Nepstad et al. 2014) and the increase of its law enforcement options (Arima et at al. 2014; Assunção and Rocha 2014; Börner et al. 2015). In addition, privately-led zero-deforestation agreements are widely credited with promoting sustainable production and accountability in the beef and soybean supply chains (Gibbs et al. 2015; Gibbs et al. 2016; Rudorff et al. 2011). Nevertheless, given the expected rise in the global demand for food, bioenergy and biomaterials in the coming decades, it is uncertain whether the relevant policies, technologies and management practices adopted to improve crop and pasture productivity are sufficiently effective to prevent the expansion of agricultural areas, deforestation and emission of greenhouse gases (Bowman et al. 2012; Nepstad et al. 2014; Gibbs et al. 2015). In this context, it is also debated whether further intensification of agricultural systems can help spare land for nature, or if farmers will seek to generate even higher income by expanding the intensified systems on cost of natural ecosystems (Cohn et al. 2014; Strassburg et al. 2014).

The future development of land-use change and in particular the agricultural sector will play an important role in achieving the ambitious targets of reducing GHG emissions that Brazil has committed itself to in context of the global climate negotiations (Rajão and Soares-Filho 2015; Moutinho et al. 2016). During September 2016, Brazil adopted the Paris agreement; its climate pledge or Nationally Determined Contribution (NDC) aims at reducing GHG emissions by 37 % below 2005 levels by 2025, with a subsequent ‘indicative’ target of 43 % reduction rate by 2030 (FRB 2015a; 2015b). Land-use related action points include increasing the share of sustainable biofuels in the Brazilian energy mix and the implementation of measures relating to land-use change and forests (implementation of forest code, zero illegal deforestation, reforestation etc.). The NDC especially targets the restoration of 15 million hectares of degraded pasture lands and the establishment of 5 million hectares of cropland-livestock-forestry systems by 2030 (MMA 2016). This is in addition to the Low Carbon Emission Agriculture Program (ABC Program) seeking to promote sustainable agricultural development by 2020 (MAPA 2012), even though the mitigation potential may be much higher (Assad et al. 2015). Nevertheless, all policies, measures and actions to implement Brazil’s NDC are still vague and there is no evidence that these actions will lead to the target (Rajão and Soares-Filho 2015).

There are several studies that apply computer models for investigating future land-use change scenarios in the Brazilian Amazon and their effects on GHG emissions. Nevertheless, the analysed scenarios often strongly focus on deforestation trajectories (e.g. Barni et al. 2015; Aguiar et al. 2016). Only few studies explicitly address the development of the agricultural sector, e.g. in terms of intensification and pasture management (e.g. Lapola et al. 2011; Chaplin-Kramer et al. 2015; de Oliveira Silva et al. 2016) or different GHGs (e.g. Galford et al. 2010).

We argue that the development of effective climate policies needs more detailed information on possible future land-use change and its respective drivers to identify adequate policy measures for reducing land use related GHG emissions. In order to explore the future pathways of land-use change in Southern Amazonia until 2030, we use a set of four existing scenarios consisting of storylines and simulated high-resolution land-use maps. These scenarios were developed as part of the Carbiocial project (Göepel et al. accepted; Schönenberg et al. 2017), and take into consideration changing agricultural production due to changing commodity demands from domestic and global markets. They also take into account different assumptions regarding agricultural intensification and the effectiveness of policies targeting the preservation of protected areas and natural ecosystems. Based on the modelled land-use maps, GHG emissions from deforestation and from agriculture are calculated and then related to the specified drivers of land-use change. The objective of our study is to identify individual drivers and sets of drivers that are suitable (according to the simulation results) for reducing these emissions and should play a prominent role in the implementation of Brazilian climate mitigation policies.

2 Methods

2.1 Land-use scenarios

The main objective of the Carbiocial project was to explore how land-use change in Southern Amazonia (federal states of Pará and Mato Grosso) might develop during the period between 2010 (base year) and year 2030, and how it will be affected by the implementation of different land-use policies. For this purpose, four scenarios that portray different plausible development pathways of the region were constructed: *Trend*, *Legal Intensification*, *Illegal Intensification* and *Sustainable Development* (Schönenberg et al. 2017). Each scenario consists of a storyline which is a short narrative of the respective future world (Appendix 1), quantitative land-use change drivers, and simulated raster maps that depict the resulting land-use patterns. The main determinants of the storylines are the linkages of the agricultural sector of Southern Amazonia to global markets (e.g. exports of soybean and meat) and the enforcement of environmental laws. Land-use change drivers were classified into three categories, including human population, agricultural development and land-use policy.

2.1.1 Human population

Under the *Trend*, *Illegal Intensification* and *Legal Intensification* scenarios, changes of human population were calculated by extrapolating the observed trend from 1973-2000 with the least squares method (Rao et al. 1999). In-migration to the Amazon region has decreased in recent years but population movement within the region is still very high (Perz et al. 2010). In Pará, this is projected to result in a population increase, from 6.9 million people in 2010 to 9.3 million people in 2030; while in Mato Grosso, we expect an increase from 2.7 million to 3.7 million people during the same period. In contrast, the storyline of the *Sustainable Development* scenario assumes that population growth in Mato Grosso and Pará is slowing down, mainly due to lower in-migration from other parts of Brazil. This slowdown is expected to be more dominant in Mato Grosso than in Pará where still many additional job opportunities are created due to the pioneer dynamics of the agricultural frontier. Accordingly, the population growth rate was adjusted by -10 % for Mato Grosso and -5 % for Pará for every five years.

2.1.2 Agricultural development

In the *Trend* scenario, crop production between 2010 and 2030 increases in line with the historic development from 1973-2000. Again, a trend extrapolation was calculated with the least squares method. Information on increase in crop yield as a result of technological advances (e.g. plant breeding, improved agricultural management) were derived from a global scenario analysis with the economic trade model IMPACT (Rosegrant 2012) – this was conducted in the context of food security research (Vervoort et al. 2013). The soybean production in Mato Grosso, for instance, is projected to increase by 42 % and by 178 % in Pará. At the same time, further intensification of the agricultural sector leads to increased crop yields (e.g. soybean + 40 %).

The *Legal Intensification* and the *Illegal Intensification* scenario share the same assumptions regarding agricultural development, but include different assumptions regarding land-use policy and law enforcement (see below). Both scenarios are characterised by an even stronger increase in crop production (e.g. soybean by 72 % in Mato Grosso and by 236 % in Pará) and livestock numbers, due to a growing demand for some agricultural commodities mainly from Asian countries (Fearnside and Figueiredo 2015).

Crop yield increase is similar to the *Trend* scenario. Additionally, both scenarios presume a further intensification of cattle ranching. In Pará, a maximum possible intensification rate of 4.5 % per 5-year time step (see section 2.2), up to a limit of 30 % is defined. That means that the biomass productivity of pasture land can be 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 mechanised, large scale, and world market oriented (Jasinski et al. 2005; Arvor et al. 2013; DeFries et al. 2013), the maximum intensification rate is 9 % up to a value of 50 %. These assumptions are based on observed pasture intensification rates in Brazil. According to Wint and Robinson (2007) and Lapola et al. (2014), the stocking density of pastures in Brazil rose continuously from 1990 to 2010, with a total increase of 45 % during that period. Pasture intensification is achieved by the restoration of degraded pasture and the establishment of improved management systems. In order to avoid additional greenhouse gas emission as requested by the NDC, we assume the adoption of management systems with no additional input of N-fertiliser. Examples that rely on the introduction of N-fixing forage legumes in combination with P-K fertiliser and higher yielding grass species are explained in Dick et al. (2015) and Cardoso et al. (2016). Due to a global shift towards a more vegetarian diet that is founded on WHO recommendations (e.g. Srinivasan et al. 2006; Stehfest et al. 2009), the *Sustainable Development* scenario depicts a strong decrease in livestock numbers and a significant increase in food crop production (soybeans, beans, fruits and vegetables) to compensate for the calorie intake formerly derived from animal products. As a result, crop yields increase faster than in other scenarios.

Tables S1 and S2 (Appendix 2) summarise the development of crop productions, yield increases and livestock numbers in the scenarios (see also Göpel et al. accepted).

2.1.3 Land-use policy and road infrastructure

In the land-use scenario simulations, land-use policy was considered either as a constraint of land conversion within designated areas (e.g. for nature protection) or as a factor prohibiting (or not prohibiting) the conversion of a specific land-use type (e.g. forest). Access to road infrastructure typically improves the attractiveness of a piece of land for agricultural development or settlement.

In the *Trend* scenario, natural land which is not protected can be converted into agriculture and settlement area. Moreover, the improvement of the north-south highway transect known as the BR-163 (Cuiabá-Santarém) and its connection to newly established harbours for export crops in Pará State increases the likelihood that adjoining areas will be transformed into agricultural land.

These assumptions are also valid for the *Legal Intensification* scenario, but natural land that is converted between 2010 and 2030 is, in contrast, only partly used for agriculture. Since according to the new Brazilian forest code, 80 % of each agricultural field in the Amazon should remain forest (Soares-Filho et al. 2014), the respective raster cells of the simulated maps were classified as mosaic land-use type (Legal Reserve). The policy settings for the *Illegal Intensification* scenario weaken the protection status of natural land within designated areas. While the conversion of natural ecosystems within indigenous and military areas is still prohibited, the conversion of forest and Cerrado within other types of protected areas is allowed. The most rigorous protection of natural land is assumed in the *Sustainable Development* scenario. In addition to natural land within protected areas, forests outside their boundaries are also fully protected and cannot be converted into agricultural land.

2.2 Simulation of land-use change

Land-use and land-cover change (LULCC) was simulated with the spatially explicit LandSHIFT model (Schaldach et al. 2011; Lapola et al. 2010). The model 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 900 m x 900 m grid cells that covers the territories of the federal states of Mato Grosso and Pará. LandSHIFT simulates the spatiotemporal dynamics of settlements, cropland and pasture by spatially allocating their state-level drivers to the raster level in 5-year time steps. These drivers include human population, livestock numbers, crop production and crop yield increases owing to technological change in each of the four scenarios (see section 2.1). Cell-level information comprises the state variables "land-use type", "human population density" and "grazing livestock density", as well as a set of parameters that describe its landscape characteristics (e.g. terrain slope), road infrastructure and zoning regulations. Model output are raster maps of the land-use pattern in the base year 2010 and in the year 2030 under the 4 scenarios (Göpel et al. accepted). The resulting land-use change was analysed with a GIS and used as the starting point for the calculation of GHG emissions.

2.3 CO_2-emissions from land-use change

For each scenario, net CO_2-emissions from land-use change were calculated with equation 1, based on the empirical approach described in the Renewable Energy Directive of the European Union (JRC 2011). CO_2-emissions to the atmosphere generally result from the conversion of natural ecosystems (rainforest and Cerrado) to pasture or cropland as well as from the conversion of pasture to cropland. In contrast, the conversion from cropland to pasture results in an additional uptake of CO_2 from the atmosphere.

$$e_l = (CS_R - CS_A) * F * \frac{1}{Y} \qquad \text{(Equation 1)}$$

with

e_l = annualised emissions from carbon stock change due to LUC [tCO_2]

CS_R = carbon stock in soil and vegetation associated with the land-use type in 2030 [$tC\ ha^{-1}$]

CS_A = carbon stock in soil and vegetation associated with the land-use type in 2010 [$tC\ ha^{-1}$]

F = factor for the conversion of C to CO_2 (Default = 3.664)

Y = annualising of carbon stock changes over a 20 year period

In our study, CS_R reflects the carbon stock in 2030, while CS_A represents the carbon stock in 2010. The calculation takes into account the carbon stocks in soil and vegetation for each raster cell. Cell-level information regarding soil type and climate type as well as land use, including soil and climate type dependent default values for soil organic carbon and vegetation carbon stocks (above and below ground) were derived from JRC (2011) and EC (2010). An overview of the parameter values used for our study is given in Appendix 3. The calculation of carbon stocks for mineral soils and organic soils is consistent with the IPCC Tier 1 methodology (IPCC 2006). After the carbon stocks for 2010 and 2030 were determined for each cell, the annualised GHG emissions from LUC (e_l) were computed. To obtain the change in carbon stocks during the simulation period, CS_A is subtracted from CS_R. Then, the yearly emissions related to these carbon stock changes were calculated for a time frame of 20 years by allocating it in 20 equal parts to each year. This procedure reflects that some emissions occur during the conversion process itself while others occur over a long period of time after the conversion.

2.4 N_2O- and CH_4-emissions from agriculture

Our assessment focusses on N_2O- and CH_4-emissions after forest clearing (persisting land use) and does not consider emissions that originate from the clearing process (harvest of forest, burning of biomass) or from changes in vegetation carbon (e.g. forest regrowth).

We used the average N_2O-emission factors reported in the review of Meurer et al. (2016) for different land-use types in Brazil. For example the applied emission factor for cropland is 0.8 kg $N_2O\ ha^{-1}\ y^{-1}$ (Appendix 4, Tab. S6). Since the authors of that review found only a low response of N_2O-emissions from cropland soils to the application of fertiliser, the same factor was applied for 2010 and 2030, even though the projected yield increase suggests a higher fertiliser input in 2030. For pasture, Meurer et al. (2016) showed the non-linear relation between N_2O-fluxes from soils and pasture age (years since conversion), and hence distinguished between pastures below or above 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 the estimation of total N_2O-fluxes. The emission factors for methane (Appendix 4, Tab. S6) are based on a literature review by Meurer (2016). Cropland is reported to be a sink for atmospheric CH_4. In contrast, positive fluxes from pastures were reported by almost all references included in that study.

2.5 CH_4-emissions from livestock

CH_4-emissions caused by enteric fermentation were calculated, consistent with the IPCC Tier 1 methodology (IPCC 2006), by multiplying the average annual population of an animal type (cattle for meat production, cattle for dairy production, sheep, and goats) expressed in livestock units (LU) with an appropriate emission factor. Methane emissions from manure were calculated by multiplying the average annual population of an animal type by the emission factor in respect to the regional characteristics of manure handling and the mean yearly temperature in the region the LU is associated with (Appendix 4, Tab. S7).

2.6 Global warming potential

The 100-year global warming potential (GWP) values from AR5 (Stocker et al. 2013) were used for the conversion of CH_4 and N_2O-emissions into CO_2 equivalents (CO_{2e}) where 1 unit of CH_4 has the GWP of 28 units of CO_2 and 1 unit of N_2O the GWP of 310 units of CO_2.

3 Results

3.1 Land-use change and resulting CO_2-emissions

The main driver of CO_2-emissions in our study region is the conversion of carbon-rich ecosystems such as tropical rainforest and Cerrado to agricultural land. The maps in figure 1 indicate the locations of cropland and pasture expansion until 2030 in the investigated scenarios. Table S8 (Appendix 5) includes an overview of the calculated land-use changes and respective CO_2-emissions in the scenarios.

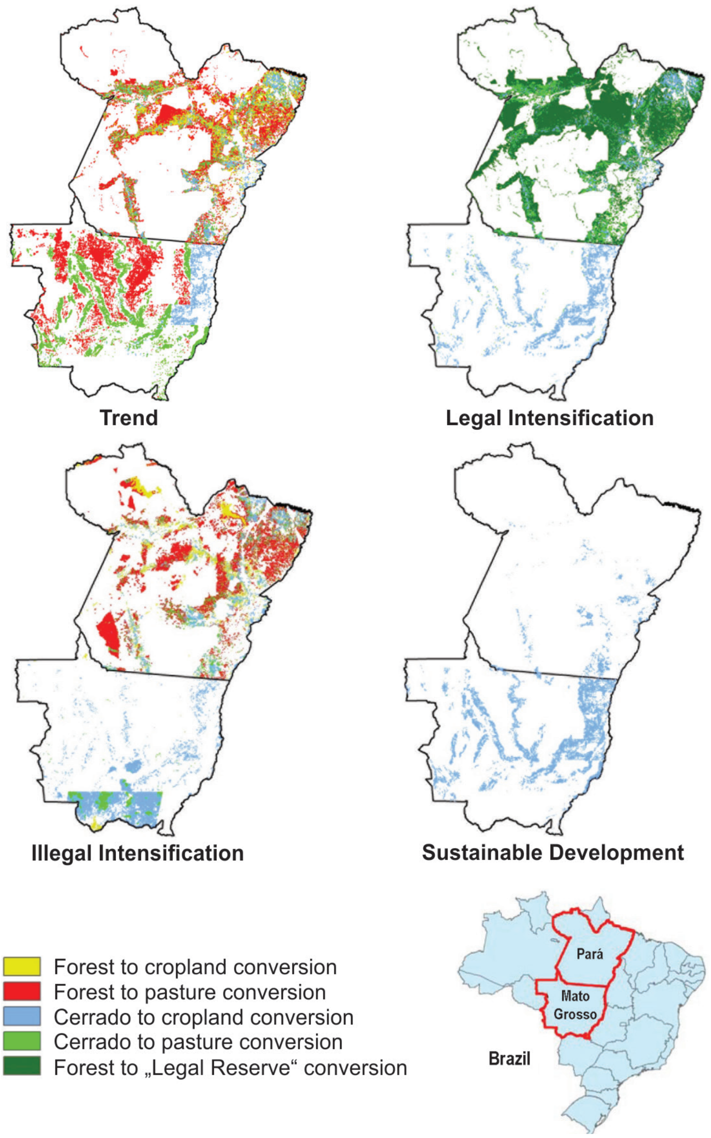

Fig. 1: Location of land conversion from natural ecosystems to pasture and cropland byl 2030 in the Carbiocial scenarios, based on data calculated with the LandSHIFT model (Göpel et al. accepted). Legal Reserve describes a mosaic land-use type that consists of 20 % agriculture and 80 % natural land.

The largest conversion of natural ecosystems and related CO_2-emissions were calculated under the *Trend* scenario. The main contributor is the expansion of pasture that replaces 34,160 km² of Cerrado and 118,300 km² of forest with annual CO_2-emissions of 311 Mt. An additional 16,833 km² of forest and 12,430 km² of Cerrado are converted into new cropland with 55.2 Mt CO_2-emissions per year (Fig. 2). The annual CO_2-emissions from land-use change under the *Illegal Intensification* scenario are slightly lower and amount to 339.5 Mt. Similar to the *Trend* scenario, the conversion of 66,135 km² of forest and 9,345 km² of Cerrado to pasture is the main source of these emissions (185.4 Mt/a), followed by cropland expansion with 154 Mt/a CO_2-emissions due to the conversion of 59,965 km² of Cerrado and 34,176 km² of forest. The CO_2-emissions under the *Legal Intensification* scenario are significantly lower and amount to 155.9 Mt/a. The main source of CO_2-emissions is the transformation of 57,340 km² of forest and 21,933 km² of Cerrado to cropland (139.9 Mt/a). It is worth noting that under *Legal Intensification,* the conversion of forest leads to a mosaic land use (Legal Reserve) that consists of 20 % agricultural area and 80 % of natural land. The remainder is due to the conversion of 12,900 km² of pasture to cropland. The lowest emission pathway was achieved under the *Sustainable Development* scenario where deforestation is strictly forbidden. In this case, the main source of GHG emissions is the conversion of pasture to cropland (40.8 Mt/a), followed by the conversion of Cerrado to cropland (21.5 Mt/a).

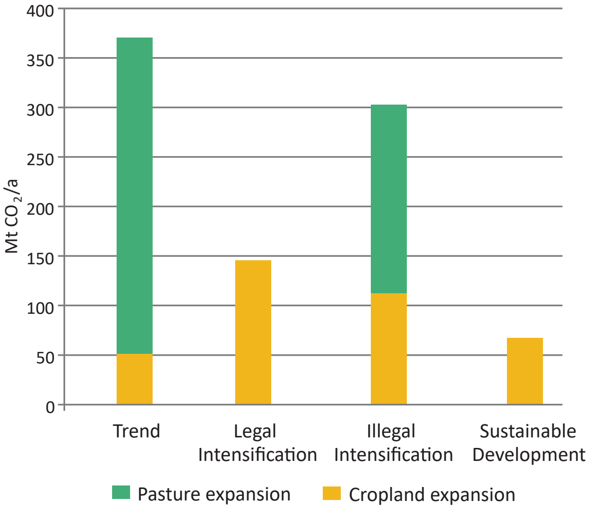

Fig. 2: Mean annual net CO_2-emissions between 2010 and 2030 from cropland and pasture expansion in the Carbiocial scenarios. The data includes emissions from the conversion of natural ecosystems, as well as from the conversion of pasture to cropland and vice versa.

3.2 N_2O- and CH_4-emissions from agricultural soils

Figure 3 depicts the N_2O- and CH_4-emissions from agricultural soils in 2010 and under the different scenarios in 2030. The highest emissions can be found in the *Trend* scenario, mainly as it is characterised by the strongest expansion of pasture areas. As cropland area only slightly expands, we also find only a slight increase of the related N_2O-emissions and CH_4-uptake. The two intensification scenarios show clear differences in their emission patterns. While under *Illegal Intensification,* N_2O-emissions from cropland and pasture are in the same order of magnitude, under *Legal Intensification,* cropland is the dominant source of N_2O-emissions as pasture area slightly decreases. This decrease goes hand in hand with higher grazing livestock densities on the pasture land. Consequently, the CH_4 emissions from pasture are also lower compared to *Illegal Intensification*. Since the *Sustainable Development* scenario shows the strongest increase in cropland area and at the same time the strongest decrease in pasture area, also the N_2O-emissions from these two sources are the highest and lowest among all scenarios, respectively. Similar trends are found for the CH_4-emissions, which are the lowest from pasture, while cropland forms the largest sink.

3.3 CH_4-emissions from livestock and manure management

The highest annual CH_4-emissions from livestock and manure management are calculated for the two intensification scenarios. Here, the growing livestock numbers within the region are responsible for an emission increase from 1.78 Mt in 2010 to 3.46 Mt in 2030. In relation to the slightly lower livestock numbers under the *Trend* scenario, the annual CH_4-emissions in 2030 amount to 2.87 Mt. In contrast, the *Sustainable Development* scenario is characterised by decreasing livestock numbers. Accordingly, the annual CH_4-emissions from livestock and manure decrease to 0.5 Mt in 2030.

3.4 Global warming potential of greenhouse gas emissions

As shown in figure 4, the highest total GWP is calculated for the *Trend* scenario, followed by the *Illegal Intensification* scenario. The GHG emissions

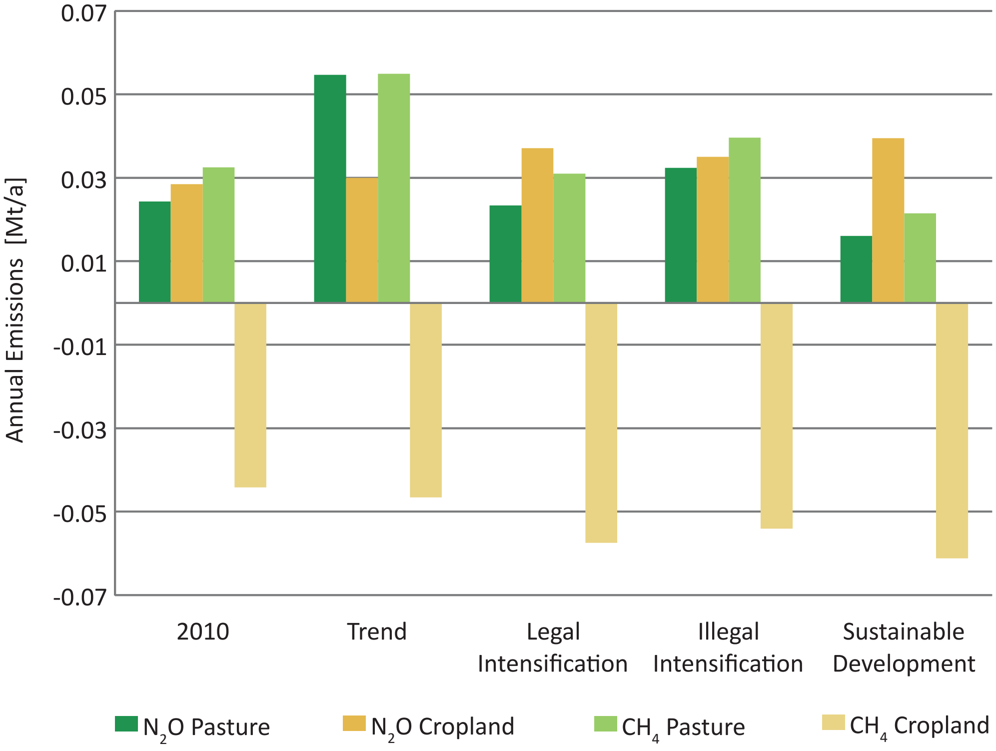

Fig. 3: Annual N_2O- and CH_4-emissions and uptake from agricultural soils in 2010 and 2030

under *Legal Intensification* have a significantly lower GWP, mainly due to the reduction of deforestation. The lowest GWP is achieved under *Sustainable Development*. The emissions from land-use and land-cover change (LUCC) in 2010 are similar to the *Trend* scenario.

4 Discussion

4.1 Policy implications

In all four scenarios, an expansion of agricultural area at the cost of natural ecosystems could be observed between 2010 and 2030. This means that the assumed increases of crop yields and biomass productivity of pasture could not compensate for the rise in production of agricultural commodities. The strongest increases were calculated for the *Trend* and the *Illegal Intensification* scenarios with pasture expansion being the dominant driver of land-use change. These results confirm that the growing demand for agricultural commodities from world markets will continue to account for a significant share of deforestation and related greenhouse gas emissions in Southern Amazonia if current government policies and multinational agreements are not fully implemented and other mechanisms created (e.g. Nepstad 2014). The effective implementation and enforcement of conservation policies together with agricultural intensification, depicted in the *Legal Intensification* scenario is crucial for mitigating the pressure of a growing agricultural production on natural ecosystems. While cropland expansion and CO_2-emissions from deforestation have a similar order of magnitude as in the *Illegal Intensification* scenario, pasture area slightly decreases. Here, the strict protection of conservation area leads to a lower availability of potentially suitable land for pasture expansion. In consequence, grazing livestock densities on existing pasture land are also increasing. This intensification requires further optimisation of grazing management as well as the restauration of degraded pastures (e.g. Cohn et al. 2014), as defined in the ABC Program. Due to the compliance to the Brazilian forest code, the resulting land-use pattern has very different characteristics from the aforementioned scenarios as the newly allocated cropland on former forest land has a mosaic land use consisting of 20 % cropland and 80 % of the original natural land-cover type. Especially when the patches of natural land cover are connected to corridors, this might have positive effects on biodiversity and vegetation

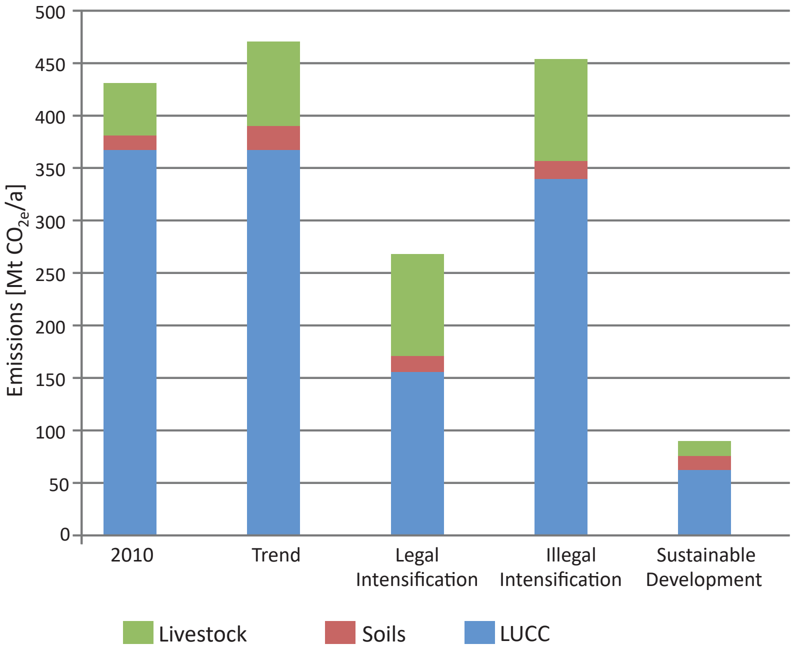

Fig. 4: Global warming potential of land-use related greenhouse gas emissions in 2010 and under the four Carbiocial scenarios in 2030

carbon storage compared to larger farm entities (e.g. Chaplin-Kramer et al. 2015), but the fact is that agricultural activities are spread over a larger region (see Fig. 1), e.g. with higher requirements for road infrastructure. Another negative side effect is that locations 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 realised on other locations with lower crop yields which might lead to an over-proportional net expansion of cropland.

While N_2O-emissions from agricultural soils are the smallest fraction, methane emissions from livestock play a prominent role in all three scenarios due to the growing number of grazing animals assumed in the storylines. Although deforestation is strictly forbidden under *Sustainable Development*, still more than 30,000 km² of Cerrado vegetation would be converted into cropland. Nevertheless, in total, more than 65 % of the new cropland is allocated on former pasture land that is abandoned due to the decreasing livestock numbers. The land-use change related emissions are the lowest among all scenarios. Other important assumptions underlying the *Sustainable Development* scenario that are responsible for lower GHG emissions are the lower meat consumption together with a lesser world market oriented agricultural production. Here, two positive aspects go hand in hand: first is the reduction of methane emissions from livestock; and, second is that the abandoned pasture land can buffer the additional demand for cropland. Consequently, the scenario shows the smallest conversion rates of natural ecosystems.

Coming back to the original question of the role of future land-use change in Southern Amazonia to reach the aims of Brazil's National Climate Plan, we find that using the starting year 2010 of our simulations as a reference point, only under the *Sustainable Development* and the *Legal Intensification* scenarios can emission reductions be achieved (-38 % and -79 %). In contrast, emissions are increasing under *Illegal Intensification* and *Trend*. These results clearly underline that agricultural intensification and effective conservation policies are essential for mitigating land use related GHG emissions as required by the national climate plan. Therefore, economic instruments that encourage intensification of agricultural production and nature conservation will have to play a key part in Brazil's national climate policy. On the other hand, we found that even these measures might not be sufficient for reaching the ambitious greenhouse gas reduction targets if demands from global food and energy markets trigger an increase in agricultural production within the region. At this point, the *Sustainable Development* scenario illustrates that changing human consumption patterns might play an essential role for a successful climate mitigation policy (Bringezu et al. 2012).

4.2 Comparison with other studies

Similar to the scenarios of the Legal Amazon presented by Aguiar et al. (2016), we followed a normative scenario approach with qualitative (storylines) and quantitative elements (computer simulation), building on the story and simulation approach, introduced by Alcamo et al. (2008). In contrast to scenarios that concentrate on deforestation trajectories alone (e.g. Barni et al. 2015; Soares-Filho et al. 2006; Aguiar et al. 2016), our storylines include a broad range of societal and political aspects, e.g. raising the question of possible implications of changes in human lifestyle and consumption pattern on land-use change (e.g. Stehfest et al. 2006). Moreover, to our knowledge, these scenarios are the first ones that explicitly address the situation within Mato Grosso and Pará considering various greenhouse gases. The comparison of our results with other studies is difficult due to differences in the the scenario assumptions and the spatial extent of the studies. For example, Aguiar et al. (2016) project yearly CO_2-emissions from land-use change between -290 Mt (net carbon uptake) and 731 Mt for the whole Legal Amazon during the decade 2021 – 2030, compared to 62,3 - 366 Mt per year in our study for Southern Amazonia. Interestingly, the processes that lead to the lowest emission trajectories are different. While Agauiar et al. (2016) identify regeneration of secondary forest as the main driver for carbon uptake (not integrated into our analysis), the emissions in the *Sustainable Devleopment* scenario are solely caused by transformation of Cerrado and pasture into cropland.

4.3 Uncertainties and limitations

Uncertainties related to land use modelling in the study region are discussed in Göpel et al. (accepted). Examples include the land cover data sets used for model initialisation as well as the simplified representation of agricultural management within LandSHIFT. Double cropping that has been adapted by close to 60 % of the farmers in Mato Grosso (e.g. Lapola et al. 2014) was included in our model by future crop yield increases but not in a spatially explicit way. Moreover, intensification of the livestock sector only considers the improvement of pasture productivity but neglects livestock keeping in feedlots as an alternative or complementary intensification strategy. The inclusion of these processes into the LandSHIFT model will play an important role in our future research efforts. The analysis of GHG emissions was done with relatively simple empirical model approaches that are well tested and widely applied for emission reporting (IPCC 2006) and the evaluation of sustainability aspects in the biofuel arena (EC 2010). Therefore, our results represent the state-of-the-art of this type of greenhouse gas accounting. A higher level of detail could be achieved, e.g., by using more elaborated soil carbon data (Bernoux et al. 2002), by making more detailed assumptions regarding carbon optimised agricultural management, and by including the process of forest regrowth that can have a significant effect on the regional carbon balance as illustrated by Aguiar et al. (2016).

5 Conclusion

Our study provides new insights into the interplay between different drivers of land-use change and agricultural development, and the resulting effects on GHG emissions in Southern Amazonia. In light of the described limitations, the 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 dynamics of land-use change with its environmental consequences. Emission reductions compared to the reference year 2010 could only be achieved under the *Legal Intensification* (-38 %) and *Sustainable Development* (-79 %) scenarios. In both cases, agricultural intensification combined with strict conservation policies were identified as essential prerequisites to slow down the loss of natural ecosystems. These results indicate that the conception and strong enforcements of laws and regulations targeting the effective development of the agricultural sector and protection of ecosystems should be integral elements of Brazil's national climate policy. Also, the results highlight the need to develop higher environmental awareness on the individual and societal level.

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Authors

Prof. Dr. Rüdiger Schaldach
Jan Göpel
Center for Environmental Systems Research
University Kassel
Wilhelmshöher Allee 47
34117 Kassel
Germany
schaldach@usf.uni-kassel.de

Michael Klingler
Geographisches Institut
Universität Innsbruck
Bruno-Sander-Haus 6
A-6020 Innsbruck
Austria
Michael.Klingler@uibk.ac.at

Appendix 1: Scenario storylines

The development of the scenario storylines is described in detail by Schönenberg et al. (2017). In the following the main elements of the storylines are summarized.

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

The *Legal Intensification* and the *Illegal Intensification* scenarios are characterized by a further increase of crop production and livestock numbers due to a growing demand for these agricultural commodities from Asian countries. Additionally the scenarios presume the intensification of cattle ranching. The two scenarios differ in respect of the assumed enforcement of environmental law. Under Legal Intensification the conversion of protected areas of any kind is not allowed. In addition, we assume compliance with the Brazilian forest code which implies that the expansion of agricultural area is realized as the new "Mosaic" land-use type, leaving 80 % of natural land on the newly converted grid cell intact (Legal Reserve). 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 Brazilian forest code does not apply.

The *Sustainable Development* scenario describes a society with a social model based on participation and 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), it is characterized by a strong decrease of livestock numbers and a significant increase of crop production (soybeans, beans, fruits and vegetables) for compensating the calorie intake formerly realised by animal products. Due to less immigration from other parts of Brazil, population increase is lower than in the other scenarios.

Appendix 2: Scenario driver

Tab. S1: Development of crop production and crop yields in the study region between 2010 and 2030 under the 4 scenarios. The high change rates of beans and soybean in Pará are due to the substitution of dietary meat intake and relatively low production values in 2010. Data for 2010 is derived from IPEA (2017).

	Crop type	**Crop yield**				**Crop production**			
		[t/ha]	Change 2010 – 2030 [%]			[kt]	Change 2010 – 2030 [%]		
		2010	*Trend*	*Legal/Illegal Intensification*	*Sustainable development*	2010	*Trend*	*Legal/Illegal Intensification*	*Sustainable development*
Pará	Fruits	16.9	42.4	42.4	85.1	751.4	123.5	123.5	273.6
	Maize	2.2	70.3	70.3	121.4	519.3	89.4	129.1	55.6
	Groundnut	2.3	40.4	40.4	82.5	0.2	109.7	109.7	57.9
	Beans	0.7	49.4	49.4	94.2	36.5	146.8	146.8	1978.8
	Rice	1.7	61.6	61.6	110.0	263.9	145.4	145.4	125.7
	Cassava	15.8	45.9	45.9	89.7	4596.1	67.1	67.1	88.8
	Soybean	3.4	39.2	39.2	80.9	243.6	177.8	236.1	2448.0
	Sugarcane	68.4	51.4	51.4	96.8	668.7	8.1	8.1	8.1
Mato Grosso	Fruits	14.0	42.4	42.4	85.1	62.2	226.6	226.6	542.8
	Maize	4.9	70.3	70.3	121.4	8164.2	-0.5	20.4	69.2
	Groundnut	1.7	40.4	40.4	82.5	7.8	-13.2	-13.2	55.0
	Beans	0.9	49.4	49.4	94.2	133.8	-24.4	-24.4	701.3
	Rice	2.4	61.6	61.6	110.0	686.3	97.4	97.4	125.7
	Cassava	13.9	45.9	45.9	89.7	496.1	8.8	8.8	103.0
	Soybean	3.2	39.2	39.2	80.9	18787.8	42.1	71.9	119.7
	Sugarcane	68.3	51.4	51.4	96.8	14564.7	71.9	71.9	71.9

Tab. S2: Development of livestock numbers in the study region between 2010 and 2030 under the 4 scenarios (IPEA 2017)

State	**2010**	**Change 2010 – 2013 [%]**		
	Livestock Units	Trend	Legal/Illegal Intensification	Sustainable Development
Pará	8,121,010	+103	+146	-70
Mato Grosso	16,970,600	+49	+80	-70

Appendix 3: Calculation of CO_2 emissions from land-use change

CO_2 emissions from land-use change were calculated according to the guidelines from the European Commission (EC 2010) based on the IPCC Tier 1 approach. In the following, the applied equations and parameter values that are fully described in EC (2010) are summarized. The calculation of carbon stocks in the base year (CS_R) and the scenario (CS_A) is done according to the following equation:

$$CS = SOC + C_{veg} \quad \text{(Eq.1)}$$

SOC = soil organic carbon
C_{veg} = above and belowground biomass

SOC is calculated according to Equation 2:

$$SOC = SOC_{ST} * F_{MG} * F_{LU} * F_I \quad \text{(Eq. 2)}$$

SOC_{ST} = standard soil organic carbon in the 0-30 cm topsoil layer.
F_{MG} = management factor reflecting the difference in soil organic carbon associated with the principle management practice compared to the standard soil organic carbon.
F_{LU} = land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard soil organic carbon.
F_I = input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon.

Tab. S3: Aboveground and below ground biomass of vegetation [t C/ha]

Vegetation type	C_{veg}
Cropland	0
Sugar cane	5
Grassland	8.1
Shrubland	53
Tropical rain forest	198

Tab. S4: Standard soil organic carbon in the 0-30 cm topsoil layer [t C / ha]

Climate region	Soil type			
	High activity clay soils	Low activity clay soils	Sandy soils	Wetland soils
Tropical, moist	65	47	39	86
Tropical, wet	44	60	66	86

Tab. S5: Factors reflecting the influence of land use (F_L), management (F_{MG}) and input (F_I) on soil organic carbon

Land use type (F_{LU})	Management (F_{MG})	Input (F_I)	F_{LU}	F_{MG}	F_I
Savannah, grassland (tropical moist, wet)	Normally managed	Medium	1	1	1
Cropland (annual /perennial) (tropical moist, wet)	Reduced tillage	Medium	0.48 /1	1.15	1

Appendix 4: Coefficients for N_2O- and CH_4-emissions

Tab. S6: Land use-specific emission coefficients of N_2O [kg N_2O ha^{-1} yr^{-1}] and CH_4 [kg CH_4 ha^{-1} yr^{-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
Pasture				-2.19	1.2[b – d, h, i]	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[e - i]	1.65

[a] Meurer et al. (2016), [b] Steudler et al. (1996), [c] Carmo et al. (2013), [d] Fernandes et al. (2002), [e] Verchot et al. (2008), [f] Metay et al. (2007), [g] Piva et al. (2014), [h] Carvalho et al. (2014), [i] Neto et al. (2011)

Tab. S7: Coefficients for the calculation of CH_4-emissions from livestock [kg $head^{-1}$ yr^{-1}] according to IPCC (2006). In Pará we assume 96 % of cattle for meat production and 4 % diary, in Mato Grosso 98 % meat and 2 % diary.

	Enteric fermentation	Manure management
Cattle dairy	57	2
Cattle meat	49	1
Sheep	5	0.37
Goat	5	0.26

Appendix 5: Simulation results

Tab. S8: Transition matrix - total land-use change and related annual CO_2-emissions in the 4 Carbiocial scenarios

		Trend		Sustainable Development		Legal Intensification		Illegal Intensification	
		km^2	CO_2 [Mt/a]	km^2	CO_2 [Mt/a]	km^2	CO_2 [Mt/a]	km^2	CO_2 [Mt/a]
Forest	to cropland	16833.42	48..81	0.00	0.00	57340.50	139.87	34176.33	115.15
Cerrado		12430.26	7..42	44844.84	21.49	21933.18	9.53	59965.92	34.83
Set aside		192.78	0..07	548.37	0.15	219.51	0.08	42.93	0.02
Pasture		0.00	0.00	86166.99	40.77	12900.65	6.46	6630.66	4.10
Forest	to pasture	118299.69	325.74	0.00	0.00	0.00	0.00	66135.69	191.93
Cerrado		34160.13	0.05	3.24	0.00	0.00	0.00	9543.42	0.02
Set aside		0.00	0.00	0.00	0.00	0.00	0.00	405.00	-0.10
Cropland		23453.55	-14.77	0.00	0.00	0.00	0.00	10369.62	-6.55
Cropland	to set aside	417.96	-0.17	0.00	0.00	0.00	0.00	89.91	-0.04
Pasture		0.00	0.00	0.00	0.00	0.00	0.00	1.62	0.00
	Total	205787.79	367.16	131563.44	62.41	92393.84	155.94	187361.10	339.34