MODELLING LAND USE CHANGES IN BRAZIL

2000-2050

A report by the REDD-PAC project

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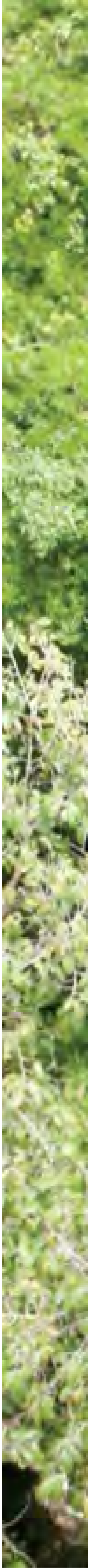

Cooperating Institutions

INPE Instituto Nacional de Pesquisas Espaciais, Brasil

IPEA Instituto de Pesquisa Economica Aplicada, Brasil

IIASA International Institute for Applied System Analysis

UNEP-WCMC United Nations Environment Program, World Conservation Monitoring Centre

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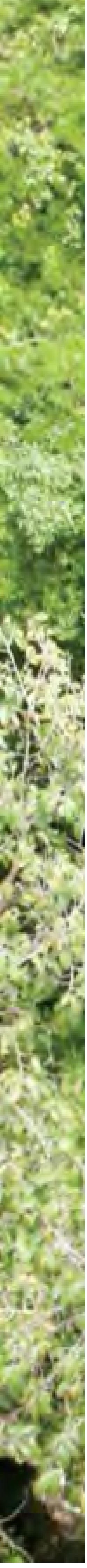

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Executive Summary

This report describes the methods and results of the REDD+ Policy Assessment Centre project (REDD-PAC) project, that supports decision making on REDD+, biodiversity and land use policies in Brazil. A consortium of leading research institutes (IIASA, INPE, IPEA, UNEP-WCMC), supported by Germany's International Climate Initiative, joined forces to study policies that balance production and protection in Brazil.

Brazil aims to reduce emissions from deforestation and land use as a contribution to climate change mitigation and to conserve the country's rich biodiversity. The country has pledged to cut its greenhouse gas emissions to 37% below 2005 levels by 2025 and intends to reach a 43% cut by 2030. This is the first time a major developing country has committed to an absolute decrease in emissions.

The REDD-PAC project team adapted the global economic model GLOBIOM (developed by IIASA) to analyse land use policies in Brazil. GLOBIOM is a bottom-up partial equilibrium model focusing on major global land-based sectors (agriculture, forestry and bioenergy). It projects future land use and agricultural production for the whole country, taking account of both internal policies and external trade. Model projections show that Brazil has the potential to balance its goals of protecting the environment and becoming a major global producer of food and biofuels. The model results were taken into account by Brazilian decision-makers when developing the country's intended nationally determined contribution (INDC), submitted to UNFCCC COP-21 in Paris in 2015.

To project land use change in Brazil up to 2050, we built a novel land cover and land use map for Brazil in 2000. It combines information from the IBGE vegetation map, remote sensing land cover maps, and IBGE statistics for crop, livestock and planted forests. For validation, we compared the projections for 2010 with official statistics on deforestation and agricultural production. Differences between IBGE survey data and model projections in 2010 are less than 10%. Deforestation in Amazonia, as measured by INPE, was 16.5 Mha in the period 2001-2010, while the model projects 16.9 Mha of deforestation. The good validation results give us confidence that GLOBIOM-Brasil can capture the main trends of land use change in the country.

To support the development and achievement of ambitious national commitments on emission reductions, we used GLOBIOM-Brazil to model how Brazil's Forest Code will shape future land use. Model projections consider a set of scenarios, based on discussions with the stakeholders at the Brazilian Ministry for the Environment. The base scenario projects the resulting land use change if the Forest Code is put in practice as planned. The counterfactual scenario is a "business as usual" case that considers what happens without the Forest Code. When we contrast these two scenarios, we see how crucial the Forest Code is for environmental protection.

We consider three alternatives to base Forest Code scenario: what if crop farmers (as distinct from livestock farmers) are the only ones to buy environmental reserve quotas? What if the Forest Code had not included the environmental reserve quotas? What if small farms are not exempted from recovering their legal reserve deficits? These scenarios show what is the relative importance of the rules of the Forest Code for each of the country's biomes.

In the Forest Code scenario, the model projects a total forest cover in Brazil to be 430 Mha in 2030 and 425 Mha in 2050. Forest area in Amazônia will stabilise at 328 Mha from 2030 onwards, considering both regrowth and legal cuts of mature forest. In the Cerrado, total forest will level off at 45 Mha. Forest regrowth in Brazil will reach 10 Mha by 2030. If crop farmers are the only ones that buy quotas, forest regrowth in 2030 increases to 20 Mha, because livestock farmers will have to restore more forest. In this scenario, more mature forests (a further 7 Mha) are lost in Amazônia. Environmental reserve quotas affect Amazônia and Cerrado more than other biomes and have significant effects on preservation of mature forest and forest regrowth.

Croplands in Brazil expand in the coming decades in all scenarios, increasing from 56 Mha in 2010 to 92 Mha in 2030 and reaching 114 Mha in 2050. Land area for crop production more than doubles compared to 2010. These results point out that environmental regulations (Forest Code and protected areas) do not prevent cropland expansion in Brazil, but allow farmers to produce more food and biofuels.

The model projects a significant decrease in pastureland as cattle ranchers improve their practises to increase livestock productivity. Pasture area decreases by 10 Mha in 2030 compared to 2010, with further cuts of 20 Mha by 2050. In 2030, there will be 230 M heads of cattle in Brazil, occupying 30% less area per head than in 2000.

The Forest Code can bring about a major decrease in greenhouse gas emissions in Brazil. Emissions from deforestation reach 110 $MtCO_2e$ in 2030, a 92% decrease since 2000. Brazil will bring forest-related emissions to zero after 2030, due to forest regrowth and reduced deforestation. Increase in pasture productivity will limit the loss of natural land, curbing emissions. Emissions from crop and livestock production reach 480 Mt CO_2e by 2030, most as CH_4 from enteric fermentation and manure from cattle. These emissions are expressed in terms of Global Warming Potential (GWP). When converted to Global Temperature Potential measures (the IPCC's second recommended indicator), Brazil's emissions from crop and livestock are 160 Mt CO_2e in 2030. The GTP metric has potential advantages over GWP, since it better express surface temperature changes. In the GTP metric, the Brazilian total projected emissions for 2030 are 1,1 Gt CO_2e. Emissions from land use and land cover change, including agriculture and forestry, are projected to account for 28% of those.

Conversion of natural ecosystems for human use leads to loss and fragmentation of species habitats. Although many of the national priorities for biodiversity are under protection, habitats of many important species are unprotected. Out of 311 threatened species assessed, 20 species lose over 25% of their potential habitat in the business as usual scenario. Enforcing the Forest Code reduces this number to 6 species. The main biomes under threat are the Caatinga and the Cerrado. The dry forests of the Caatinga, projected to lose 11 Mha from 2010 to 2050. By 2050, over 51% of the natural Caatinga forests identified as important for biodiversity but not protected could be lost. When the loss of both mature forest and natural lands are considered, the Cerrado could lose over 20% of its unprotected areas of biodiversity importance.

The overall message of this report is the crucial importance for Brazil of implementing the Forest Code. To do so, the country faces major challenges. A high quality rural environmental cadastre is essential to make sure illegally deforested area in Brazil be restored. Brazil needs to set up a monitoring system for the whole country as powerful as the one in place for Amazônia. It is crucial to limit the legal reserve amnesty to those who are small farmers, avoiding illicit break-up of large farms. The market for environmental quotas needs to be regulated to avoid improper land grabbing and enhance forest conservation. If Brazil succeeds in applying the Forest Code for its territory, there will be multiple benefits for its citizens, including biodiversity protection, emissions mitigation, and positive institution building.

Background of the Study

REDD+ and land use change models

The United Nations Framework Convention on Climate Change (UNFCCC) encourages developing countries to engage in a range of activities to reduce emissions from land use, land use change and forestry (LULUCF) called REDD+[1]. The UNFCCC has requested that countries aiming to engage in REDD+ activities develop: (a) a national strategy or action plan; (b) a national forest reference emission level; (c) a robust and transparent national forest monitoring system for monitoring and reporting REDD+ activities, under national circumstances; (d) a system for providing information on how the safeguards are being addressed and respected. These elements were first requested at UNFCCC COP-16 and confirmed in the Warsaw Framework during UNFCCC COP-19.

[1] REDD+ refers to: Reduction of Emissions from Deforestation and forest Degradation plus the conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks.

The REDD-PAC (*REDD+ Policy Assessment Centre*) project aims to support Brazil in further developing its REDD+ policies and plans for emission reductions in the LULUCF sector. We use the GLOBIOM-Brazil land use change model, developed by IIASA and enhanced by the Brazilian members of the project team. UNEP-WCMC contributes with a detailed analysis of the possible impacts of land use change on biodiversity. Land use change models are useful tools for policy-making. These models assess what factors are driving land use change, which areas face most pressures for change, and how policies and actions may change future land use. Beyond land use change, such models can be used to estimate effects on emissions, agricultural production and biodiversity.

Forest reference emission levels: UNFCCC decisions and Brazilian submission

The UNFCCC Conference of the Parties (COP) has defined forest reference emission levels (FREL) as: *"…benchmarks for assessing each country's performance in implementing [REDD+] activities."* UNFCCC provides guidance on REDD+ FREL submissions, so that they should:

1. Maintain consistency with national GHG inventories (UNFCCC, Decision 12/CP.17, paragraph 8).

2. Give information and rationale on FREL development (UNFCCC, Decision 12/CP.17, paragraph 9 and Annex). Countries are expected to submit information on data used and how they accounted for national circumstances. Information on data sets, methods, and descriptions of relevant policies and plans should be transparent, complete, consistent, comparable, and accurate[2]. The information provided should allow FREL reconstruction.

3. Allow for a step-wise approach and using sub-national FRELs as an interim measure (Decision 12/CP.17, paragraph 10 and 11). The decisions allow countries to extend their FREL over time from a subnational (e.g. biome) level to cover all forest area in the country. UNFCCC also lets parties improve FRELs over time by including better data and improved methods.

[2] TCCCA-principles

Brazil was the first country to submit a forest reference emissions level (FREL) to the UN Framework Convention for Climate Change. The submission is focused on the Amazônia biome, where Brazil has been collecting rigorous forest cover change data since 1988. The basis for Brazil's submission is the commitments made in the Copenhagen COP-15 Conference to cut deforestation in Amazônia by 80% relative to the average of the period 1996-2005. Brazil is making good this pledge, as deforestation in Amazônia fell from 27,700 km^2 in 2004 to 5,100 km^2 in 2012, decreasing by 82%[3].

[3] Brazil has a reliable information system that provides an annual assessment of gross deforestation for the Legal Amazônia, known as PRODES, which is carried out at the National Institute for Space Research (INPE) from the Ministry of Science, Technology and Innovation (MCTI).

The current Brazilian FREL submission is limited to the Amazônia biome and makes no commitments beyond 2020. Our results take a long term view, so that future reference level submissions can take into account all of Brazilian emissions related to land use. GLOBIOM-Brazil covers the land use of the whole country, and considers internal consumption of land products and the effects of international trade. The scenarios modelled help to identify the trade-offs between using land for agriculture and preserving areas.

Biodiversity policy in Brazil

Brazil is one of the most biodiversity rich countries in the world and has also become a global leader in biodiversity conservation efforts. The Brazilian National Congress ratified the United Nations Conference on Biological Diversity (UNCBD) through a national decree in 1994 that was later turned into a law on biodiversity, soon after the convention first came into force. Together with existing laws relevant to biodiversity conservation, including the Forest Code and the Wildlife Act, these actions set up a National Biodiversity Strategy.

The Brazilian government bases its national biodiversity legislation on the notion of the six biomes occurring in the country. Creating protected areas is the main strategy for biodiversity conservation in all biomes, although there are large differences among biomes in the total area under protection (ranging from 3% of the area of the Pampa to 47% of Amazônia).

In 2013, Brazil released national biodiversity targets for 2020, which build on the UNCBD's Aichi Biodiversity Targets (MMA 2013). These came from the initiative *"Dialogues on Biodiversity: Building the Brazilian Strategy for 2020"*. The targets include:

- reducing the rate of loss of native habitats by at least 50% compared to 2009 rates (Goal 5);
- increasing the coverage of National System of Conservation Units (SNUC) to at least 30% of the Amazônia and 17% of each of the other terrestrial biomes (Goal 11);
- reducing the risk of extinction of threatened species (goal 12);
- increasing the resilience of ecosystems and the contribution of biodiversity to carbon stocks through conservation and recovery actions, including through the recovery of at least 15% of degraded ecosystems (goal 15).

Brazil's INDC submission to COP-21

In October 2015, the Government of Brazil submitted its Intended Nationally Determined Contribution (INDC) to the UNFCCC [Brazil, 2015]. Brazil intends to commit to reduce greenhouse gas emissions by 37% below 2005 levels in 2025, and further reduce emissions by 43% below 2005 levels in 2030[4]. Brazil's current actions are significant, having reduced its emissions by 41% in 2012 in relation to 2005 levels in terms of GWP-100.[5]

Brazil's contribution is consistent with emission levels of 1.3 $GtCO_2e$ (GWP-100) in 2025 and 1.2 $GtCO_2e$ (GWP-100) in 2030, corresponding, respectively, to a reduction of 37% and 43%, based on estimated emission levels of 2.1 GtCO2e (GWP-100) in 2005 [Brazil, 2015].

The country's submission points out that Brazil already has a large biofuel programs and reduced the deforestation rate in the Brazilian Amazonia by 82% between 2004 and 2014. Brazil's energy mix today consists of 40% of renewables (75% of renewables in its electricity supply).

The Brazilian INDC states the country's intended measures:

1. *"increasing the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030, by expanding biofuel consumption, increasing ethanol supply, including by increasing the share of advanced biofuels (second generation), and increasing the share of biodiesel in the diesel mix"*.

[4] By adopting an economy-wide, absolute mitigation target, Brazil will follow a more stringent modality of contribution, compared to its voluntary actions pre-2020.

[5] GWP-100 is a standard IPCC measure of global warming potential of greenhouse gases emissions.

2. *"in land use change and forests:*

    - *strengthening and enforcing the implementation of the Forest Code, at federal, state and municipal levels;*
    - *strengthening policies and measures with a view to achieve, in the Brazilian Amazonia, zero illegal deforestation by 2030 and compensating for greenhouse gas emissions from legal suppression of vegetation by 2030;*
    - *restoring and reforesting 12 million hectares of forests by 2030, for multiple purposes;*
    - *enhancing sustainable native forest management systems, through georeferencing and tracking systems applicable to native forest management, with a view to curbing illegal and unsustainable practices;"*

3. *"in the energy sector, achieving 45% of renewables in the energy mix by 2030, including:*

    - *expanding the use of renewable energy sources other than hydropower in the total energy mix to between 28% and 33% by 2030;*
    - *expanding the use of non-fossil fuel energy sources domestically, increasing the share of renewables (other than hydropower) in the power supply to at least 23% by 2030, including by raising the share of wind, biomass and solar;*
    - *achieving 10% efficiency gains in the electricity sector by 2030."*

4. *"in the agriculture sector, strengthen the Low Carbon Emission Agriculture Program (ABC) as the main strategy for sustainable agriculture development, including by restoring an additional 15 million hectares of degraded pasturelands by 2030 and enhancing 5 million hectares of integrated cropland-livestock-forestry systems (ICLFS) by 2030".*

5. *"in the industry sector, promote new standards of clean technology and further enhance energy efficiency measures and low carbon infrastructure".*

6. *"in the transportation sector, further promote efficiency measures, and improve infrastructure for transport and public transportation in urban areas."*

The GLOBIOM-Brazil scenarios are fully compatible with Brazil's INDC submission. They were defined and implemented with strong interaction with the team from Brazil's Ministry for the Environment that was responsible for drafting the INDC. The results from the Forest Code scenario, reported below, were used by the Brazilian government as part of their work in developing the projections of emissions from land use and land cover change that are part of Brazil's INDC.

The GLOBIOM model and its use in Brazil

GLOBIOM overview

The GLObal BIOsphere Management model (GLOBIOM)[6] is a bottom-up partial equilibrium model focusing on major global land-based sectors i.e. agriculture, forestry and bioenergy. IIASA has been developing the model since 2007 [Havlik et al., 2011], based on work on the ASM-GHG model [Schneider et al., 2007].

[6] More information in the GLOBIOM model is available at the website www.globiom.org.

The main characteristics of GLOBIOM are:

- *Market-equilibrium model*: GLOBIOM is built on the neoclassical theory assumptions.[7] Endogenous adjustments in market prices lead to the equality between supply and demand for each product and region. There is a unique equilibrium, i.e. the agents do not have interest to change their actions once equilibrium is reached.
- *Optimization model*: The aim of the optimization problem is to maximize the sum of the consumers and of the producers' surplus. Prices are not explicit but are given by the dual of the market balance equations.[8]
- *Partial equilibrium model*: GLOBIOM focuses on crops, livestock, forestry and bioenergy, other sectors are not included. The agricultural and forestry sectors are linked in a single model and compete for land.
- *Spatial price equilibrium model*: a specific category of partial equilibrium and linear programming models, which is useful for analysing interregional flows of commodities [Samuelson, 1952][Takayama and Judge, 1971]. The model relies on the homogeneous goods assumption; the price difference between two regions is explained by trade costs only[9]. This allows the model to represent of bilateral trade flows.
- *Recursive-dynamic model*: GLOBIOM runs for periods of 10 years using recursive dynamics. Unlike fully dynamic models, the agents of the economy do not take into account future value of parameters over several periods of time. The optimal decision in period *t* depends on decisions that the agents have taken in the period *t-1*. When each new period starts, the conditions for land use are updated using the solutions of the simulations from the previous period. The model is brought up to date for each time step using exogenous drivers such as GDP and population growth.

[7] Agents make decisions which give them with the greatest benefits As the agents buy or sell more goods, their increments in satisfaction become lower.

[8] The solution satisfies discrete constraints including equalities and inequalities. GLOBIOM includes non-linear functions that are linearised using stepwise approximation [McCarl and Spreen, 2007].

[9] The equilibrium solution is found by the maximisation of total area under the excess demand curve in each region minus the total transportation costs of shipments.

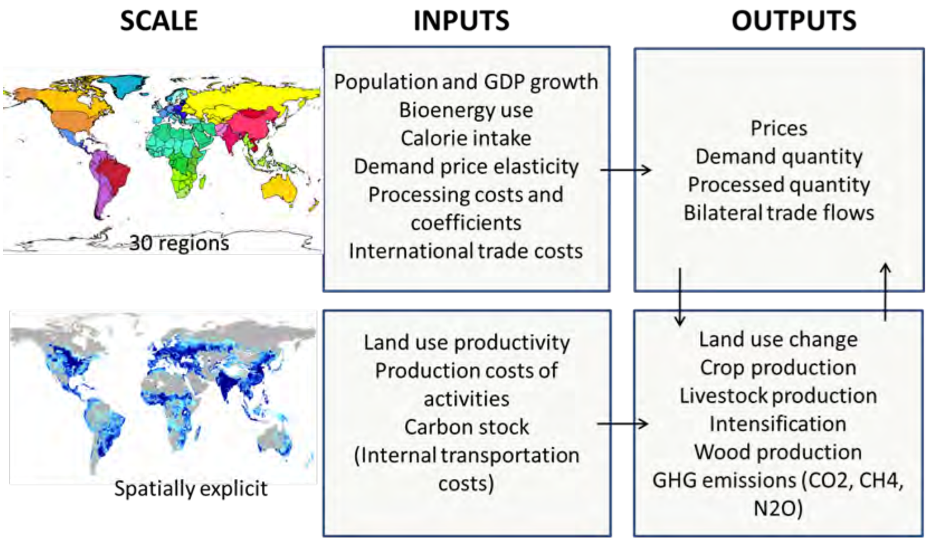


Figure 1: Main inputs and outputs of GLOBIOM at different scales.

The originality of GLOBIOM comes from representing drivers of land use change at two different geographical scales, as shown in Figure 1. Land related variables, such as land use change, crops cultivation, timber production and livestock number, vary according to local conditions. Final demand, processing quantities, prices, and trade are computed at the regional level. In GLOBIOM, regional factors influence how land use is allocated at the local level. Local constraints influence the outcome of the variables defined at the regional level. This ensures full consistency across multiple scales.

The smallest spatial resolution in GLOBIOM is a 5'x 5' cell, whose size is about 10x10 km^2 at the equator[10]. In this spatial scale, the model defines *homogeneous response units* (HRUs). An HRU is a set of 5'x 5' cells that share the same altitude, slope, and soil characteristics. These partitions are defined as possible combinations of five altitude classes, seven slope classes and five soil classes [Skalský et al., 2008]. HRUs define the landscape constraints for the model.

[10] Cell size varies between 100,000 ha on equator to about 10,000 ha in high latitudes.

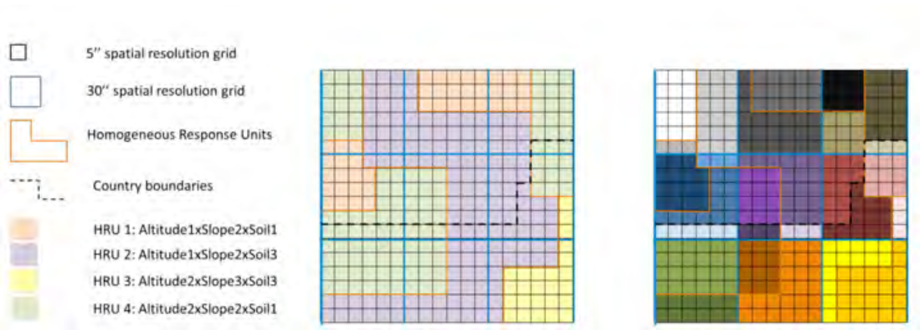


Figure 2: Spatial elements used for the delineation of homogeneous land characteristics (left) and definition of simulation units (right).

The Earth's land area is divided into 212,707 *simulation units*, polygons whose size varies between 5' and 30' spatial resolution grid (Figure 2). These units are the intersection of a 30' x 30' spatial resolution grid, the grid of homogeneous response units (HRU) grid and country boundaries. Simulation units are the spatial basis for the entire GLOBIOM modelling cluster which also includes the biophysical Environmental Policy Integrated Climate (EPIC) model [Williams, 1995] for estimations of agricultural productivity and the G4M forest growth model [Kindermann et al., 2008].

GLOBIOM represents production from cropland, pasture, managed forest and short rotation tree plantations (*'planted forests'*). The model includes 18 crops, 5 forestry products and 6 livestock products (four types of meat, eggs and milk). Livestock production systems cover five different species, based on ILRI/FAO work [Notenbaert et al., 2009][Seré et al., 1995]. Livestock data uses process-based models for ruminants. Data for the monogastrics is based on literature review and expert knowledge. Production types are Leontief-type (i.e. fixed input and output ratios). We account for changes in the technological characteristics of primary product production, allowing multiple production types (ranging from subsistence to intensive agriculture) to be used in the model.

Regional adaptation of the GLOBIOM model

GLOBIOM is a global model which can be used for detailed regional analysis [Mosnier et al., 2014][11]. The bottom-up approach of the database construction for GLOBIOM allows a flexible spatial resolution of the land use activities and a flexible aggregation of countries into regions.

[11] Regional models are easier to validate in countries that have annual agrarian surveys, such as Brazil.

In a regional study, we can better capture the main drivers of local land use change. Specific regional datasets are gathered to replace coarser information from global datasets including national land cover maps, statistics at sub-national level, and regional land use policies. Transportation costs are also calculated across simulation units for each commodity. We list the improvements made to adapt GLOBIOM to GLOBIOM-Brazil in Annex 1.

(a) Simulation units

(b) Municipalities

Figure 3: Simulation units (a) and municipalities (b) of Brazil.

Involving local stakeholders strengthens regional studies. It helps modellers to identify the main shortcomings in their assumptions, and to design scenarios that are more relevant for policy-makers. Working with stakeholders helps to increase their trust in the modelling results and the uptake of these results for policy design.

There are 11,003 simulation units in Brazil (Figure 3(a)). Since many statistics are available at the municipality scale, one of the first tasks has been to compute the intersection of each simulation unit with each municipality (Figure 3(b)). There are 5,565 municipalities in Brazil. One simulation unit can spread over several municipalities and one municipality can spread over several simulation units. The final grid resolution level of the model (during the optimisation) is set to 30' (ca. 250,000 hectares) i.e. the simulation units are aggregated over the HRUs. It gives 3001 spatial units in Brazil where land use and land use change are endogenously computed.

Land cover and land use data sets for Brazil

This section presents the land cover and land use data sets used in the simulations of the GLOBIOM model adapted for Brazil [12]. Since GLOBIOM is sensitive to the quality of the input data, a good land use and land cover map is essential for using the model. The challenge faced by land use modellers in Brazil is the lack of adequate maps. While crop area from different data sources in Brazil are consistent, there are large differences in estimates of forest and pasture areas. To produce a consistent land cover-land use map for Brazil, we combined information from different sources.

[12] The datasets are available for download as a web feature service (WFS) on the REDD-PAC website `http://www.redd-pac.org`. A separate technical document describes the data available in the WFS.

In our work, we used data sets produced by NASA and by the following Brazilian public institutions and NGOs, whom we thank for providing the date: *EMBRAPA (Brazilian Agricultural Research Corporation), FUNAI (Brazilian National Indian Foundation), IBGE (Brazilian Institute for Geography and Statistics), INPE (Brazilian National Institute for Space Research), MMA (Federal Ministry for the Environment), SOS Mata Atlântica*, and *UFMG/CSR (Centre for Remote Sensing, Federal University of Minas Gerais).*

The major biomes of Brazil

Land use and land cover data in Brazil are organized according to the country's six major terrestrial biomes (Figure 4): Amazônia (mainly tropical rain forest), Cerrado (tropical savanna), Caatinga (semi-arid deciduous shrubland and semi-deciduous dry forests), Mata Atlântica (tropical and subtropical forest, much depleted), Pantanal (extensive wetlands) and Pampa (mainly natural grassland). Each of these biomes has unique inter-annual and seasonal variability, presenting unique challenges for mapping land cover and land use.

The Brazilian Amazon forest covers an area of 4 million km^2. Most of the native vegetation is moist evergreen dense forest, supported by the region's significant rainfall. Due to the intense human occupation in the last decades, about 17% of the original forest has been removed. Annual deforestation rates increased from 2001 to 2004 from 18,165 km^2 to 27,970 km^2. Since 2005, deforestation rates dropped to low values; in 2014, the estimated rate was

5,200 km^2. These lower rates are associated with control actions conducted by the Brazilian government, including law enforcement and creation of protected areas.

The Cerrado is the second biggest Brazilian biome and encompasses about 2 million km^2, or about 25% of the country's land area. Its main habitat types include: forest savanna, wooded savanna, park savanna and mixed grass and woody savanna. In the past 35 years, more than half of the Cerrado's original area has been converted to agriculture. It is estimated that only about 1,000,000 km^2, or 50% of the original vegetation, remains intact today [MMA/Brazil].

Figure 4: The six biomes of Brazil.

The Caatinga biome covers over 800,000 km^2 and makes up around 10% of the Brazilian landmass. It is a mosaic of scrub vegetation and patches of dry forest. It is best described as seasonally dry tropical forest, since its flora (shrubs and trees) consists of dry forest species rather than savanna species [Santos et al., 2011]. Over 50% of the trees lose their leaves in the dry season. Scrub vegetation is dominated by *Cactaceae* and *Bromeliaceae* species. The predominant Caatinga landscapes are flattened depressions (300-500 metres), with a rainfall regime ranging from 240 to 900 mm/year and a 7-11-mo dry season.

The Brazilian Mata Atlântica had an original area of 1,482,000 km^2, covering 17% of Brazil. Mata Atlântica has a range of forest formations including dense rain forest, open and mixed semi-deciduous and deciduous forests. This forest is distributed over various topographic and climatic zones and regions, ranging from sea level to 2,700 m in altitude. Since Mata Atlântica is in the most densely populated areas in Brazil, it has been badly degraded. Only 12% (157,000 km^2) of the original forest remains [Ribeiro et al., 2009].

The Pantanal is a large continuous wetland, covering about 140,000 km^2 of lowlands in the upper Paraguai river basin. There is a great variety of flora and fauna, controlled by an annual flooding pulse with amplitude from 2 to 5 metres and duration of 3 to 6 months. Despite including a UNESCO a World Heritage Site, the biome is also an area of extensive cattle ranching; it is estimated that more than 40% of its forests and savannas have been altered by the introduction of exotic grass species for cattle ranching [Harris et al., 2005].

The Pampa is in the South of Brazil, occupying an area of 63% of the state of Rio Grande do Sul, within the South Temperate Zone. The vegetation is made of natural grasslands, with sparse shrub and tree formations. Livestock production (cattle and sheep) is the main economic activity. The soils of the Pampa are fragile and intense human use has led to soil degradation in many areas [Roesch et al., 2009].

Each biome poses unique challenges for mapping land use and land cover. Arguably, biomes with stable cover (Amazonia and Pampa) are easier to map from remote sensing data than those with large seasonal differences, such as Cerrado and Caatinga. In particular, mapping the Cerrado presents major challenges. There are large differences between land cover maps of the Cerrado, since it is hard to distinguish planted pasture from shrublands and sparsely wooded savannas. Two recent surveys, both based on remote sensing, are revealing. IBGE estimated an area of 40 Mha of cultivated pastures in the Cerrado in 2012. By contrast, EMBRAPA and INPE measured 60 Mha of pasture for the same year. These differences stem from the independent definitions of 'pasture', 'natural pasture', and 'cultivated pasture' used in the studies. Much work remains to be done to get a consensus on the land cover classes that can be mapped using remote sensing in the Cerrado. Given these uncertainties, we derived a novel land use and land cover map for Brazil combining remote sensing data with statistical information from IBGE surveys, described in the next section.

IBGE vegetation map

The IBGE vegetation map [IBGE, 2012] describes the original (i.e., before recent human occupation) vegetation classes in Brazil, as of 2000 (Figure 5). It is focused on the natural vegetation areas; areas with human presence and land use are not classified in detail. Despite its coarse scale (1:5,000.000), the map is a good guide for describing the native vegetation land cover types. It is used by the Brazilian Government as the basis for the Forest Reference Emission Level report submitted to UNFCCC for REDD+ results-based payments.

The IBGE vegetation map distinguishes 52 vegetation classes and includes the original composition of the following native forest formations and associated ecosystems. Forest classes are split into ombrophilous (dense, mixed and open) and deciduous. The authors distinguish different types of savannas, including woody, open, and steppe-like. There are also contact classes, where different types of forests coexist and also savannas with forests.

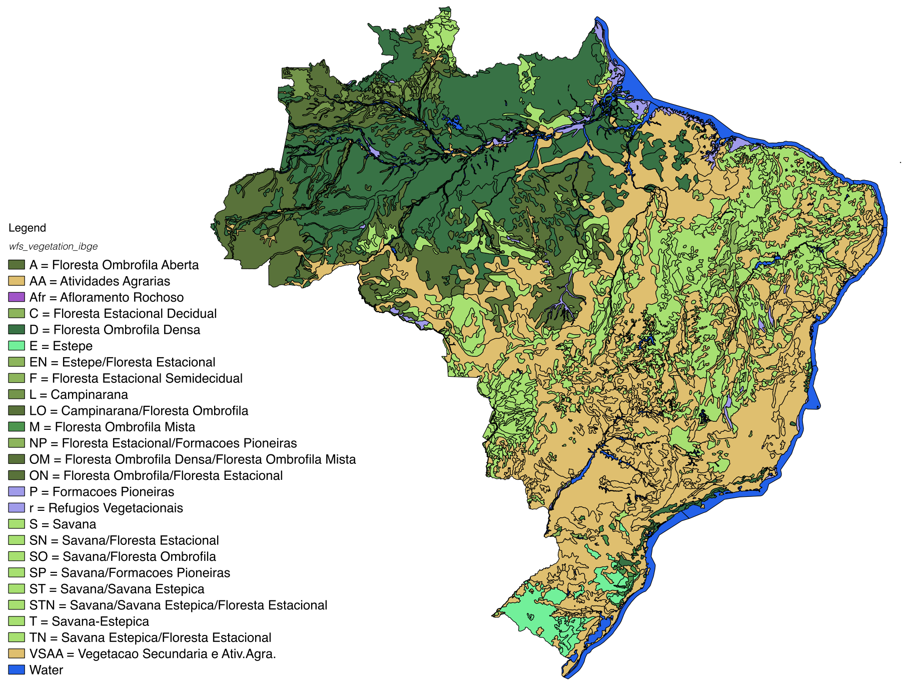
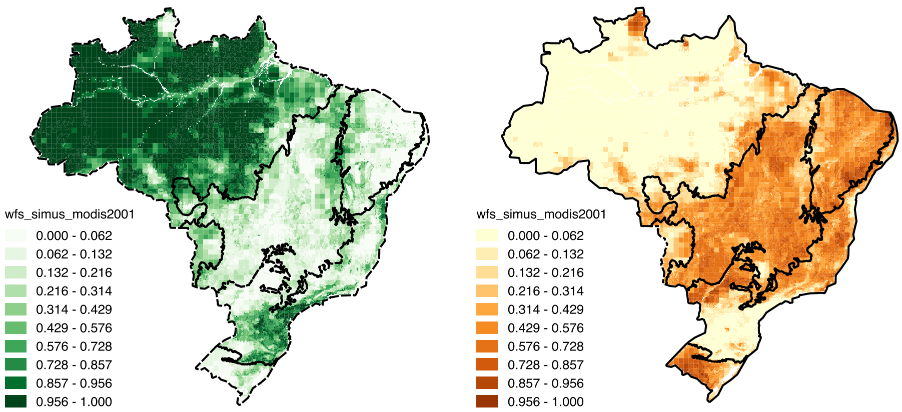


Figure 5: IBGE vegetation map.

MODIS land cover map

Derived from remote sensing, the MODIS land cover product provides information about the current state and seasonal-to-decadal scale dynamics of global land cover. It describes land cover properties derived from observations spanning a year's input of MODIS data [Friedl et al., 2010]. Its main land classification scheme has 17 land cover classes defined by the International Geosphere Biosphere Programme (IGBP). There are 11 natural vegetation classes, 3 developed and mosaicked land classes, and 3 non-vegetated land classes (Figure 6).



(a) (b)

Figure 6: Proportions of forest (a) and grassland (b) per simulation unit, derived from the MODIS land cover map for year 2001.

Designers of the MODIS land cover map recognise that spectral–temporal separability of many classes is ambiguous. There is inherent confusion between *'savannas'*, *'woody savannas'* and *'grasslands'*. Inclusion of mixture classes creates problems (e.g., *'agricultural mosaic'*, *'mixed forests'*). These ambiguities are inherent to remote sensing data, given the limitations of spatial resolution of the MODIS sensor.

IBGE Agricultural census and yearly crop and cattle surveys

We used three data sets from IBGE: the 2006 Agricultural Census, the yearly Municipal Crop Production survey (PAM) from 2000 to 2010, and the yearly Municipal Livestock Production survey (PPM) from 2000 to 2010. The PAM survey provides the information on planted area, harvested area, amount produced, average yield and production value of permanent and temporary crops by municipality. The PPM survey has information on herd inventories, quantity and value of animal products, and the number of milked cows and sheared sheep by municipality. The 2006 Agricultural Census provides data on the number of establishments, land use, characteristics of the establishment, livestock heads, vegetable and animal production.

The Census is a reliable source of information in the south, northeast and southeast regions of Brazil. There is much underreporting in the Amazônia biome, arguably caused by land tenure issues, and much uncertainty on pasture areas in the Cerrado. Consider the case of the 15 municipalities in Amazônia with the largest deforestation area in 2006. Table 1 shows the deforestation measured by INPE compared with the agricultural area reported in 2006 Agricultural Census. For each municipality, the deforested area is much greater than the census agricultural area. Since much land used for cattle raising in Amazônia does not have proper property rights, farmers omit information about them.

Municipality	Area (km^2)	PRODES (km^2)	Census (km^2)	Diff (%)
São Felix do Xingu (PA)	84249	14550	10185	75%
Paragominas (PA)	19452	8256	1920	330%
Marabá (PA)	15127	7495	3062	145%
Juara (MT)	21430	7290	4816	51%
Porto Velho (RO)	34636	6909	1951	254%
Santana do Araguaia (PA)	11607	6589	5143	28%
Cumaru do Norte (PA)	17106	6475	3335	94%
Santa Luzia (MA)	6193	5545	2003	177%
Altamira (PA)	159701	5517	3689	70%
S.M. das Barreiras (PA)	10350	5491	5496	0%
Novo Repartimento (PA)	15433	5433	2311	135%
Tapurah (MT)	11610	5392	1086	397%
Rondon do Para (PA)	8286	5191	2753	89%
Acailandia (MA)	5844	5149	3882	33%

Table 1: Comparison between 2006 Agricultural census data and 2006 PRODES data for selected municipalities in Amazônia.

Protected areas, public forests and indigenous lands

There are two types of environmental protection areas in Brazil: areas of full protection and those of sustainable use. The full protection group has five types: *'ecological station'*, *'biological reserve'*, *'national park'*, *'natural monument'*, and *'wildlife refuge'*.

The sustainable use group includes: *'environmental protection area'*, *'area of relevant ecological interest'*, *'national forest'*, *'extractive reserve'*, *'wildlife reserve'*, *'private natural heritage reserve'* and *'sustainable development reserve'*. Figure 7 maps the protected areas in Brazil.

Figure 7: Protected areas in Brazil including Federal, State and Municipal conservation units and Indigenous Lands (in yellow), superposed onto the Brazilian biomes.

'Ecological stations' aims to preserve nature and to support scientific research[13]. Public visitation is prohibited, except for educational purposes. *'Biological reserves'* protect the biota inside its boundaries, without human interference or environmental modifications. *'National parks'* are areas of ecological relevance and scenic beauty, fit for scientific research and ecological tourism. *'Natural monuments'* protect rare natural sites, both singular or of great scenic beauty. *'Wildlife refuges'* protect natural environments of resident or migratory fauna.

[13] The description of protected areas in Brazil is based on the documentation available on the site of the Instituto Socioambiental

'Environmental protection areas' (APA) are relevant for environmental protection, allowing limited human occupation. An APA protects biological diversity and controls occupation, ensuring a sustainable use of natural resources. *'Areas of relevant ecological interest'* are small extensions that shelter rare examples of biota with little or no human occupation. *'National forests'* have forest cover of predominantly native species, and are open to sustainable use and to scientific research. *'Extractive reserves'* are used by traditional extractive populations. *'Sustainable development reserves'* shelter traditional populations, whose existence is based on sustainable exploitation of natural resources.

Brazil has 698 indigenous lands in Brazil, with a total extension of 1,135,975 km^2 covering about 13% of the country's land area. Brazil's Constitution defines indigenous lands as those destined to native peoples, being *"indispensable to preseve the environmental resources necessary for their well-being and necessary for their physical and cultural reproduction"*.

Conservation Units in Amazônia cover 1,223,882 km^2, which is 29% of the area of the Amazônia biome (4,196,943 km^2). Recent studies [Soares-Filho et al., 2010] have shown that in the Brazilian Amazônia all protection regimes helped reduce deforestation. The total accumulated deforestation in the forest areas of these units until 2009 is 13,249 km^2 that is 1.47% of their extent.

Mata Atlântica forest remnants

The NGO "SOS Mata Atlântica" and INPE carry out regular mapping surveys and produce the Atlas of Mata Atlântica Remnants (Figure 8). The study covers the situation of the Atlantic Forest in 3,284 municipalities in 17 states. It includes data on Protected Areas, watersheds and priority areas. This data is available on the internet and is included in the GLOBIOM-Brazil database.

Figure 8: Remnants of forest cover in Mata Atlântica.

PRODES forest non-forest cover map for Amazônia

Since 1988, INPE monitors the deforestation in Amazônia with the PRODES system. PRODES uses remote sensing to get yearly data on the location and extent of the deforestation in the Legal Amazônia. The Brazilian government officially designates Legal Amazônia as an area of 5,016,136 km^2 that includes all seven states of the North Region (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins), as well as part of Mato Grosso in the Center-West Region and most of Maranhão in the Northeast Region. For a map of Legal Amazônia, see Figure 9. The scientific community takes PRODES to be the standard reference for ground truth in Amazônia deforestation. All PRODES data, methods, maps and statistics are available on the web. The PRODES data set is used in the GLOBIOM-Brazil model for validating the GLOBIOM estimates for deforestation in Amazônia for the period 2001-2010.

Figure 9: The Legal Amazônia area in Brazil (blue). Legal Amazônia comprises the whole Amazônia biome and parts of Cerrado and Pantanal.

The reference land cover and land use map for Brazil in 2000

To create one single composite land cover and land use map for Brazil fit for GLOBIOM modelling, we combined data from various sources. We first produce an input land cover map from the IBGE vegetation map. In the Legal Amazônia, we used the MODIS land cover data to improve the IBGE map. We also used data from SOS Mata Atlântica to refine the forest information for this biome. We then disaggregated the IBGE land use data to the simulation unit scale. We combined this data with the land cover information to produce the final map (Figure 10).

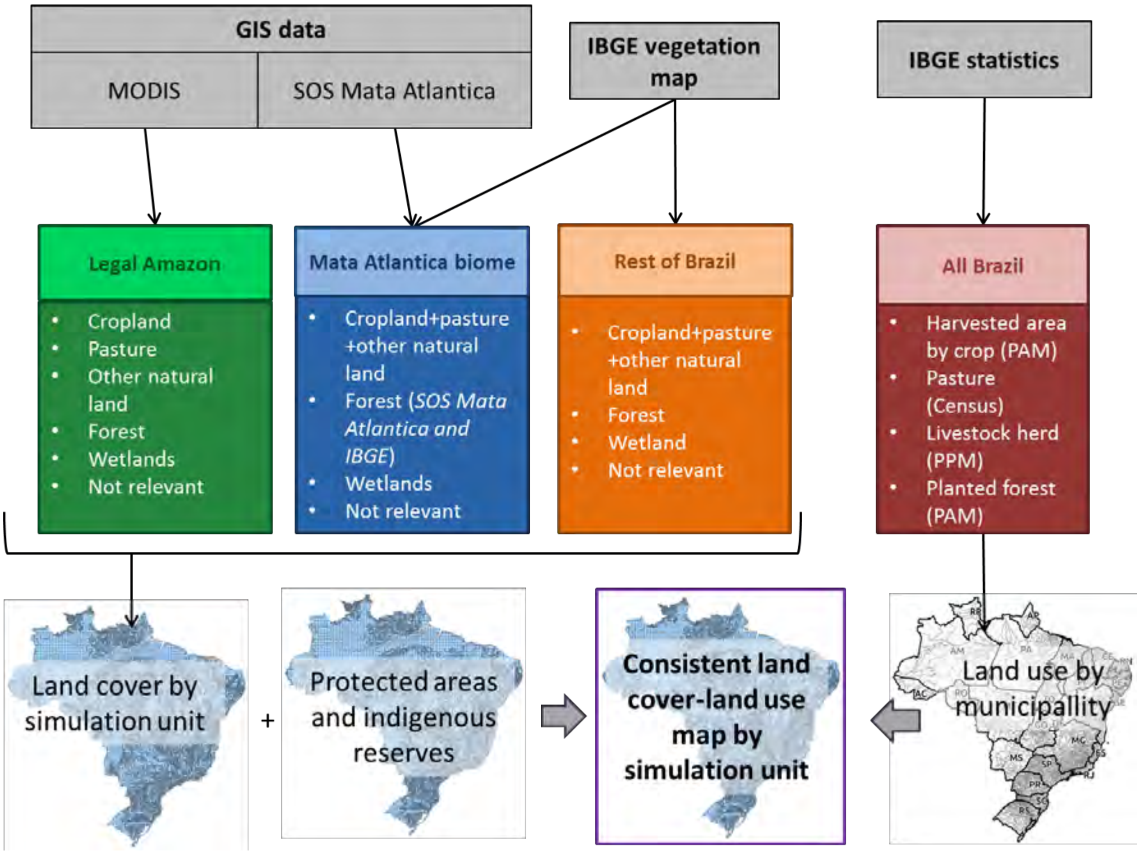


Figure 10: Creating a consistent land cover-land use map for Brazil.

GLOBIOM land cover class	IGBP land cover class	IBGE vegetation class
Cropland, Pasture, or Natural Land	Cropland/Natural Vegetation mosaic Croplands or pasture Grassland - Pasture	Vegetação Secundária e Atividades Agrárias Atividades Agrárias Estepe Arborizada Estepe Gramíneo-Lenhosa Estepe Parque Estepe/Floresta Estacional
Forest	Deciduous Broadleaf Forest	Floresta Estacional Decidual Montana Floresta Estacional Decidual Submontana Floresta Estacional Decidual Terras Baixas Floresta Estacional Semidecidual Aluvial Floresta Estacional Semidecidual Montana Floresta Estacional Semidecidual Submontana Floresta Estacional Semidecidual Terras Baixas Floresta Estacional/Formações Pioneiras Savana Estépica/Floresta Estacional Savana-Estépica Arborizada Savana-Estépica Florestada
	Evergreen Broadleaf Forest	Campinarana Arborizada Campinarana Florestada Campinarana/Floresta Ombrofila Floresta Ombrófila Aberta Aluvial Floresta Ombrófila Aberta Submontana Floresta Ombrófila Aberta Terras Baixas Floresta Ombrófila Densa Aluvial Floresta Ombrófila Densa Montana Floresta Ombrófila Densa Submontana Floresta Ombrófila Densa Terras Baixas Floresta Ombrófila Densa/Floresta Ombrófila Mista Floresta Ombrófila Mista Alto-Montana Floresta Ombrófila Mista Montana Floresta Ombrófila/Floresta Estacional
	Woody savannas	Savana Arborizada Savana Florestada Savana/Floresta Estacional Savana/Floresta Ombrófila
Not Relevant	Barren or sparsely vegetated	Afloramento Rochoso Refúgios Vegetacionais Alto-Montano Refúgios Vegetacionais Montano
	Water	Coastal water mass Continental water mass
Natural Land	Closed Shrublands Open Shrublands	Campinarana Arbustiva Campinarana Gramíneo-Lenhosa Savana-Estépica Gramíneo-Lenhosa Savana-Estépica Parque
	Savannas	Savana Gramíneo-Lenhosa Savana Parque Savana/Formações Pioneiras Savana/Savana Estépica Savana/Savana Estépica/Floresta Estacional
Wetlands	Permanent wetlands	Vegetação com Influência Fluvial e/ou Lacustre Vegetação com Influência Fluvio-marinha Vegetação com Influência Marinha

Table 2: Mapping between GLOBIOM, IGBP and IBGE land cover classes.

GLOBIOM land use and land cover classes

GLOBIOM is a global model that aims to capture the most important causes of land use change. Its land cover and land use classes balance the need for detailed information on land use and the availability of global data sets. This balance led its designers to define the following classes:

- *Mature forest*: this class covers all unmanaged forests which could be either primary or secondary forests. Both the evergreen rain forest of Amazônia and the deciduous forests of the Caatinga are included in this class.
- *Managed forest*: these are forests that are exploited in a sustainable way. In Brazil, managed forests are those included in the National Plan for Management of Public Forests, which is administered by the Brazilian Forest Service.
- *Planted forest*: these are short-rotation plantations, with single or few species and uniform planting density, that are used by the wood and paper industries. Brazil has a significant number of planted forests with pinus and eucalyptus species, most located in the Mata Atlântica.
- *Natural land*: areas of non-forests natural vegetation, such as shrublands, sparsely wooded savannas and natural grasslands.
- *Cropland*: areas planted with one of the 18 GLOBIOM crops. The crops covered in GLOBIOM are barley, dry beans, cassava, chick peas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, wheat, and oil palm.
- *Other Agricultural Land*: areas planted with crops not modelled by GLOBIOM. In Brazil, these include for instance coffee and fruit trees.
- *Pasture*: areas with natural or man-made pasture used for livestock ranging. Pastures make up the largest areas of land use in Brazil.
- *Wetlands*: areas with permanent water cover, or areas that are regularly flooded. In Brazil, most of the Pantanal is considered to be part of this class. However, since there is a large cattle herd in the Pantanal, part of the Pantanal is classified in GLOBIOM as pasture.

Mapping IBGE vegetation classes to GLOBIOM classes

The IBGE vegetation map (see Figure 5) is the basis for the GLOBIOM input land cover map outside Legal Amazônia. The IBGE map derives from expert knowledge, field visits and remote sensing. This is relevant in areas where seasonal variability makes it harder for vegetation types to be distinguished using pure remote sensing, for example the Caatinga biome.

The IBGE map distinguishes 52 vegetation classes and corresponds to years 2001 and 2002, which are close to the GLOBIOM base year 2000. We aggregated these vegetation classes into land cover classes that are related to GLOBIOM (see Table 2 and Figure 11). We created a buffer class (*'crop, pasture or natural land'*) that includes all areas in the IBGE map that have agricultural use. After creating the land cover map, areas in this buffer class are broken into *'crop'*, *'other agricultural land'*, *'pasture'* and *'natural land'*, using IBGE survey and census data.

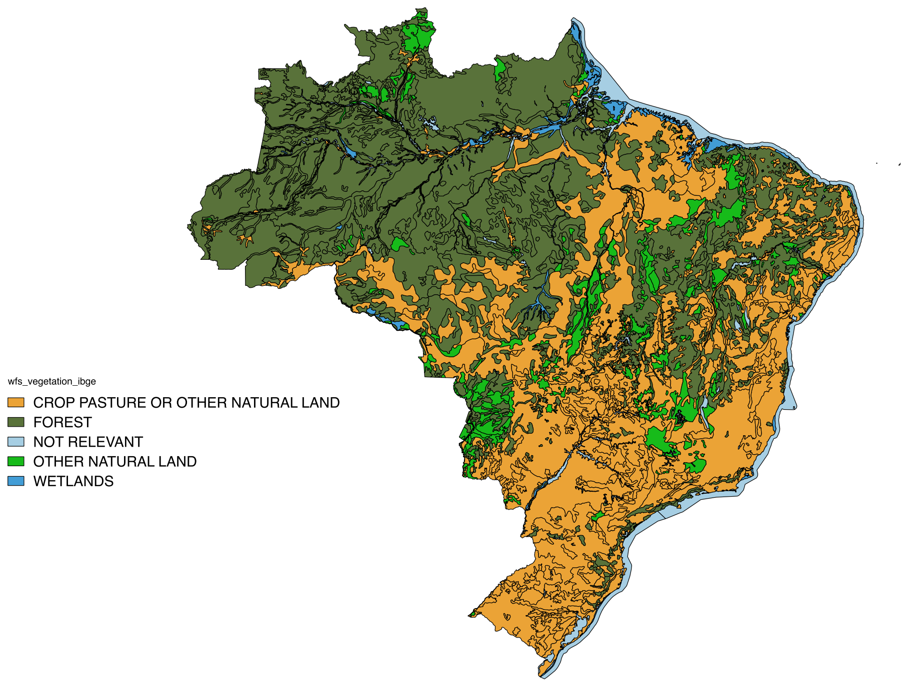


Figure 11: IBGE land cover map reclassified in GLOBIOM classes.

We labelled all IBGE classes named as *'forest'* in the Brazilian FREL submission to UNFCCC as *'forest'* in GLOBIOM. Steppe classes (*'estepe'*) were labeled as *'crop, pasture or natural land'*, since they are likely to include natural pastures as well as unused natural grasslands. IBGE classes associated to shrublands (*'arbustiva'*, *'gramíneo-lenhosa'*) and to non-forested savannas correspond to *'natural land'* in GLOBIOM. Classes associated with barren land and closed water areas are considered to be *'not relevant'* in GLOBIOM. Areas classified by IBGE as *'anthropic areas'* got the label *'crop, pasture or natural land'*, since IBGE does not distinguish between croplands and area used for cattle pasture.

Mapping MODIS land cover to GLOBIOM classes

Given the coarse spatial scale (1:5,000,000) of the IBGE vegetation map, small patches of pasture or crops are not mapped in Amazônia. On the other hand, remote sensing data from MODIS is good in tropical forest areas, where the tree cover is permanent and forest removal is easily identifiable. For this reason, we used satellite-based MODIS land cover data in Legal Amazônia instead of the IBGE vegetation map.

Furthermore, data provided by IBGE census on pasture is not reliable in the Legal Amazônia, where cattle raising is associated with expanding frontiers. MODIS provides pasture area for every year, so no extrapolation of census data is necessary. Using MODIS data thus avoids imprecisions associated with the census in Amazônia. The mapping between the MODIS classes and the GLOBIOM classes is shown in Table 3.

MODIS Land Cover (IGBP classes)	Preliminary GLOBIOM class
Evergreen Needleleaf Forest	Forest
Evergreen Broadleaf Forest	Forest
Deciduous Needleleaf Forest	Forest
Deciduous Broadleaf Forest	Forest
Mixed Forest	Forest
Closed Shrublands	Natural Land
Open Shrublands	Natural Land
Woody Savannas	Forest
Savannas	Natural Land
Grasslands	Crop, Pasture or Natural Land
Permanent Wetlands	Wetlands
Croplands	Crop, Pasture or Natural Land
Urban and built-up	Not Relevant
Cropland/Natural vegetation mosaic	Crop, Pasture or Natural Land
Water	Not Relevant
Snow and Ice	Not Relevant
Barren or Sparsely Vegetated	Not Relevant

Table 3: Mapping between MODIS land cover data and GLOBIOM land cover classes.

Improving forest data in Mata Atlântica biome

The IBGE vegetation map underestimates the forest in the (*Mata Atlântica*), which used to have substantial forest cover. Only small patches of remnants are left, which the IBGE vegetation map does not capture well. We used the detailed map of forest remnants from SOS Mata Atlântica to improve the land cover map. Most of the forest patches are located in areas that are classed by IBGE as agrarian. Compared to the IBGE map, the area of GLOBIOM *'forest'* class increased.

Managed and planted forests

For the *'managed forest'* class, we used information from the Brazilian National Forest Service on forest areas under federal concession. Under the Public Forest Concession Law, national forests can be opened for sustainable exploration under SFB's supervision. This exploration model ensures that only a few trees can be felled each year, and that protected species are preserved. Remote sensing surveys from INPE point out that forest concessions have a limited impact on forest area depletion. GLOBIOM-Brazil deals with managed forests in the same way as protected forests. They are set aside and cannot be converted to crop or pasture lands.

Representation of planted forests in GLOBIOM-Brazil uses information provided by IBGE Agricultural Census of 2006. These short rotation plantations are located mostly on the Mata Atlântica biome and make up 7.65 Mha in 2010. The Brazilian government plans to increase silviculture as one of its strategies for emission mitigation on forestry. In the future works, we plan to develop different scenarios of green incentives for silviculture. In the current version, planted forest are driven by market forces.

Protected areas

Protected areas in a broad sense (including indigenous lands, sustainable use areas, and public forests) cover large parts of Brazil. Data on protected areas combines three inputs. MMA provides information about 1,158 conservation areas in its Conservation Units dataset, and FUNAI maps the indigenous areas. The map of public forests from SFB includes areas of forest concessions, under the Public Forest Concession Law. These areas are taken as restrictions in the GLOBIOM scenarios; crops and pasture cannot be put there.

The maps for protected areas, indigenous lands, public forests, and sustainable use areas correspond to year 2013, more than a decade after the GLOBIOM base year 2000. Analysts from MMA informed us that one of the criteria for selecting new protected areas is where there is no consolidated crop or animal production. According to this premise, if a protected area was created in 2013, for example, it is expected that there was no crop or pasture production in that area before. In cases where there were farms established in the area, they are mostly forced out, as in the case of he Raposa Serra do Sol reservation[14]. Therefore, it makes sense to consider the protected areas created after 2000 when allocating crop or pasture into simulation units for 2000.

[14] for a presentation of the Raposa Serra do Sol case, from the native peoples perspective, please see http://www.survivalinternational.org/tribes/raposa

Wetlands

Representation of wetlands in GLOBIOM derives from areas in the MODIS land cover map and in the IBGE vegetation map that are under strong marine or fluvial influence. These areas include the flooded forests in the lower part of the Amazonas river, large parts of the Amazonas river delta, and parts of the Pantanal biomes. These areas are fixed in the model. There are no crops or livestock area there and there will be no expansion of agricultural activities in the future.

Preliminary land cover map

The MODIS vegetation map (inside Legal Amazônia), the combined IBGE-SOSMA vegetation map (outside Legal Amazônia) and the protected areas map were merged into the preliminary land cover map, that includes the classes: *'forest'*, *'natural land'*, *'crop, pasture, or natural land'* (which covers all area that is influenced by human use), *'wetlands'* and *'not relevant'*.

We then made additional corrections to the preliminary land cover map. All *'crop, pasture, or natural land'* areas in protected areas were moved to class *'natural land'*. We then corrected the IBGE classification for Pantanal. In the IBGE vegetation map, the Pantanal is considered as a pristine biome, divided in classes *'forest'* or *'natural land'*. However, there is much animal production in the Pantanal, as the areas of natural land are used as pasture for cattle. Thus, we moved the areas that IBGE consider as natural vegetation in the Pantanal to the mixed class called *'crop, pasture and natural land'*. In this way, these areas can be associated to pasture, based on livestock data from the PPM and allocated using the algorithm described in the next section.

Table 4 presents the total areas for each GLOBIOM-compatible class, including areas inside and outside protected areas. After producing the preliminary land cover map, we then distributed it into the GLOBIOM simulation units, by computing the intersection between the simulation units and the land cover map.

Aggregated GLOBIOM classes	Total Area (kha)
CROP PASTURE OR NATURAL LAND	362,083
Inside Protected Areas	26,034
Outside Protected Areas	336,049
FOREST	464,436
Inside Protected Areas	215,872
Outside Protected Areas	248,564
NOT RELEVANT	8,929
Inside Protected Areas	1,403
Outside Protected Areas	7,527
WETLANDS	3,886
Inside Protected Areas	1,308
Outside Protected Areas	2,578
Total	839,335

Table 4: Areas of classes of the GLOBIOM preliminary land cover map.

To allocate specific land use activities in the aggregated class *'crop, pasture and natural land'*, we merge the land cover map at the simulation unit scale with IBGE information on agriculture and animal production. When we exclude the protected areas, indigenous lands, public forests, and areas for sustainable use, the area for *'crop, pasture, or natural land'* is 336.049 million hectares. This is the amount of land available in the simulation units for crops and pasture. Since IBGE data is available at the municipality scale, we use an algorithm that assigns agriculture and livestock data into simulation units, considering protected areas.

Allocation of pasture area by simulation unit

We used data from Gasques et al. [2012] to estimate pasture area per municipality for the year 2000, except for Legal Amazônia[15]. Since the 2006 IBGE census under-reports pasture area in Legal Amazônia (see Table 1), we used MODIS grassland area estimates to a proxy for pasture area in this region.

[15] Gasques et al. [2012] used data from the IBGE 2006 census and from the PPM.

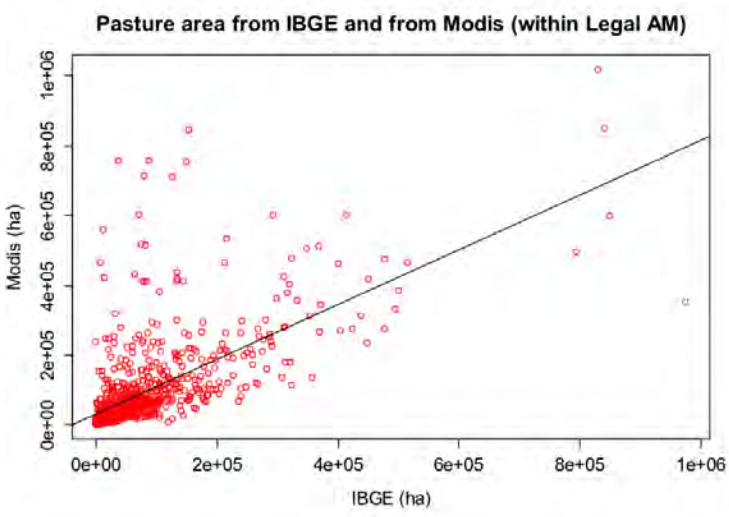


Figure 12: Comparison of pasture area IBGE Census and from MODIS inside Legal Amazônia.

Figure 12 compares grassland area from MODIS and pasture area from IBGE 2006 census inside Legal Amazônia. The coefficient of correlation is 66%. Figure 13 compares grassland area estimates from MODIS and pasture area from IBGE for municipalities outside Legal Amazônia. The correlation coefficient is higher (83%). In both cases, differences increase for larger municipalities; for large properties covering more than one municipality, IBGE assigns all production to only one municipality.

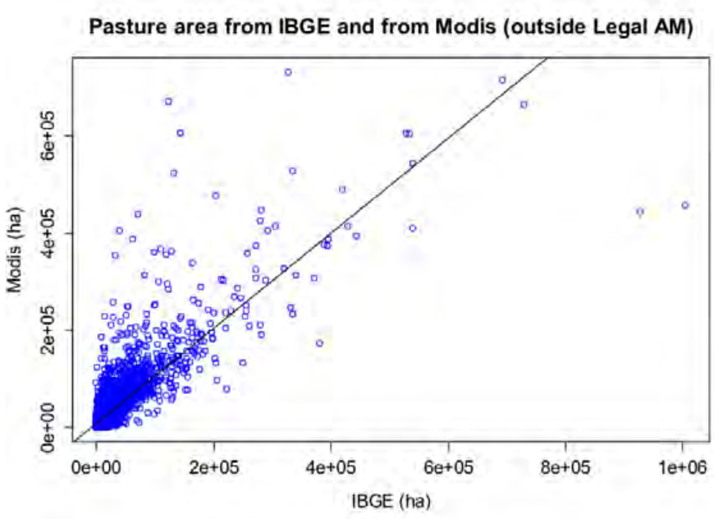


Figure 13: Comparison of pasture area IBGE Census and from MODIS outside Legal Amazônia.

We compared our estimates of pasture area in the municipalities in 2000, based on the PPM, with estimates of pasture derived from the IBGE 2006 agricultural census (outside Legal Amazônia) and grassland data from MODIS (inside Legal Amazônia). Inside Legal Amazônia, all municipalities with animal production according to PPM also had grassland area according to MODIS. Out of the 4,794 Brazilian municipalities outside Legal Amazônia, only 28 municipalities had animal production on the PPM, but no pasture area in the 2006 Census. These mismatches as inevitable, given that the PPM is a survey.

To avoid inconsistencies, we assigned pasture areas to the 28 municipalities outside Legal Amazônia that had cattle according to PPM but no pasture according to IBGE, based on an average estimate of Tropical Livestock Units (TLU) per hectare.[16] Therefore, the additional pasture area assigned to municipality k is simply the total TLU for municipality k, according to PPM, divided by the average TLU/ha for the state in which municipality k is located.

[16] Tropical Livestock Units (TLU) correspond to a measure of livestock production, which tries to harmonize production from different types of livestock. For example, 100 heads of cattle correspond to 70 TLUs.

IBGE Cropland and planted forest data

The data for crops is taken from IBGE's PAM (Municipality Crop Production Survey). GLOBIOM handles 18 individual crop in its land cover class *'cropland'*. They make up 86% of the total cultivated area in Brazil in 2000. The other crops cover 7 million hectares in 2000; they are assigned to the *'other agricultural land'* class (Figure 14). For planted forests, we used the numbers per municipality from the IBGE Agriculture Census 2006. Planted forests were not distinguished by species.

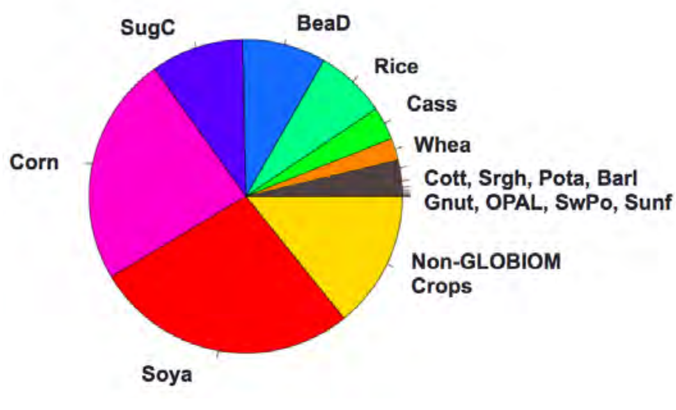


Figure 14: Division by crop of total cultivated area in Brazil in 2000 according to IBGE PAM data.

The agricultural production area reported for 187 municipalities is bigger than the municipality area itself (see Figure 15). In most of these, the reported production area is up to 1.7 times larger than the total area; in extreme cases, it is even 23 times as large. Possible reasons include large farms with area in various adjacent municipalities but is registered in one municipality. The municipality reported in the agricultural census or in one of the annual surveys (PPM, PAM) is the municipality where the main house is located. Other reasons may be intentional or unintentional misreporting. We corrected these problems using an optimisation algorithm, described in the next section.

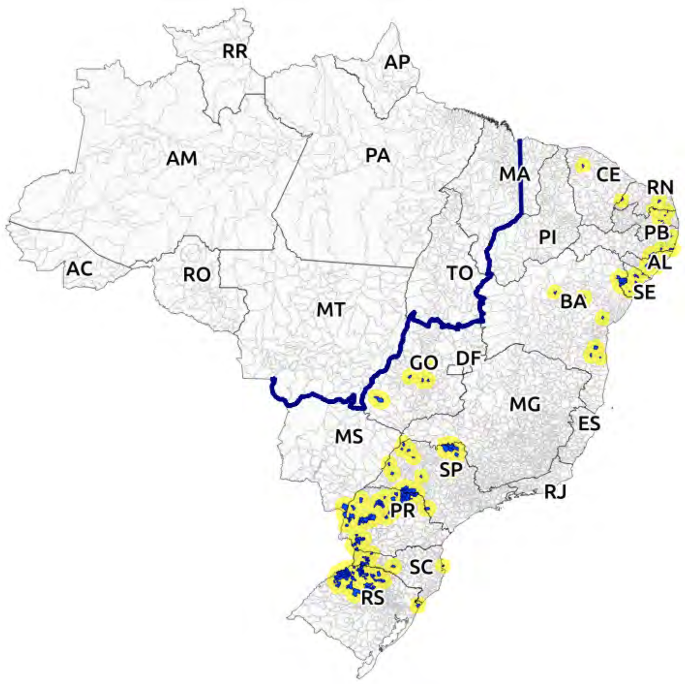


Figure 15: Municipalities with more agricultural production area reported in the PAM than total available area. The blue line shows the limit of Legal Amazônia.

Allocating crop and livestock data to simulation units

We now describe the method used to allocate crop, pasture and planted forest data into simulation units. The estimated productive area is 236 Mha. We need to distribute this area in the 336 Mha of available land from the *'crop, pasture and natural land'* class in the GLOBIOM simulation units. Our procedure addresses inconsistencies in IBGE data when converting municipality-scale data to GLOBIOM simulation units. Our aim to have an optimised and consistent assignment of productive area to simulation units.

The algorithm splits the production area of a municipality to all simulation units that intersect with it, considering the size of the overlap. A simulation unit that makes up 10% of a municipality receives 10% of its productive area – unless it does not have enough available land. The excess production area is put into neighbouring simulation units, with preference given to nearby simulation units that also overlap with the same municipality.

The algorithm tries to find the best possible assignment, using known constraints. Let $m(i)$ be the production area for municipality i. Our goal is to distribute $m(i)$ into simulation units. We have to find values $x(i,j)$ corresponding to the production area in municipality i, assigned to simulation unit j, such that $\sum_j x(i,j) = m(i)$, for all municipalities $i = 1,\ldots,N$.

Let $\delta_{i,j}$ be the share of municipality i inside simulation unit j, and $\gamma_{i,j}$ the share of simulation unit j inside municipality i. If municipality i and simulation unit j coincide, then $\delta_{i,j} = \gamma_{i,j} = 1$. In general, we have $0 \leq \delta_{i,j}, \gamma_{i,j} \leq 1$, and $\sum_i \delta_{i,j} = \sum_j \gamma_{i,j} = 1$.

A simple method to assign areas from municipality i to simulation unit j is to specify the allocation function $y(i,j)$ as

$$y(i,j) = \gamma_{i,j} * m(i). \tag{1}$$

In this simple method, each simulation unit receives cropland and pasture according to its share in the municipality's total area. The total area put into simulation unit j is given by $\sum_i y(i,j)$.

Due to data inconsistencies, sometimes the area available for productive use $s(j)$ in simulation unit j is less than the total area $\sum_i y(i,j)$ estimated by equation (1), such that $\sum_i y(i,j) > s(j)$. This happens, for example, for simulation units with protection areas which cannot be assigned as productive land. Thus, the simple method above does not work in all cases.

To consider these cases, we propose the following adjustment:

$$s^*(i,j) = \min\left(\sum_i y(i,j), s(j)\right) \tag{2}$$

and let

$$y^*(i,j) = y(i,j) * \left[\frac{s^*(j)}{s(j)}\right] \tag{3}$$

where $s^*(j)$ is the production area assigned to the simulation unit j by the simple method, unless there is not enough available area, when $s^*(j)$ is the available area for production in the simulation unit.

By construction,

$$\sum_i y^*(i,j) \leq s(j) \tag{4}$$

so as we never put more area into a simulation unit than the available free area $s(j)$. Besides, if the simulation unit j has enough available area $s(j)$, we will have

$$\sum_i y^*(i,j) = s(j), y^*(i,j) = y(i,j). \tag{5}$$

Thus, we have an additional restriction:

$$x(i,j) \geq y^*(i,j). \tag{6}$$

If there is not enough area in the simulation unit for the expected production area, we put the surplus area in other locations. Let $d(i,j)$ to be the distance between municipality i and simulation unit j. If there is an intersection between municipality i and simulation union j, we consider the distance function $d(i,j)$ as:

$$d(i,j) = \sqrt{(w * [1 - \delta_{i,j}] + w * [1 - \gamma_{i,j}])} \tag{7}$$

where $\delta_{i,j}$ is the share of municipality i inside simulation unit j, and $\gamma_{i,j}$ is the share of simulation unit j inside municipality i. The weight w controls how important intersections are; we chose w to be 1.

If there is no spatial intersection simulation unit j and municipality i, we take the function $d(i,j) = k$ + [the Euclidian distance between the centroids of simulation unit j and municipality i]. The constant k takes a positive value to prioritise assignment of data from municipality i to simulation units which it overlaps.

Because of the value of k, the distances $d(i,j)$ are much lower in situations where municipality i and simulation unit j overlap than otherwise. Given an area from municipality i, the algorithm first tries to put this area into overlapping simulation units. If there is no sufficient available area within the closest units, the method then tries to put them into closest units nearby. For our work, we use $k = 10$.

In our minimization problem, the effective number of considered municipalities N can be smaller than the total number of municipalities. We do not consider municipalities that have no agricultural land ($m(i) = 0$). It is also not necessary to consider simulation units without available land ($s(j) = 0$), with only forests or forests and protected areas. The resulting minimization problem still has more than 61 million decision variables $x(i,j)$. To further reduce the number of decision variables, we consider only cases where $d(i,j) \leq c$, where c is a threshold chosen so as to allow for a solution under our computer resources constraints. For our choice of threshold, we ended up with around 6 million possible decision variables $x(i,j)$, combining municipalities i and simulation units j. Neither increasing the threshold nor allowing for more decision variables, changed the solution.

The resulting final optimisation problem for assigning production areas (crops, pasture and planted forests) into simulations units corresponds to the following set of equations, which give us a smooth version of the minimum distance algorithm:

$$min\left(\sum_{i,j}\left(x(i,j) * d(i,j)^2\right)\right) \tag{8}$$

subject to

$$\sum_{i} x(i,j) \leq s(j), j = 1, ..., J \tag{9}$$

and

$$\sum_{j} x(i,j) = m(i), i = 1, ..., N \tag{10}$$

If we had enough area in all simulation units, so as $\sum_i y(i,j) \leq s(j)$, the solution for the optimisation problem is $x(i,j) = y(i,j)$, because of the restriction $x(i,j) \geq y^*(i,j)$. When there is enough land available per simulation unit, the production area of the municipality is distributed between the simulation units, depending on the size of the intersection. For simulations units for which $\sum_i y(i,j) > s(j)$, the algorithm puts the extra municipality production into surrounding simulation units (based on the weights for d(i,j) for the cost function to be minimised).

In both versions (smooth and non-smooth) of the algorithm, there is an explicit neighbouring sprawl effect. We always find a location to put the declared production area. If there is no sufficient free area within the simulation units intersecting the municipality, the production area is transferred to simulation units intersecting surrounding municipalities.

The main result from the previous algorithm is the sequence of variables $x(i,j)$, corresponding to the total production area from municipality i assigned to simulation unit j. We then use this information to transform information at the municipality level into information at the simulation unit level. The idea is quite straightforward. Let $r(i,j)$ be the variable indicating the share of productive area from municipality i put into simulation unit j, calculated as

$$r(i,j) = \frac{x(i,j)}{\sum_j x(i,j)} \tag{11}$$

Let $v(i)$ be any variable, at the municipality scale. The variable $v(i)$ can be, for example, the area for corn production (in hectares), the total area for planted forest, the area for pasture, or the number of heads of cattle. To find the value for the specific variable $v^*(j)$ at the simulation unit j, we can use the expression:

$$v^*(j) = \sum_i \Big(r(i,j) * v(i) \Big) \tag{12}$$

Employing the previous expression, we can find the value of any variable at the simulation unit scale, based on information at the municipality scale. The algorithm tries to find the optimum assignment of productive areas from municipalities into simulation units. It resolves inconsistent cases, to find a solution where all productive areas are allocated in a consistent way.

Using this optimisation algorithm, we then allocated land use data to the simulation units, where each unit gets its share of cropland and grassland to be consistent with the IBGE data.

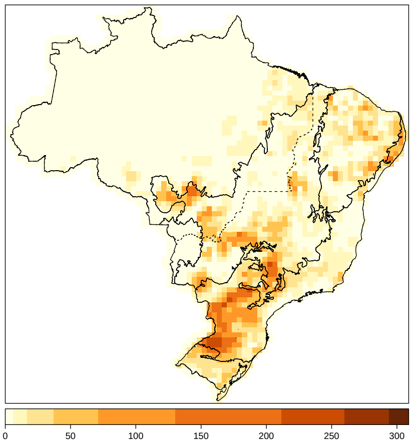
Results and Discussion

The final land cover map comprises the land cover classes used by GLOBIOM: *'natural and managed forest', 'wetlands', 'not relevant', 'cropland', 'planted forest', 'pasture', 'other agricultural land' and 'natural land'.* Table 5 presents an overview over the amounts of land in the different land use classes, aggregated by biomes. The pasture area combines pasture outside Legal Amazônia according to the IBGE 2006 census, and pasture inside Legal Amazônia according to MODIS. The total area of all land use classes is smaller than Brazil's official area, since the simulation units leave out water bodies such as the Amazonas river.

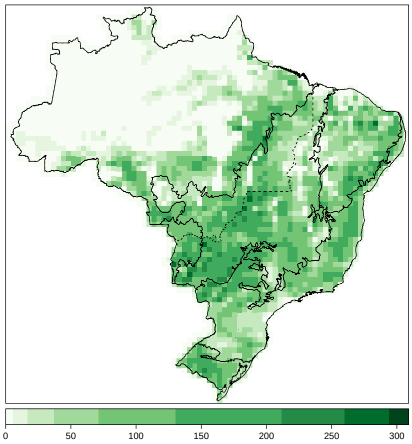
Biome	SIMU area (1000ha)	Crop (1000ha)	Pasture (1000ha)	Forest (1000ha)	Others (1000ha)
Amazônia	412,494	3,724	31,881	350,181	26,708
Caatinga	82,638	6,252	20,360	41,997	32,353
Cerrado	202,488	15,259	82,821	50,793	53,615
Mata Atlântica	113,731	22,820	35,613	17,322	58,514
Pampa	15,772	2,115	7,485	146	6,026
Pantanal	12,211	27	3,758	3,997	4429
Brazil	839,334	50,197	181,918	464,436	142,783

Table 5: Area of GLOBIOM classes per Brazilian biomes.

Figures 16 and 17 show some of the resulting maps, whose distribution closely matches that of the IBGE land use data outside Legal Amazonia, and MODIS data inside Legal Amazonia.



(a) Cropland

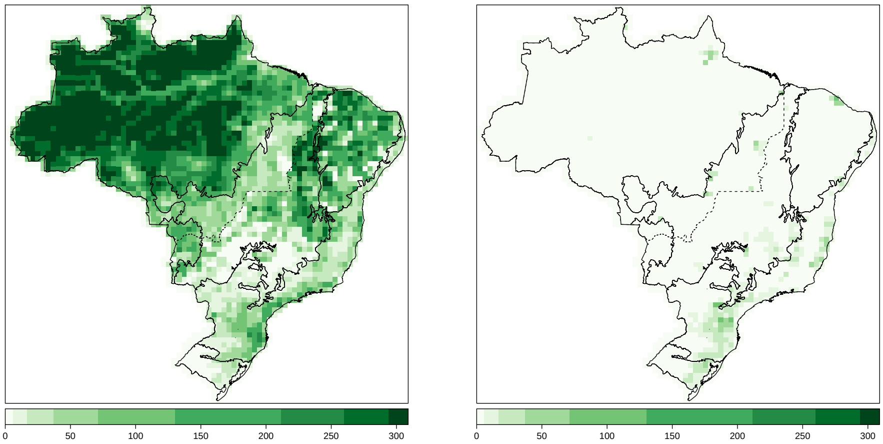


(b) Pasture

Figure 16: Final land cover map with areas of (a) crops (b) pasture. Values are in thousand of hectares per 50 x 50 km^2 cell.

To improve on these maps, we need to improve on the current sources for land cover. The IBGE vegetation map is arguably the best current description of native vegetation types in Brazil. However, it is available in a coarse scale (1:5,000,000) and does not provide information on anthropic areas. The SOS Mata Atlântica dataset is more detailed and captures well the fragmented forest remnants well. In future work, we hope to include similar surveys for the Cerrado biome, currently being carried out by INPE and EMBRAPA.

Surveys on crop and livestock production have inconsistencies, which the algorithm presented above tries to solve. The method we propose is general and can be applied to cases where data available for aggregated spatial units (in this case: municipalities) needs to be disaggregated to smaller spatial units, considering restrictions in available area.



(a) Mature Forests (b) Planted Forests

Figure 17: Final land cover map with areas of (a) forest and (b) planted forests. Values are in thousand of hectares per 50 x 50 km^2 cell.

Our future research will include work to improve pasture location and area. As an economic activity, pasture has the highest use of land in Brazil, and is the main driver for deforestation in the Amazônia. Pasture area is reported, at the municipality level, in the agricultural census, which happens only every ten years. We plan to explore in more details how satellite information can be combined with the data on numbers of animals (PPM) to obtain better estimates of pasture area in Brazil.

Drivers of land use change in GLOBIOM-Brazil

Internal transport costs

GLOBIOM needs information on how much it costs to transport produced goods to the consumer. The cost of transport differs by merchandise and by destination. Some goods are consumed inside the country, so the cost to be considered is the cost to the interior markets, for example from the southern plains to the population agglomerations in the Southeast. Other goods are exported, usually by ship freight, so we need to consider the cost of shipping to the nearest seaports.

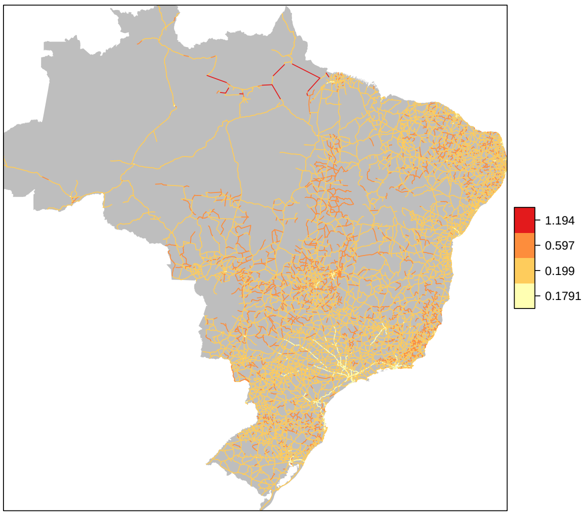
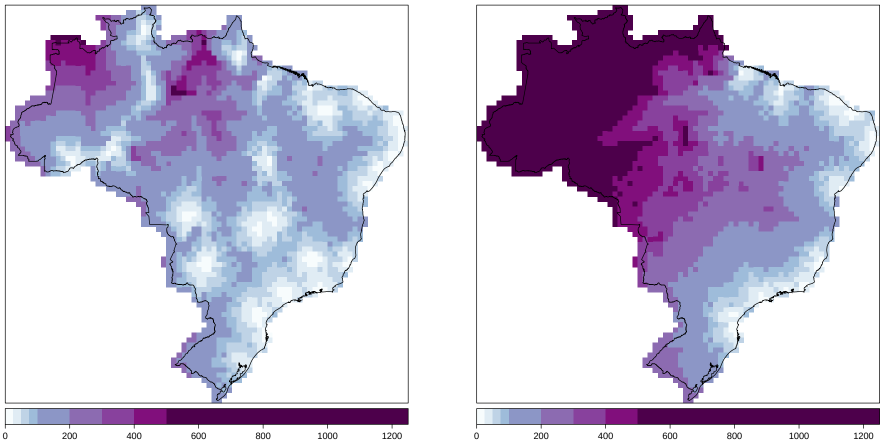


Figure 18: The road network in Brazil based on PNLT data, expressed as BRL per freight ton per km.

The base data comes from the 2012 National Plan for Logistics and Transportation (PNLT). This plan includes the federal roads and a transportation cost within them, which varies from BRL 0.1791 to BRL 0.597 per freight ton per km. The data has some inconsistencies. Some roads inside Amazônia had to be edited to connect them to the rest of the country. The cost of transport on such roads is set as double the cost specified in the database, making it similar to the cost outside roads.

We compute the cost of transportation in USD per metric ton for agricultural commodities and in USD per m^3 for wood products. Costs depend on location of the production area, its connectivity to the road network and where the goods are consumed. The internal transportation costs are computed at the spatial grid resolution of GLOBIOM-Brazil (equivalent to 50 x 50 km^2).

We use an algorithm based on the generalised proximity matrix proposed by Aguiar et al. [2003]. We take the centroid of each grid cell as the starting point to compute the costs. In this algorithm, the path from the starting to the ending point enters the road network only once. The path leaves the road only on the closest location to destination. If there is no road touching the starting or the ending points, we estimate an additional cost to enter or to leave the roads. The algorithm requires that all roads must be connected. The shortest paths inside the network are computed using the Dijkstra algorithm.



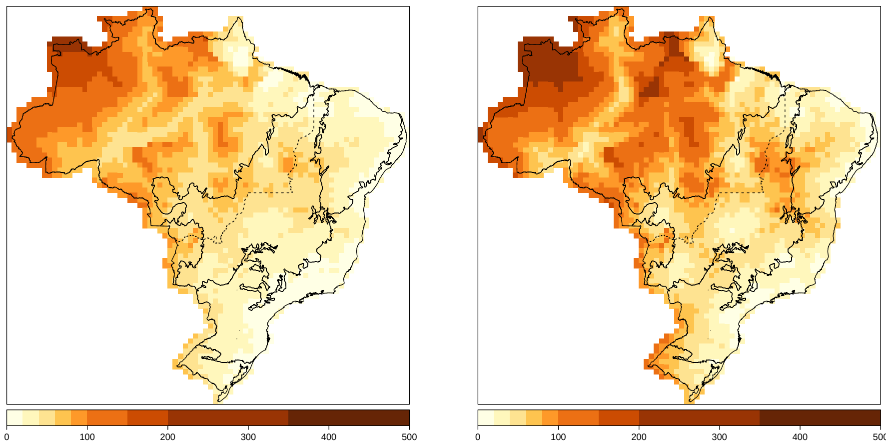
(a) Capitals (b) Seaports

Figure 19: Transportation costs in BRL per ton to the nearest state capital (a) and to nearest seaport (b). Light blue means lower costs and purple means higher costs.

Figure 18 shows both the original PNLT infrastructure map used as input for the algorithm to build the transportation maps. We did not add state roads to the input data. They increase the computational cost, but due to the resolution of GLOBIOM the outcomes are not better.

The proximity matrix was computed for state capitals and for export ports. Figure 19(a) shows the cost to the nearest state capital and Figure 19(b) shows the cost to the nearest export seaport (right). Transport costs range from BRL 2.11 per ton to BRL 512.02 for capitals and from BRL 5.08 per ton to BRL 1145.44 per ton for ports.

We derived the final transportation costs using the proportions of internal consumption and export per product. Since Brazil exports 44% of the produced soybeans, the transportation cost for soybeans for each grid cell is 0.44 times the cost to the nearest port plus 0.56 times the cost to the nearest capital. The final maps converts from BRL to US$ using the exchange rate US$1.00 = BRL 1.954. The transportation maps were computed for each agriculture, livestock and forestry product. Figures 20(a) and 20(b) show the final transportation maps for soybeans and bovine meat, in US$ per ton.



(a) Soya

(b) Bovine Meat

Figure 20: Combined transportation costs in US$ per ton for (a) soybeans and (b) bovine meat)

Figure 20(b) shows the costs of the transportation matrix for bovine meat. Considering the existence of informal road networks in Amazonia, it is likely that we overestimate the actual cost. To improve our calculation, we plan to improve the road network in Amazonia, by using information that is not part of the national plan (PNLT).

The land transition matrix

GLOBIOM-Brazil allows different land transitions, the most important for emissions and biodiversity being those of forest and natural land to cropland or pasture. We also consider that forest regeneration will take place when pasture or cropland is left to comply with the legal reserve criteria. These possible changes make up the so-called land transition matrix, which shows all the possible transitions from one land use or land cover to another (see Figure 21).

Forests can also be used for timber exploitation and be converted to managed forests, as in the case of forest concessions. The model allows for conversion of natural land, cropland, and pasture to planted forest. Eucalyptus and pines are the trees most commonly planted in Brazil. Plantations have undergone a rapid expansion over the last decade. The Ministry of Agriculture is expecting a further increase, with a target of 9 million hectares of eucalyptus by 2020.

GLOBIOM-Brazil includes a cost for land conversion, using a non-linear cost function. The cost per converted hectare increases with the total converted area. Land can also be abandoned in GLOBIOM if the activities are no longer profitable. In this case, we assume the land reverts to class *'natural land'* at the end of the 10-year time-step.

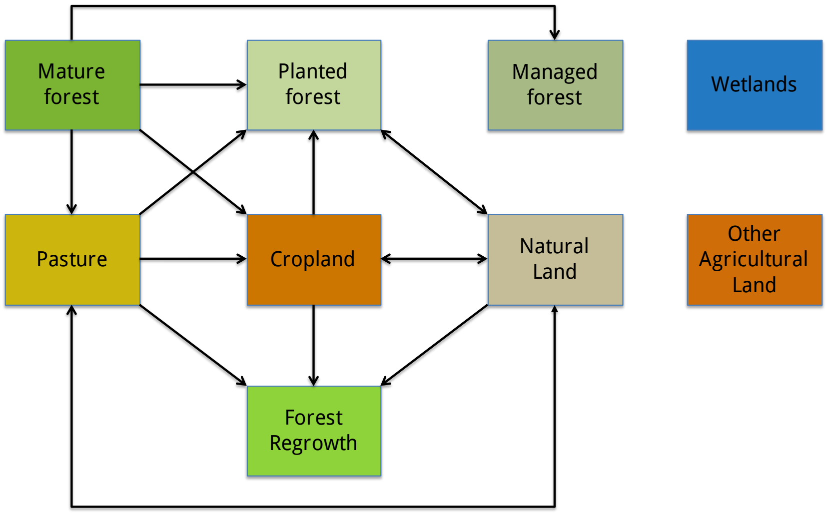
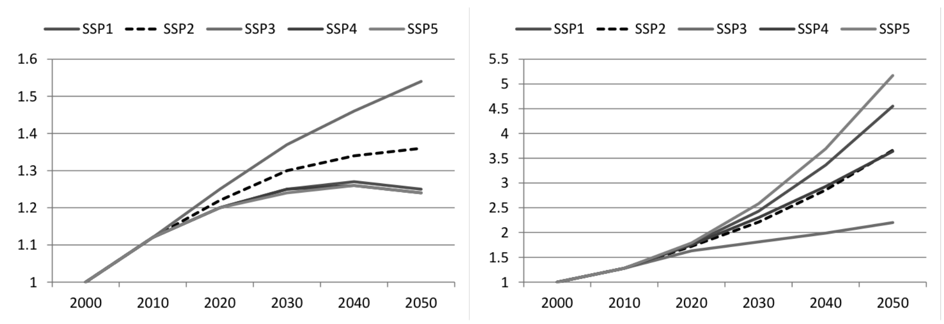


Figure 21: Allowed transitions (arrows) for GLOBIOM-Brazil land use/ land cover classes.

GDP and Population Growth, Food and Energy Demand

Modelling land use change in Brazil depends on having a realistic projection for the internal and external demand foe the country's production of food, wood and biofuels. Food demand is driven by growth of population and GDP per capita, and wood demand by GDP per capita growth. We also consider changes in food consumption patterns and internal and external demand for biofuels.



(a) Population

(b) GDP

Figure 22: Growth projections for (a) population, and (b) GDP per capita in Brazil until 2050

For GDP and population projections we use the Shared Socio-economic Pathways (SSPs) developed for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC); the SSPs provide storylines of possible futures [Kriegler et al., 2012]. We take the middle-of-the-road SSP2 scenario as our baseline. In this scenario, the population in Brazil grows by 30% in 2030 (Figure 22)[17] and by 35% by 2050 compared to 2000. For GDP per capita, Brazil is slightly above the world average, with an increase of 120% in 2030 and of 250% in 2050 compared to 2000 level (Figure 22).

[17] This projection is in line with the latest estimates from IBGE, that project Brazil's population to be 223 million by 2030 from to 173 million by 2000 (a growth of 29%)

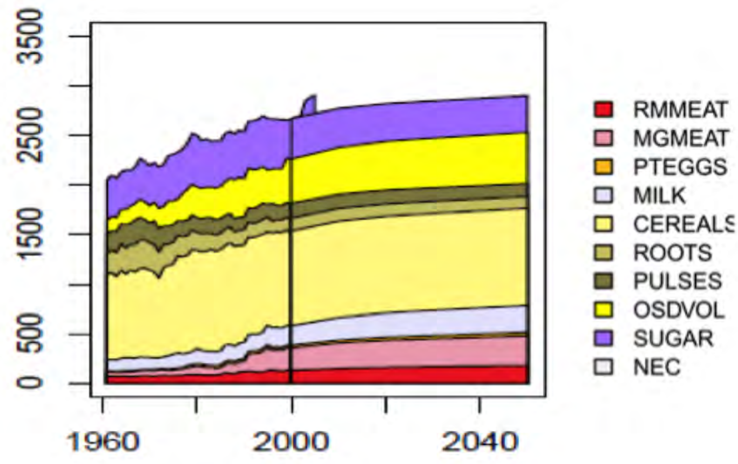


Figure 23: Projection of the structure of food consumption per capita (kcal/ day) in Brazil. Source: Alexandratos and Bruinsma 2012.

Food consumption by region depends on the evolution of GDP and income elasticities. Each commodity group responds differently to the increase in income (cf. Engel products). Income elasticities are based on scenarios of future diets by the Food and Agriculture Organization of the United Nations (FAO) [Alexandratos and Bruinsma, 2012] and base year elasticities reproduce the trend in the food balance sheets. Different assumptions on GDP growth lead to different levels of consumption [Valin et al., 2014].

Figure 23 projects how daily food consumption evolves in Brazil with the SSP2 scenario. The final computed demand will be different from the initial exogenous value, depending on changes in prices and in the price elasticity of consumption, which is region and product specific.

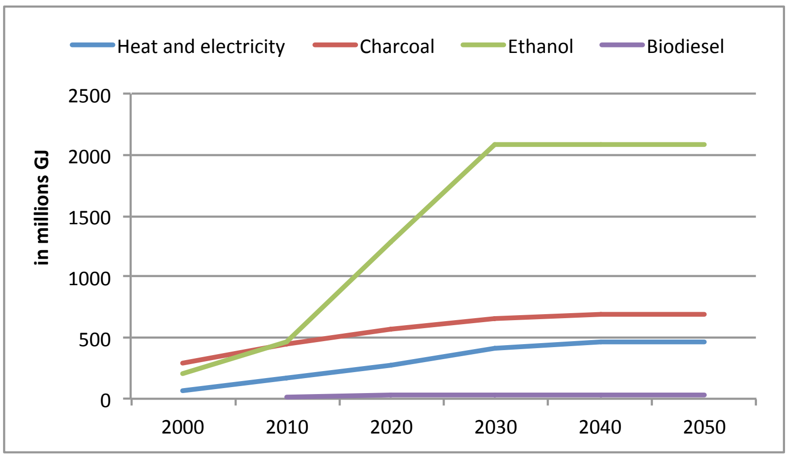


Figure 24: Projected demand for bioenergy for Brazil. Source: World Energy Outlook, 2010.

For bioenergy, demand is set up exogenously using the World Energy Outlook (WEO) 2010 projections [OECD/IEA, 2010] for biomass demand for heat and power generation, and direct biomass consumption (e.g. charcoal for steel industry). For bioethanol and biodiesel, we use the targets set-up by the countries. The bioenergy demand is defined at the WEO 17 regions level, Brazil being one separate WEO region. From these projections, bioethanol use will continue to strongly increase in Brazil until 2030 (Figure 24). Biodiesel use is also expected to increase in Brazil but the overall level still remains almost eight times lower than bioethanol in 2030. Since WEO projections go only until 2035 but our simulations go until 2050, we assume that bioenergy demand remains at the 2035 level in 2040 and 2050.

Determinants of land use change on the supply side

On the supply side, GLOBIOM uses data on land productivity, production costs and transportation costs in each GLOBIOM grid cell. Transformation rate of processed products and processing costs are included at the national level and input-output coefficients of livestock are distinguished by production system and agro-ecological zone. These will influence estimates of land use change.

The EPIC biophysical crop simulation model estimates productivity for each crop, each simulation unit and each management system (rain-fed low input, rain-fed high input and irrigated high input). For 2000, EPIC yields are scaled to match FAO national average productivity and in the next decades, crop yields are modified by an exogenous technological factor (Figure 25). These exogenous technological trends are based on econometric estimates where crop yields were fitted on national log GDP per capita over the period 1980-2009 in a fixed-effects panel estimation. On the input side, we use a simple assumption of a proportional increase of nitrogen utilisation to yield growth (elasticity = 1). This relates to increasing costs of production and increasing emissions from agriculture. Productivity can also increase endogenously in GLOBIOM through production reallocation to more/less productive areas and through management system change, from low to high input for instance.

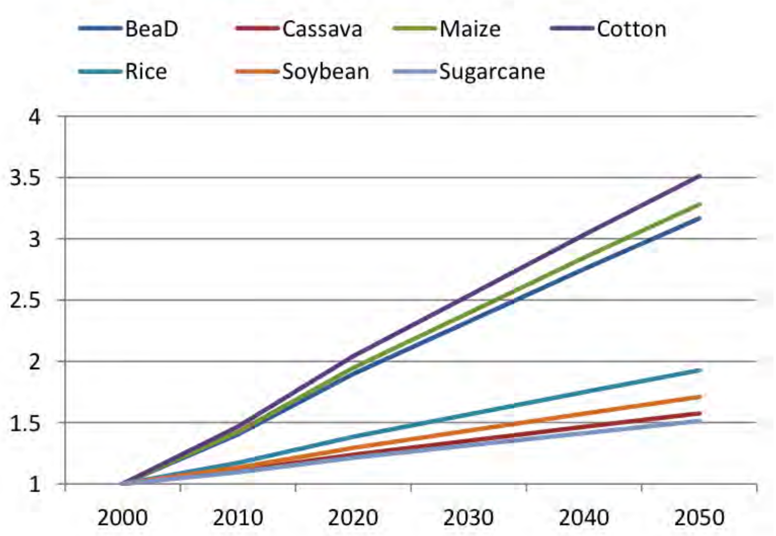


Figure 25: Projected crop productivity in Brazil: relative changes compared to 2000, using the SSP2 GDP projection.

GLOBIOM incorporates a detailed representation of the global livestock sector [Havlík et al., 2014]. Distinctions are made among dairy and other bovines, dairy and other sheep and goats, laying hens and broilers, and pigs.

Ruminants production activities are defined by agro-ecological zone -arid, humid, and temperate/highlands- and production systems -grass-based, mixed crop-livestock and other. Monogastrics are differentiated across smallholders and industrial [Herrero et al., 2013].

For each species, production system and region, a set of input-output parameters is calculated based on the approach described by Herrero et al. (2013). Feeds consist of grass, crop residues, grain concentrates, and other feedstuffs. Outputs include four meat types (beef, sheep and goat meat, poultry and pork), milk, eggs, and environmental factors (manure production, nitrogen excretion, and GHG emissions). Switches among production systems allow for feed substitution and for intensification or extensification of livestock production.

Competitiveness of the ruminant sector depends on pasture productivity. We estimate pasture productivity in Brazil by using the number of ruminants by simulation unit multiplied by their grazing requirements and divided by the pasture area.

In GLOBIOM-Brazil, short rotation plantations are used for a wide range of purposes. Based on FAO-FRA 2005 data, we have assumed that 10% of the total plantation is used for charcoal production mainly for the steering industry, 30% is used for logs production and the remaining 60% is used for pulp and paper production. We have also assumed that the rotation time is two times higher for logs production than for pulp or charcoal production.

Final use of timber	Area (Mha)	Increment (m^3/ha)	Production (Mm^3)
Logs	1.8	15.80	28.44
Charcoal	0.6	31.60	18.96
Pulp and paper	3.6	31.60	113.76
Total	6	26.86	161.16

Table 6: Parameters used to represent short rotation plantations in Brazil. Sources: authors based on IBGE Census 2006, FAO 2006, ESALQ/USP.

In Brazil, planted forests use mostly eucalyptus and pinus. These species have different rotation times and increments. We used the current shares of the planted area — 68% planted with eucalyptus and 32% with pinus — to compute a weighted average mean annual increment at the national level (Table 6). The planted area by simulation unit has been taken from IBGE Census.

International trade

As a spatial equilibrium model, GLOBIOM can track bilateral trade flows between the 30 regions of the model (Figure 26). This analysis includes both tariffs and transportation costs differentiated among products and trading partners.

Tariffs come from the MAcMap database [Bouet et al., 2004]. Imported goods and domestic goods are assumed to be identical, meaning that the only differences in their prices are due to trading costs. To compute transportation costs, for which data are lacking, the analysis uses the coefficients between freight rates and distance and estimates by Hummels [1999] of goods' weight-over-value ratio. The trade calibration method proposed by Jansson and Heckelei [2009] is applied to reconcile observed bilateral trade flows, regional net trade, prices, and trading costs for the base year. Finally, non-linear trade costs are assumed when trade costs increase with the amount of traded quantities.

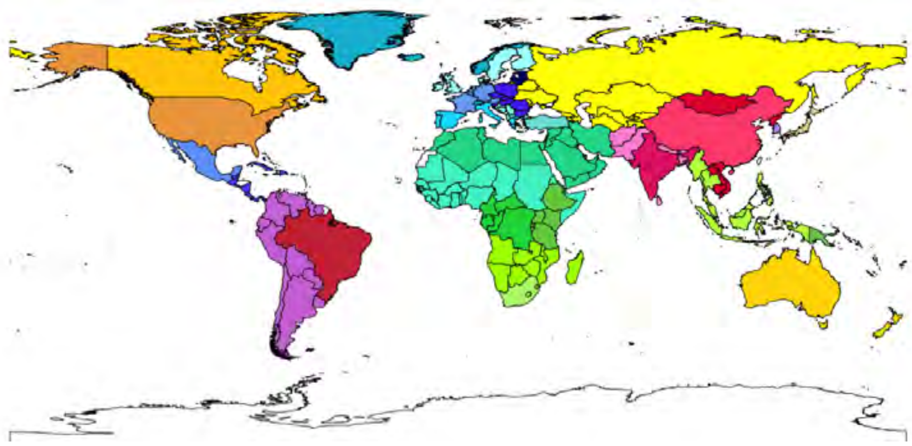


Figure 26: The 30 regions that can trade with each other in GLOBIOM.

In the framework of the REDD-PAC project, tariff changes in 2010 have been introduced in the model for China. China joined the World Trade Organization (WTO) in December 2001 and since then has undergone significant liberalisation of its trade. The country decreased the average bound tariff level to 15% for agricultural products within a range from 0 to 65%, with the higher rates applied to cereals. Chinese soybean imports have increased from 14 million tons in 2000 to 45 million tons in 2010. Over the same period Brazilian soybean exports to China have increased from 1 to 16 million metric tons while exports to other destinations have remained quite stable. Chinese trade liberalisation may have played an important role in Brazilian land use change over 2000-2010.

Impact of protected areas on land use change

This section outlines how protected areas, and production within them, is represented in the model and why. Protected areas are an important part of Brazil's efforts to achieve biodiversity conservation objectives. Protected areas in Brazil are generally effective at preventing deforestation, only 1.47% of the extent of protected areas in Amazônia had been deforested up to 2009 [Verissimo et al., 2011].

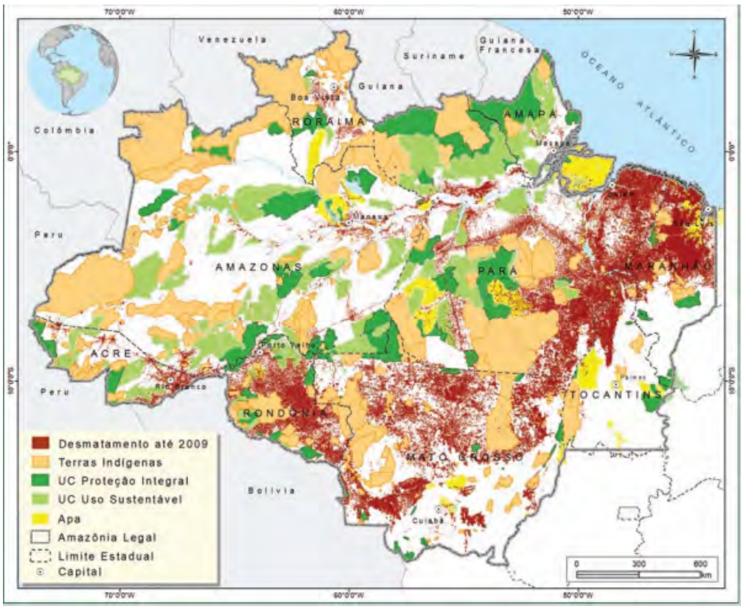


Figure 27: Conservation Units in Brazilian Amazonia (different shades of green, yellow and pink) and deforestation until 2009 (in dark red) (source: Veríssimo et al. 2011).

In many countries, protected areas are often located in remote areas that may suffer less conversion simply due to their remoteness and difficulty of access[Joppa and Pfaff, 2009]. In Brazil, as shown in Figure 27, a large part of protected areas in Amazônia have been created to act as a barrier to deforestation. For example, during the 2000s, Brazil set up a large mosaic of protected areas in the Southwest of the state of Pará and in the Southeast of the Amazonas state, that have played a major role in blocking the advance of deforestation.

Forestry is allowed within some types of protected areas in Brazil, in particular National Forests, but there are restrictions on the type of production allowed. The focus is on sustainable exploitation of native forest, with selective logging rather than clear cutting. There are also limits to the methods and intensity of harvest and rotation lengths. Livestock grazing and agricultural land use can occur within some protected areas, e.g. extractive reserves and sustainable development reserves, but the levels are restricted to subsistence and sustainable production. Highly resource-intensive production methods, or high densities of grazing stocks, are unlikely to be allowed. However, defining universally applicable restrictions on pasture, and agricultural production more generally, in protected areas is very challenging.

The current version of GLOBIOM-Brazil bans productive uses in protected areas. Given the low intensity of land use and the low levels of deforestation inside Brazilian protected areas, excluding land use and land use conversion in them will have limited impact on the overall land use results.

GLOBIOM-Brazil Scenarios

Implementation of Forest Code provisions in GLOBIOM-Brazil

Brazil's Forest Code, approved by the Brazilian Congress in 2012, introduces restrictions to deforestation of native vegetation in private lands. The rules of the Forest Code implemented in the current version of GLOBIOM-Brazil include:

1. *Legal Reserve (LR) recovery:* the Legal Reserve provision sets the minimum percentage of forest or native vegetation to be preserved for each rural property. If the farm's forest area is below the Legal Reserve requirements, the land's natural cover has to be restored or compensated at the landowner's expense. The percentage of Legal Reserve varies from 80% in the Amazônia to 20% in other biomes (see Figure 28). For the simulation units of GLOBIOM-Brazil, the legal reserve percentages were calculated based on the data provided by Soares-Filho et al. [2014].

2. *Small farms amnesty (SFA):* the amnesty of small farms exempts landowners from the need to recover legal reserves in small properties (less or equal than 4 fiscal modules[18]). The size limit for small farms is defined by municipality, ranging from 20 ha in southern Brazil to 440 ha in the Amazônia (see Figure 28).

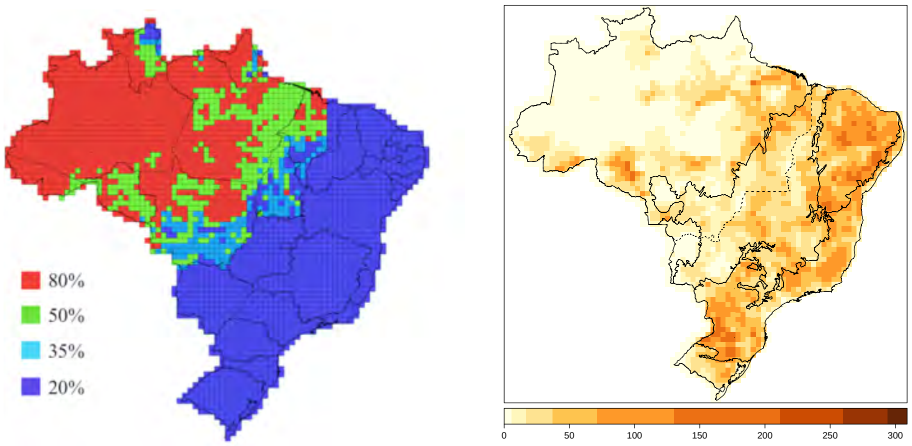
3. *Environment reserve quotas (CRA):* CRA is a tradable legal title of native vegetation surplus (called CRA, from *"cotas de reserva ambiental"* in Portuguese). Forest surplus on one property may be used to offset a legal reserve debt on another property within the same biome.

4. *Comand and control actions:* these actions include zero illegal deforestation of all areas protected by the Forest Code, and enforcement of Legal Reserve requirement. Farms with areas deforested exceeding the legal reserve limit after 2008 will have to recover its legal reserve or obtain environmental reserve quotas to compensate for the missing reserve.

[18] The fiscal module is an agrarian unit used in each municipality in Brazil. Information on agrarian structure in Brazil is available at `http:\www.incra.gov.br`.

Currently, the Brazilian government is preparing a regulation to clarify some pending issues on the implementation of the Forest Code. One key topic is whether small farms that have a deficit of legal reserve, but still have some forests left, could use these forest areas as quotas and put them on the market. MMA officials told us such use of forest remnants by small farmers would not be possible; they view this possibility as a misuse of the amnesty granted by the Forest Code. We followed their guidance and did not allow for small farmers to offer areas below the legal reserve limit as environmental reserve quotas.

A second key issue is about private properties whose owners lost their tenure rights when new preservation areas included their farms. Some of these owners have not yet been financially compensated by the federal government. There is a demand for making the areas available in the quota market. Farmers that have lost their land and have not been indemnified would receive environmental reserve quotas as compensation. We discussed the issue with government officials and they informed us that the matter is under discussion. Since we had no data on this legal dispute, acting under stakeholder advice we did not include estimates of these areas in our quota market.



(a) Legal Reserve (b) Small Farms

Figure 28: Legal Reserve percentages (a) and area of small farms (b) per simulation unit.

The current version of GLOBIOM-Brazil does not include areas of permanent preservation (APPs), aiming to conserve water resources and prevent soil erosion. This will be incorporated in a future development of the model.

Debts and surpluses of legal reserve

A crucial part of any model of future land use change in Brazil is the information on the legal reserve per property. Estimates of possible legal deforestation, and required forest restoration per property depend on accurate data on debts and surpluses of legal reserve. For this reason, the Forest Code created the environmental Rural Cadastre (CAR). The CAR is an electronic, mandatory registration for all rural properties, which aims to integrate environmental information regarding the property. When all properties are registered and validated, the CAR will provide information that enables the enforcement of environmental laws. However, the implementation of the rural cadastre (CAR) is not yet complete. To estimate debt and surpluses of legal reserves, we had to make some assumptions.

The first assumption concerns the destination of public lands. These are lands outside protected areas without designated owners. We assumed that in all of the states of Brazil, except for Amazonas, all land that is not protected is, or will be, under private ownership. In the state of Amazonas, there are many public lands that have not yet been designated, either as a protected area or given to private owners. We discussed this issue with Brazilian government officials; they expect Forest Code regulations to prevent all of these areas from being privatised. By common agreement with them, we assume that only 20% of the public lands in the state of Amazonas will become private farms.

The second assumption relates to lack of information on property boundaries. To compute the amount of land to be restored, we calculated deficits or surpluses of native vegetation for each cell (roughly 50 x 50 km at the Equator). After subtracting the protected areas, we then compute how much native vegetation still exist in the farms inside the cell. If this area is less than the requirement of the legal reserve rule, the cell has a deficit.

Inside each cell, we do not know exactly how much of the vegetation deficits or surpluses were located inside or outside small properties. We assumed the relative amount (%) of deficit or surplus inside small farms was the same as the relative amount outside small farms. The surplus or deficit for small farms S_i^{sf} inside cell i was estimated as $S_i^{\mathrm{sf}} = S_i \times p_i^{\mathrm{sf}}$, where p_i^{sf} is the percentage of small property areas inside cell i and S_i is the total vegetation surplus or deficit inside cell i. The percentage p_i^{sf} was estimated from statistics on property sizes from IBGE Agriculture Census 2006, and from information on fiscal module sizes from INCRA.

In the estimation of debts, whenever a scenario includes the amnesty for small farms, the area allocated to these properties is discounted from the vegetation deficit in the same cell. This ensures that the remaining native vegetation in an indebted (and amnestied) small farm will not be used to reduce the debt of a larger property. In other words, only surpluses are exchanged by debts ("debts can not pay debts"), an interpretation of the new Forest Code advocated by Brazil's Ministry of Environment.The debts and surpluses of legal reserves in Brazil in 2020 are shown in Figure 29.

The bigger debts occur in the region known as the 'arc of deforestation' of the Legal Amazônia, especially in the portion of Mato Grosso that belongs to Cerrado biome. The stock of surpluses in Caatinga biome is high due to the low level of legal reserve (only 20%). The Mata Atlântica is neutral without a significant debt because of the large number of small farms exempt from forest restoration.

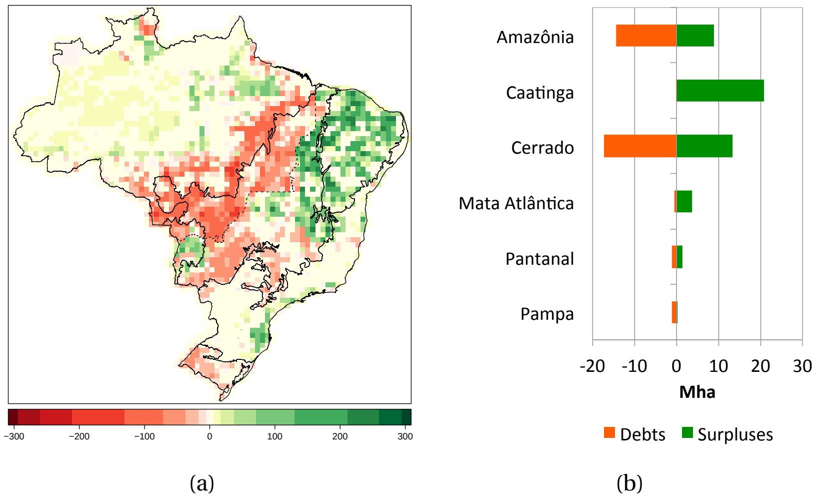


Figure 29: Debts and surpluses of Legal Reserve in Brazil in 2010 for the Forest Code scenarios, expressed (a) in thousands of ha per 50 x 50 km^2 cell, and (b) in Mha per biome.

Restoration of legal reserves is implemented with the help of a new land use class, in the GLOBIOM model, named *'forest regrowth'*, which allows for transitions from cropland, pasture and natural land areas, which are then set aside for forest regrowth in order to compensate for eventual deficits. No transitions are allowed to other land use classes. For the purpose of carbon stocks accounting, regrowing forests in Amazônia and Mata Atlântica are assumed to recover 70% of their original biomass in 25 years [Houghton et al., 2000] [Ramankutty et al., 2007], and the remaining 30% over the next 50 years. For Cerrado, Pantanal and Caatinga, restored native vegetation takes two decades to become mature. And in the Pampa, that is basically natural pasture vegetation, it takes three years to be fully restored.

Scenarios: general view

The scenarios presented in this document capture land use policies considered by the Brazilian Ministry of Environment (MMA). These simulations consider Brazil's policy options on land-use, the land-based economy, emission reduction and biodiversity. Currently, there is significant uncertainty concerning the detailed regulations associated with the Forest Code. The precise rules for determining and trading environmental reserve quotas are expected to be enacted by the Brazilian Government only in late 2015. Thus, our scenarios mostly convey alternative ways to implement the Forest Code.

Business as Usual (BAU)

The BAU scenario represents Brazil's environmental situation as it was in 2000, without effective control of deforestation. The BAU scenario allows illegal deforestation in all biomes, except for Mata Atlântica[19]. This scenario is a counter-factual approach to measure the effects of the Forest Code. It does not include the rules of the Forest Code.

[19] The Mata Atlântica law (Law No.11.428/2006) is enforced in the model after 2000 and the deforestation rates in this biome are under control in all decades.

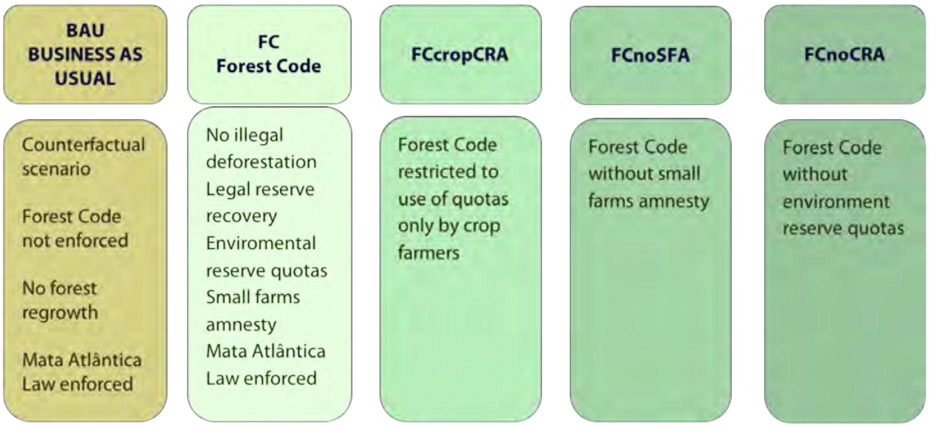


Figure 30: GLOBIOM-Brazil scenarios.

The deforestation rates obtained by the model reflect the projections of important drivers such as population and GDP growth, infrastructure network, or technological change over the next decades. Our BAU scenario does not include the forest regrowth measures defined by the new Brazilian Forest Code.

Forest Code(FC)

The FC Scenario captures the implementation of the Forest Code, approved in 2012. To build this scenario, we take the BAU as our baseline for the period 2000-2010. For the period 2011-2050, we apply the illegal deforestation ban. And after 2020, we apply the following actions:

1. Forest restoration to meet the legal reserve requirement.
2. Small Farms Amnesty (SFA).
3. Environmental reserve quotas ("cotas de reserva ambiental" or CRAs).

We then analysed the model's sensitivity to individual FC provisions. Thus, we have variations of the FC scenario, as described below.

Forest Code without environmental reserve quotas (FCnoCRA)

In this scenario, we remove the environmental reserve quotas from the Forest Code. The stock of native vegetation surpluses in the cell's biome is used through the CRA mechanism to reduce or even eliminate the local deficit. Cells with larger deficits are compensated first and cells with larger surpluses are used first to offset the debts. The comparison of the results of this scenario with the full FC scenario allows us to isolate the influence of this measure on future deforestation in Brazil when other forest code measures are implemented.

Forest Code without small farms amnesty (FCnoSFA)

The Forest Code exempts the small farmers from the need to recover the legal reserve area. The definition of a "small farm" varies nationally and is defined on a municipality scale. A small farm in the state of Santa Catarina (in the south of Brazil) will in general be about 80 ha. In the state of Amazonas (in the north of Brazil) small farms can be as large as 400 ha. However, the exemption of small farms from compliance with the legal reserve is currently under legal discussion. The Court will decide in the coming months whether it is legal to exempt some farmers from the obligation of maintaining a legal reserve. The comparison of the full FC scenario results with the ones obtained by FCnoSFA allows us to measure the influence of this mechanism mainly on agricultural production and forest restoration.

Forest Code with quotas only for croplands (FCcropCRA)

The incentive for buying quotas depends on the opportunity costs of each farmer. Landowners with high opportunity costs are more likely to compensate the legal reserve deficit by buying quotas. Landowners with low opportunity costs are more likely to reforest, passively or actively, instead of buying legal reserve quotas.

Cattle raising in Brazil covers a very large amount of area. In some locations, such as the Cerrado, there is less than one head of cattle per hectare. This situation arose because land was plentiful and cheap, and legal enforcement was not effective. In the coming decades, it is likely that better command and control actions will be in place, so that farmers in biomes such as the Cerrado and Amazônia will be constrained to improve their cattle productivity. This would bring multiple benefits for large cattle farmers, if these improved practises are recognised by the market and government certification.

Because of the low intensity of cattle raising in Brazil, and the possibility of increasing the amount of heads per hectares in the near future, we considered the situation in which cattle producers would not face opportunity costs high enough to justify buying legal reserve quotas. To this end, we have built a scenario where only the crop producers with legal reserve deficits would be interested in buying quotas. In this case, the capital investment made to set up large farms for grain production is likely to offset the costs of quota acquisition.

Summary

The scenarios described above are summarised in Table 7.

	BAU	FC	FC cropCRA	FC noCRA	FC noSFA
Mata Atlântica law	yes	yes	yes	yes	yes
Illegal deforestation	-	no	no	no	no
Private lands in AM	-	20%	20%	20%	20%
Small farms amnesty	-	yes	yes	yes	no
CRA for croplands	-	yes	yes	no	yes
CRA for pastures	-	yes	no	no	yes
Reforestation	-	yes	yes	yes	yes

Table 7: GLOBIOM-Brazil scenarios.

GLOBIOM-Brazil allows investigating the effectiveness over time of different dispositions of the Forest Code in the Amazônia and elsewhere in Brazil. The flexibility to implement different scenarios (with and without quotas or amnesty, for example) allows not only the study of the direct influence of a given policy on Brazil's deforestation rates and agricultural production, but also of eventual leakages across biomes and indirect impacts on biodiversity.

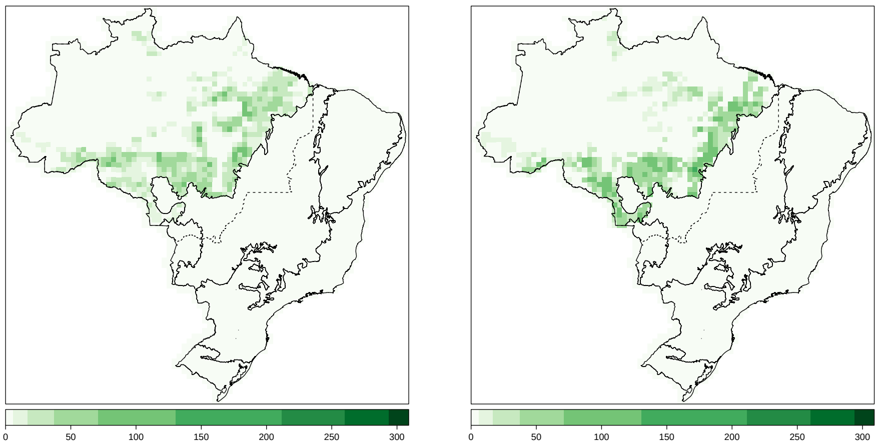
GLOBIOM-Brazil Model Validation

GLOBIOM-Brazil is calibrated with data for year 2000 as its initial condition, and run for ten year periods until 2050. The model projections for year 2010 have been validated, by comparing them with available data sets for 2010. These include: (a) harvested area of 15 GLOBIOM crops[20] from IBGE/PAM (Municipal Agriculture Census) for 2010; (b) livestock production for 2010 from IBGE/PPM (Municipal Livestock Survey); and (c) PRODES/INPE 2001–2010 Amazônia deforestation map.

[20] GLOBIOM simulates 18 different crops. However, chickpea, millet and rapeseed are not available on IBGE/PAM dataset and, consequently, they are not represented into the model.

Validation of Deforestation in Amazônia

We compared PRODES/INPE measured deforested area against GLOBIOM-Brazil projected deforestation in Amazônia for the period 2001-2010 (Figure 31). There is good agreement between GLOBIOM-Brazil and PRODES for the total deforested area and its spatial distribution. The accumulated deforestation in the period 2001-2010 is 16.5 Mha for PRODES/INPE and 16.9 Mha for GLOBIOM-Brazil.



(a) PRODES 2010 (b) GLOBIOM-Brazil 2010

Figure 31: Spatial distribution of deforested areas given by PRODES/INPE (left) and GLOBIOM-Brazil (right) in Amazônia. Values are in thousand of hectares per cell.

GLOBIOM-Brazil captures the expansion of crops and livestock in Amazonia. Since the model does not represent land speculation and does not include informal roads built by loggers and miners, it fails to capture change in the region close to São Félix do Xingu and along the BR-163 road in the State of Pará.

Validation of Cropland area and Livestock numbers

Overall, we observe a good agreement between overall census data and simulation results. Differences range from +5% in total crop area to -20% in total crop production, as shown in Figure 32. Simulated total livestock production differs from IBGE data by approximately -4Mtlu (-2%).

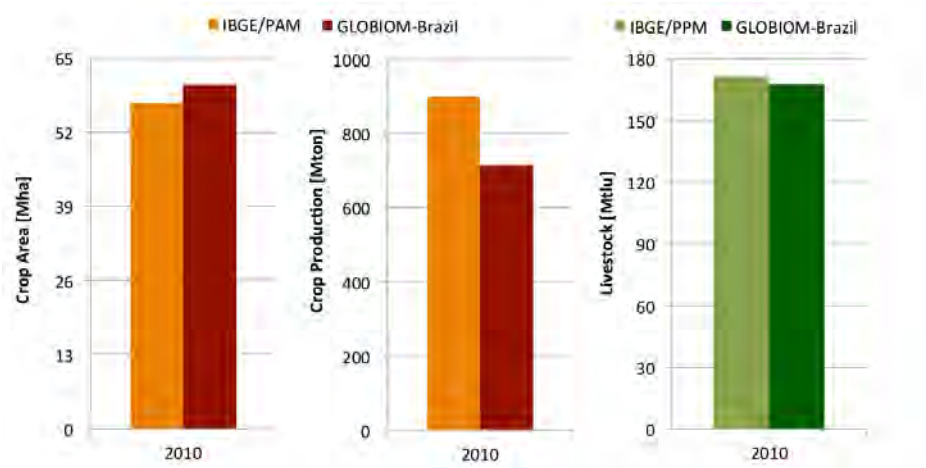


Figure 32: Brazil's aggregated numbers for crop area (Mha), crop production (Mton) and livestock production (Mtlu) in 2010.

Figure 33 shows validation results for the most important crops. The largest differences are found in the crop areas of soya (+1.4Mha), corn (+1Mha) and sugar cane (-1.4Mha). In general, GLOBIOM-Brazil projections for crop area in 2010 differ from IBGE/PAM data by less than 5%. The overestimation on crop area could result from two factors. The first source of deviation is due to estimates of international demand from Brazilian products that are above the actual values. A second factor is also related to the increase of double-cropping practices in the Cerrado, where soya and corn are planted together in the same area in different seasons. Double-cropping has had a positive effect in reducing deforestation and increasing Brazil's grain production [Morton et al., 2006]. GLOBIOM-Brazil does not yet represent double-cropping, an improvement planned for future versions.

Validation of Cropland area and Livestock numbers per biome

The next graphs show the distribution of crop area and livestock herds per biome. Figure 34 presents the distribution of livestock, and the results are quite close, when comparing GLOBIOM-Brazil estimates against IBGE reported Municipal Livestock Survey (IBGE/PPM) data. The major discrepancies found in bovine production occur in the Amazônia and Caatinga biomes but they are not more than 5%.

Figure 35 compares total crop area per biome, according to GLOBIOM-Brazil projections and IBGE/PAM reported data. The model overestimates the crop area in all biomes but Amazônia. Differences in Cerrado and Mata Atlântica are +6%, and +8% in Caatinga biome.

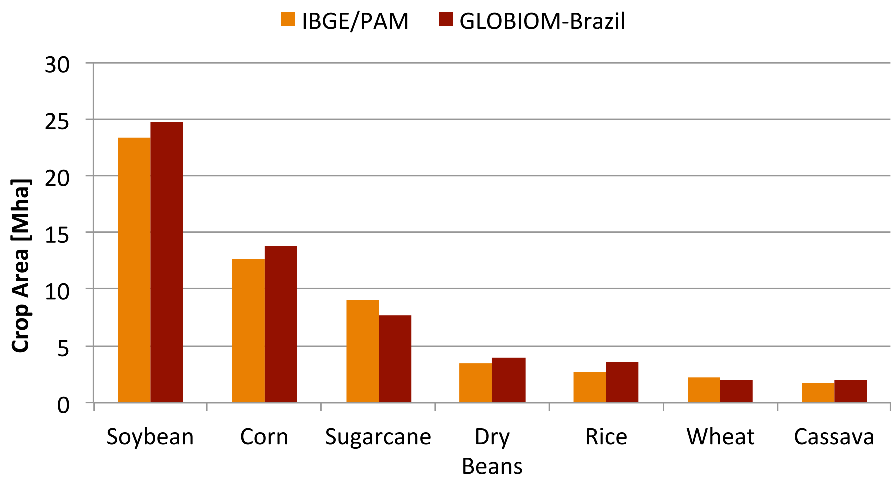


Figure 33: Crop area comparison between GLOBIOM-Brazil and IBGE/PAM in 2010 per crop type.

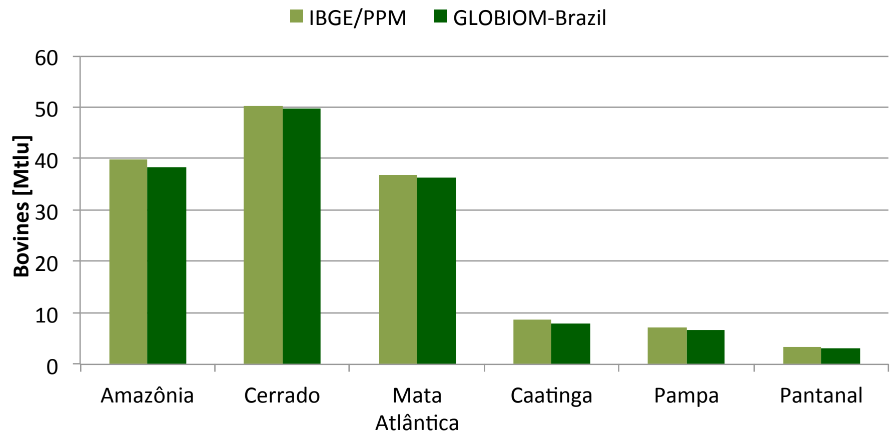


Figure 34: Bovine production (Mtlu) comparison between GLOBIOM-Brazil and IBGE/PPM in 2010 per Brazilian biomes.

Validation of Cropland and Livestock maps

To get a better picture of how GLOBIOM-Brazil is allocating crop and livestock production spatially, Figures 36, 37 and 38 below show the spatial distributions of number of bovines (in 1000tlu), crop area (in 1000ha), and area of cultivated soybean (in 1000ha), according to model estimates and to IBGE survey data for 2010. All figures are presented per grid cells (50 km x 50 km).

According to the maps, GLOBIOM-Brazil estimates have a spatial distribution quite similar to the distribution according to IBGE. Some differences for the total distribution of crops are noticeable for the states of Pará and Mato Grosso. However, the model is able to capture the agricultural frontier in Cerrado biome and MATOPIBA[21] region. For bovines, the distribution of number of heads are very similar when comparing GLOBIOM-Brazil estimates to IBGE data, with some differences observed on the border between Caatinga and Cerrado.

[21] MATOPIBA is a portmanteau word combining the names of four states in Brazil where cropland expansion will increase in the next decades: Maranhão, Tocantins, Piauí and Bahia.

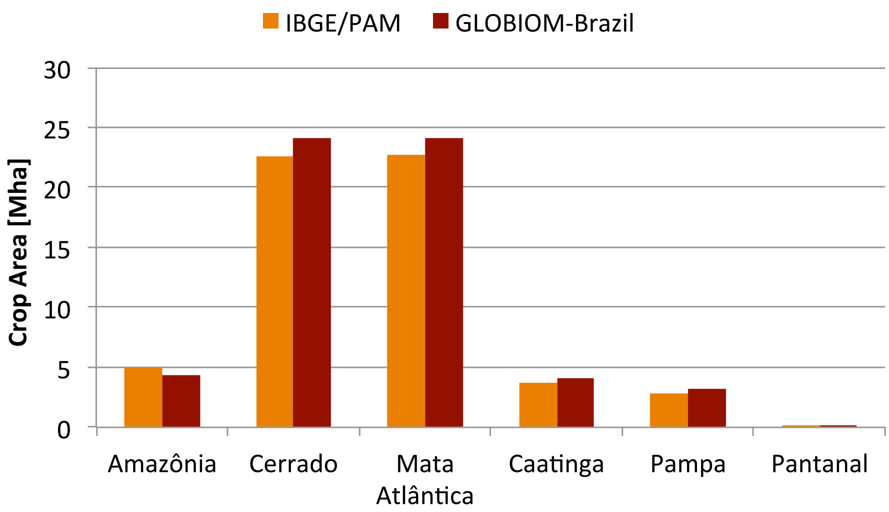
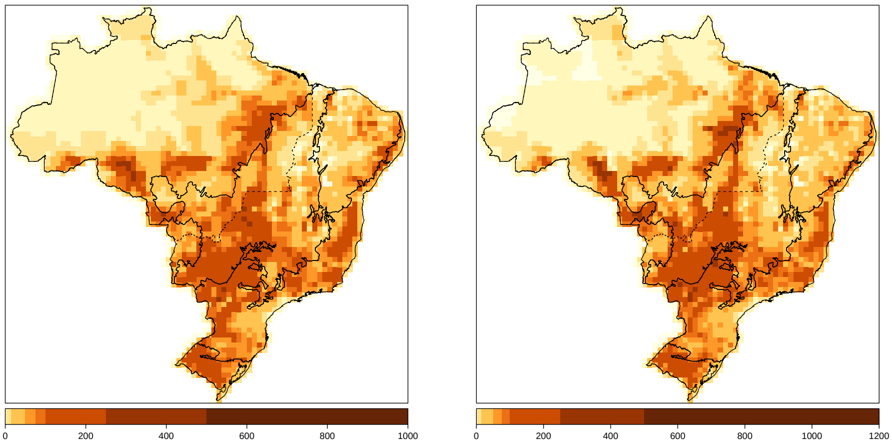


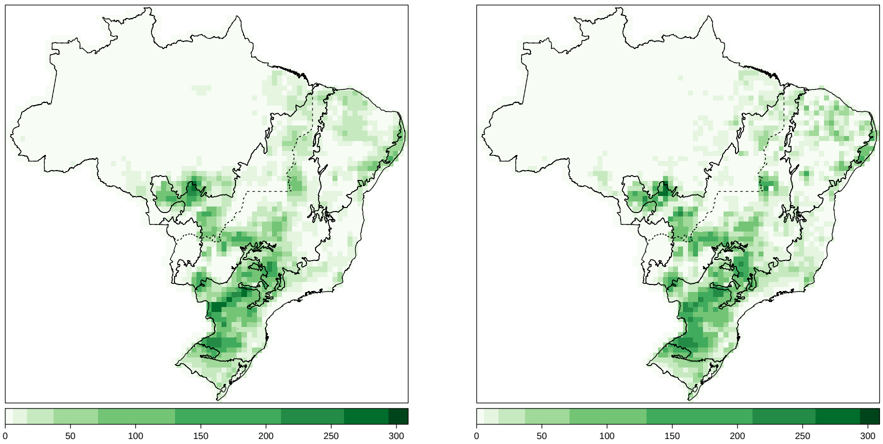
Figure 35: Crop area (Mha) comparison between GLOBIOM-Brazil and IBGE/PAM in 2010 per Brazilian biomes.



(a) Bovines IBGE/PPM (b) Bovines GLOBIOM-Brazil

Figure 36: Spatial distribution of bovines (IBGE/PPM (a) and GLOBIOM-Brazil (b)) for 2010.

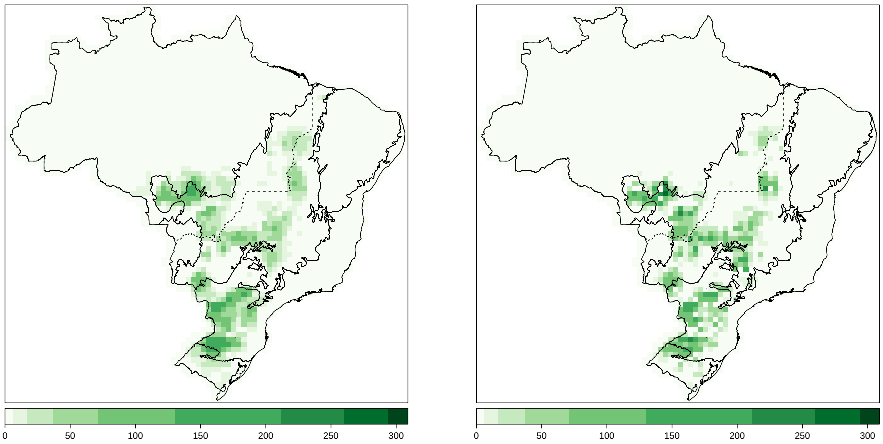
Looking at soybeans, which is the most important crop in Brazil in terms of planted area, we also see a quite similar distribution between the estimates from GLOBIOM-Brazil and the numbers reported by IBGE/PAM. Some differences are noticeable in the northeast of the state of Mato Grosso and in the state of Tocantins. GLOBIOM-Brazil tends to favour intensification over expansion, since it is driven by economic cost and does not consider the land market. In practice, some economic actors entering the market might consider to expand the agricultural frontier. This results in differences between what GLOBIOM-Brasil projects and the actual data on the field.



(a) Crops IBGE/PAM

(b) Crop GLOBIOM-Brazil

Figure 37: Spatial distribution crop area (IBGE/PAM (a) and GLOBIOM-Brazil (b)) for 2010.



(a) Soya IBGE/PAM

(b) Soya GLOBIOM-Brazil

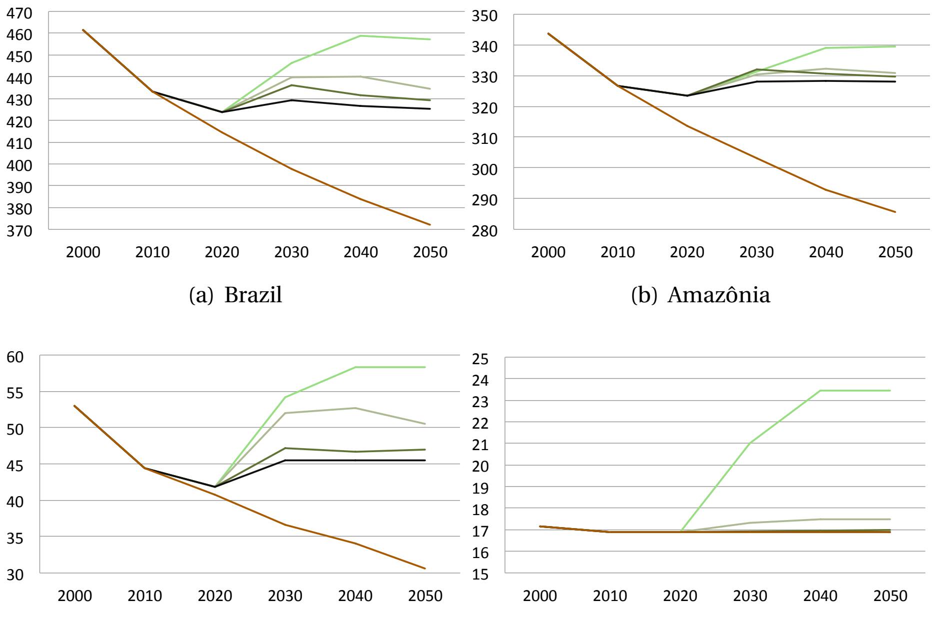
Figure 38: Spatial distribution of soybeans area (IBGE/PAM (a) and GLOBIOM-Brazil (b)) for 2010.

Land Use and Land Cover Change: 2020-2050

In this section, we present the results of GLOBIOM-Brazil projections from 2000 to 2050. These projections show how the land use drivers are interrelated and how the different measures of the forest code influence production and preservation.

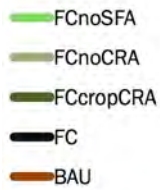
Total forest evolution

The total forest area in Brazil which includes mature forest, managed forest and forest regrowth, is predicted to stabilise or increase by 2050 compared to 2010 level thanks to the implementation of the Forest Code (Figure 50).



(a) Brazil (b) Amazônia (c) Cerrado (d) Mata Atlântica

Figure 39: Total forest area in Brazil and Amazônia, Cerrado and Mata Atlântica biomes in Mha.



The full Forest Code implementation (FC) increases total forest area by 32 Mha by 2030 and 53 Mha by 2050 compared to the BAU scenario at the national level. This increase is made up of avoiding 42 Mha of mature forest being cut and regrowth on 11 Mha of illegally deforested area by 2050 compared to BAU. This is a significant achievement if carried out. The forest area stabilises or increases in Amazônia, Cerrado and Mata Atlântica but decreases in Caatinga (11 Mha of dry forests lost from 2010 to 2050). Due to strong protection rules, the Forest Code produces a "zero deforestation" effect in Amazônia. The beneficial impact of the Forest Code on total forest area in Brazil would be even stronger without small farms amnesty (SFA) and without CRA.

Forest regrowth

The variations in forest area are partly driven by the impacts that different measures of the forest code have on forest regrowth on previously illegally deforested land (Figure 40). Total area under forest regrowth in Brazil reaches 10.4 Mha in 2030 and then stabilises in the FC scenario while in BAU this area remains under pasture or crop cultivation since there is no requirement for forest restoration on previously illegally deforested area in the BAU scenario.

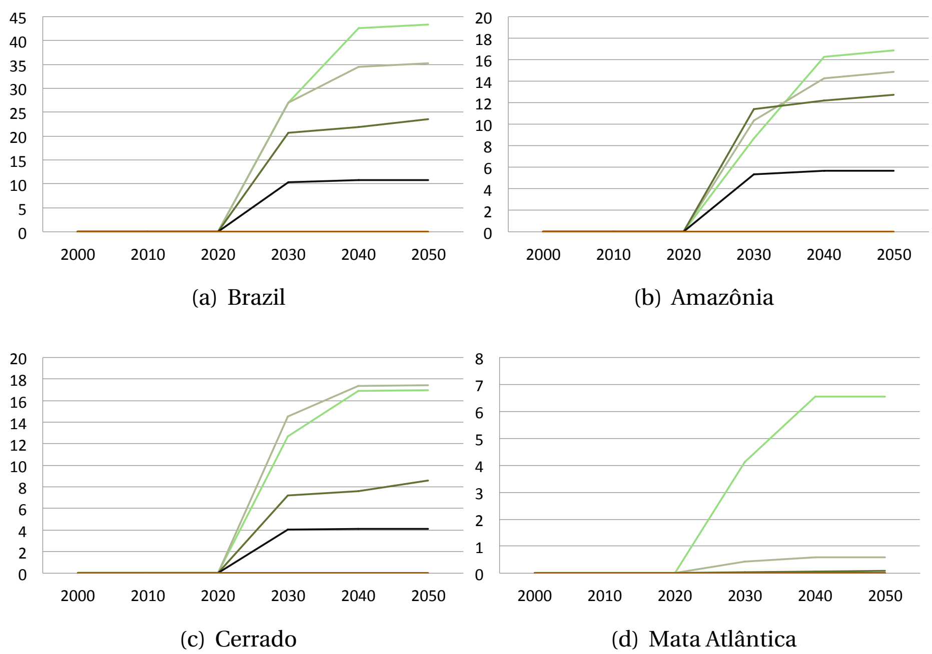
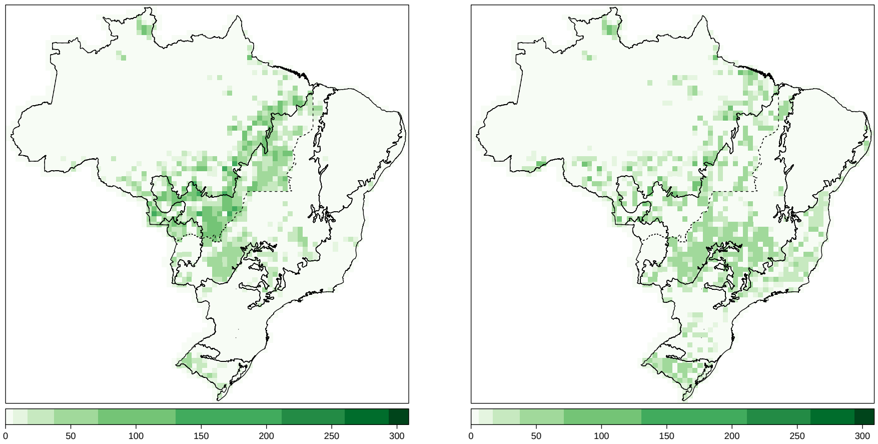


Figure 40: Projected forest regrowth for different scenarios in Brazil, Amazônia, Cerrado and Mata Atlântica in Mha.

The scenario of the forest code without the small farms amnesty (FCnoSFA) forces small land owners to restore forest on previously illegally deforested land. Positive incentives for small farmers to promote regeneration can have a big impact. This scenario leads to the highest total forest area with 17 Mha more forest regrowth than in FC in 2030 and 33 Mha more in 2050. This gain is largest in Amazônia (6 Mha), in the Cerrado (9 Mha), and in Mata Atlântica (4 Mha). Due to the concentration of small farms in Mata Atlântica, the removal of the amnesty increases total forest area by 38% compared to the FC scenario in 2050 (Figure 41(a)).

By allowing compensation of illegally deforested areas by surplus forested area, the environmental quotas also reduce forest restoration of illegally deforested land. Without them (FCnoCRA), total forest regrowth increases



(a) FC without quotas (FCnoCRA)

(b) FC without amnesty (FCnoSFA)

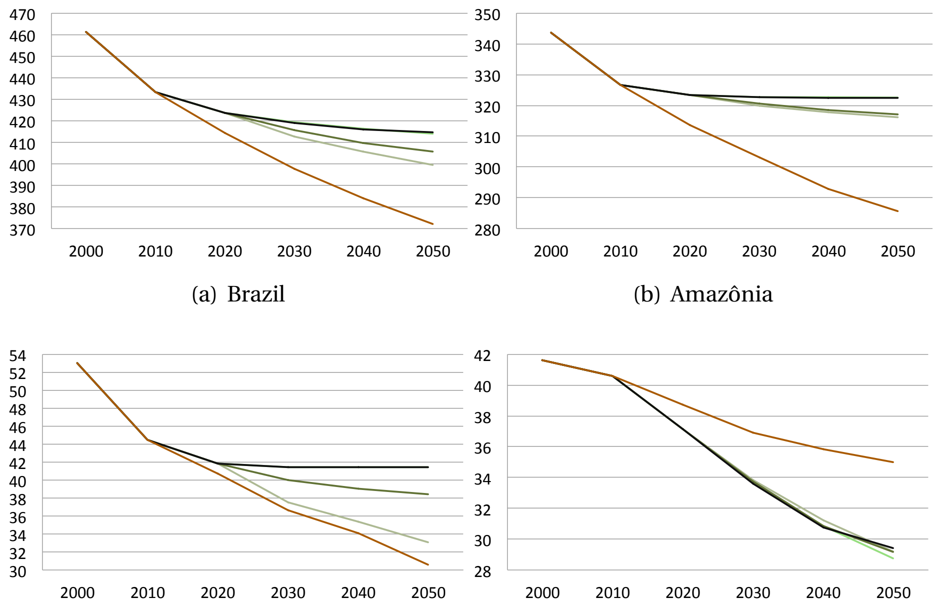
Figure 41: Spatial distribution of forest regrowth for 2030 for FCnoCRA (no quotas) and FCnoSFA (no amnesty) scenarios, in thousands of ha per 50 x 50 km^2 cell.

by 25 Mha in 2050 compared to FC (Figure 40). The effect of the quotas is especially large for Cerrado and Amazônia. In Cerrado in the absence of quotas, 13 Mha of additional forest needs to be restored in 2050. In Amazônia there would be 9 Mha more regrowth without quotas. The option with only crop farmers buying quotas (FCcropCRA scenario) leads to a middle-of-the-road outcome as only livestock farmers have to reforest their legal reserve deficits. It results in 14 Mha more forest regrowth than FC, but 11 Mha less forest regrowth than FCnoCRA in 2050.

Mature forest conservation

Although quotas reduce the potential for forest regrowth in Brazil, they help preserve mature forest. The removal of environmental quotas from FC leads to 19 Mha mature forest loss by 2050. When quotas are used only by crop farmers (FCcropCRA scenario), loss of mature forest drops to to 9 Mha in 2050 (Figure 42). In Amazônia, there is less 3 Mha of mature forest by 2030 and less 6 Mha by 2050 without the quotas, compared to the Forest Code scenario. In the Cerrado, quotas are key to maintain mature forest; without quotas, mature forests fall by 9 Mha by 2050 compared to Forest Code. If only crop farmers buy quotas, reduction of mature forest in the Cerrado is limited to 4 Mha in 2050 compared to Forest Code.

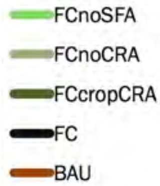
In the Mata Atlântica, the small farms amnesty is more important than quotas for mature forest preservation, since most farms are small and the stock of forest surpluses is low. Since quotas have a big impact in the Cerrado, the quotas market will affect the Cerrado more than other biomes. In Amazônia, what matters is really that the law is enforced since the difference between FC and the BAU is more than 30 Mha while FCnoCRA or FCnoSFA only reduces total forest area by 5 Mha. Forest Code enforcement is thus critical for preserving the Amazônia rain forest.



(a) Brazil (b) Amazônia

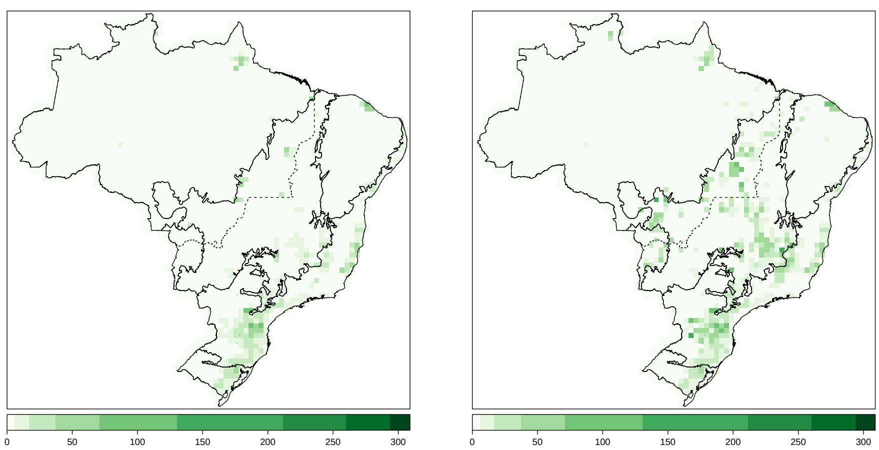
(c) Cerrado (d) Caatinga

Figure 42: Projected total mature forest in Brazil, Amazônia, Cerrado and Caatinga for different scenarios (in Mha).



Planted forests

The model projects a significant growth of planted forests with a 110% increase in area in 2050 compared to 2010. Planted forests increase from 7.65 Mha in 2010 to 12 Mha in 2030 and to 16 Mha in 2050 in the FC scenario (Figure 43). Planted forests growth is similar in all scenarios, suggesting environmental laws do not limit expansion of planted forests in Brazil. Expansion is stronger in Minas Gerais, the Cerrado region of Mato Grosso and the MATOPIBA region (Figure 43(b)).



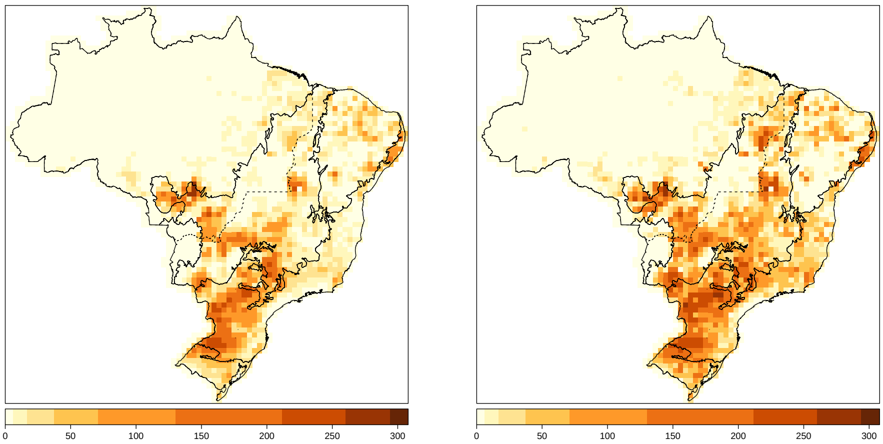
(a) 2000 (b) 2030

Figure 43: Spatial distribution of projected planted forest in 2000 and 2030 for FC scenario, in thousands of ha per 50 x 50 km^2 cell.

Crop production

In all scenarios, croplands increase in the coming decades (Figure 44). From 56 Mha in 2010, crop production is poised to increase to 92 Mha in 2030 and to reach 114 Mha in 2050, a growth of 190%[22]. The difference in total cropland between FC and BAU is 10 Mha in 2050, a loss of 9%. These results show that the forest code does not significantly limit cropland expansion in Brazil.

[22] In these estimates, we excluded the Caatinga, due to high uncertainties on the yield in this biome.



(a) 2010 (b) 2030

Figure 44: Spatial distribution of cropland projected for 2010 and 2030 in the FC scenario. Values are thousands of ha per 50 x 50 km^2 cell.

From the growth of 58 Mha in croplands in Brazil from 2010 to 2050, 52% (30 Mha) are in the Cerrado and 31% (18 Mha) in the Mata Atlântica. Most of the expansion on the Cerrado occurs outside of Legal Amazônia where Forest Code requirements for legal reserves are smaller, especially in Minas Gerais and MATOPIBA regions.

The cropland expansion is mainly driven by sugarcane, soybean and corn in all scenarios. Bioethanol target drives the sugarcane production increase. Since the bioethanol target is maintained constant after 2030, this explains why the sugarcane area increases much slower after 2030. The soybean production increases from 71.8 million tons in 2010 to 123.8 in 2030 and 152.2 in 2050 with the full forest code implementation (FC).

Soybean expansion is driven by exports which represent between 69% and 74% of the total production over the whole period. While soybean exports to the European Union stabilise after 2010, exports to China keep increasing until 2040. In 2050, 69% of Brazilian soybean exports go to China. Exports to Middle East and North Africa also raise over the period reaching 15% of total exports in 2050, an equivalent share as the European market. Soybean domestic use for animal feed also increases from 13 million tons (Mt) in 2010 to 34 Mt in 2050. Domestic use for animal feed remains the first market for corn production over the whole period. Local demand for animal feed increases by 65% between 2010 and 2030 and by 61% between 2030 and 2050.

Brazilian corn exports experience an exponential growth between 2010 and 2050, from 2.2 Mt to 39 Mt. Internal food demand increases between 2010 and 2050, but since population growth is limited to 24%, it is not the major driver of cropland expansion in Brazil in the next decades.

The largest reduction of cropland area with the implementation of the forest code occurs in Amazônia but since it is not a major area of crop production, overall impact remains small. Only 5 Mha (8%) of the increase takes place in Amazônia due to legal reserve enforcement.

Corn production is almost not affected by any of the forest code scenario with less than 1% change. Soybean area is reduced by 6% and sugarcane area is reduced by 10% in 2050 in FC compared to BAU. The scenario without environmental quotas has little impact on cropland but the removal of small farms amnesty further reduces sugarcane area by 10% and soybean area by 12% compared to BAU.

Pasture and livestock

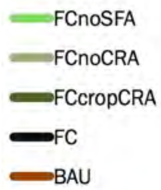
The forest code reduces the total pasture area by 15 Mha in 2030 and by 22 Mha in 2050 compared to the BAU which is equivalent to a 10% reduction (Figure 45(a)). Pastures increase from 215 Mha in 2000 to 244 Mha in 2020, and then decreases to 208 Mha in the FC scenario. The forest code accelerates and magnifies the decrease of pasture area which starts only from 2040 in the BAU. However, the impact of the forest code on the bovines number is limited to a 8% reduction. The number of bovines projected for Brazil is 160 MTLUs in 2030 and 170 MTLUs in 2050 [23] (Figures 45 and 46). The average livestock density in Brazil thus increases from 0.59 TLUs/ha in 2010 to 0.82 TLUs/ha in 2050 (a gain of 50%). This is consistent with recent data from Brazilian Ministry of Agriculture that points to an increase in pasture productivity and a decrease of pasture area.

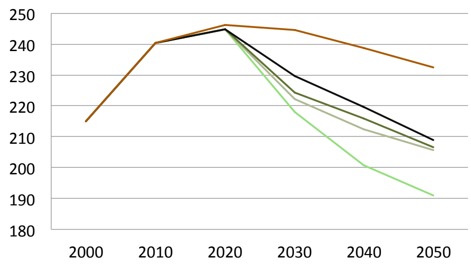
[23] A tropical livestock unit (TLU) is a standardised measure of one cattle with a body weight of 250 kg.

Total meat production doubles between 2010 and 2050 in Brazil. Beef meat increases from 10 million tons (Mt) in 2010 to 20 Mt in 2050, pork meat increases from 3.8 to 10.7 and poultry meat increases from 9 to 15 Mt with the forest code fully implemented. Beef exports increase especially after 2030, when a large share goes to Africa. The implementation of the forest code does not lead to a significant reduction of meat production because the land scarcity provides incentives to switch to more productive systems.

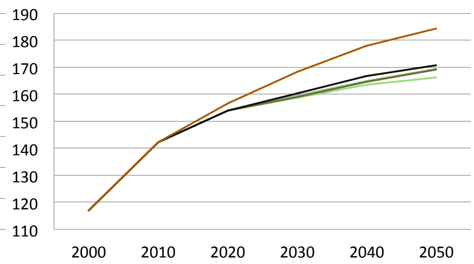
Pasture intensification and higher meat production are implemented in GLOBIOM as a higher share of intensive pasture management. This changes leads to a higher grass production by hectare (Cohn et al. [2014]). It also requires a higher use of grains to feed the livestock, which can then grow bigger and faster for the same pasture area (Havlík et al. [2014]).

Figure 45: Evolution of pasture (in Mha) and bovine heads (in MTLUs).

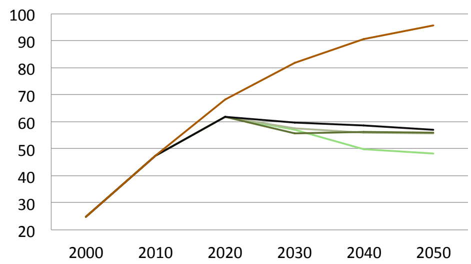




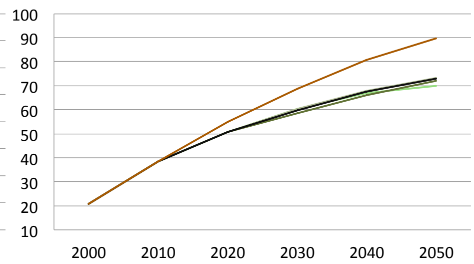
(a) Pasture in Brazil



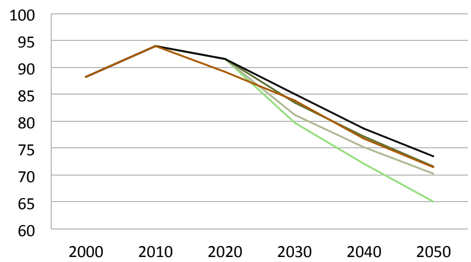
(b) Bovines in Brazil



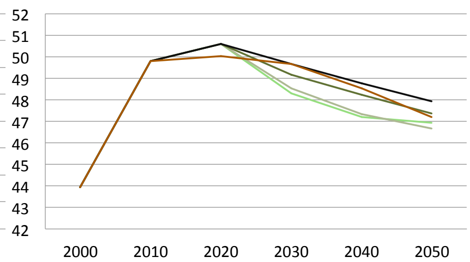
(c) Pasture in Amazônia



(d) Bovines in Amazônia

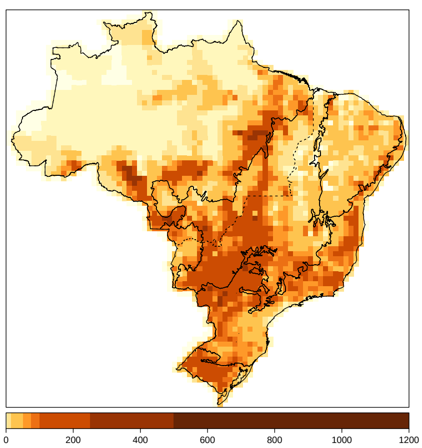


(e) Pasture in Cerrado

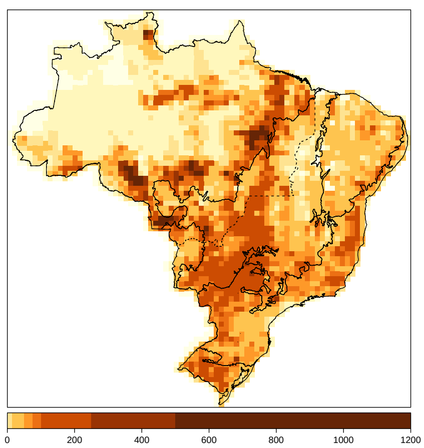


(f) Bovines in Cerrado

Figure 46: Spatial distribution bovine heads in 2010 and 2050 for FC scenario. Values are thousands of tropical livestock units (TLUs) per 50 x 50 km^2 cell.



(a) 2010



(b) 2050

Amazônia is the biome where growth of number of bovines is largest; its cattle herd grows from 38 MTLUs in 2010 to 60 MTLUs in 2030, and to 73 MTLUs in 2050 (rates of 55% and 90%). By 2050, 42% of Brazilian cattle will be herded in Amazônia. Despite the growth in the cattle herd, increase in productivity points to a stabilisation of pasture area around 56 Mha in most scenarios. Since expansion of pasture is directly linked to deforestation in Amazônia, assuring compliance with environmental law is critical to avoid a new surge in forest cuts [Arima et al., 2014]. Recent ground surveys in Pará show that property registration and supply chain agreements promote positive change in meatpacker and rancher behaviour [Gibbs et al., 2015]. Compliance with the Forest Code is crucial to foster gains in cattle productivity in Amazônia to avoid cattle expansion impacts on deforestation.

Cattle ranchers in the Cerrado cut their pastures more than in Amazônia, already in BAU. Cattle herd in the Cerrado remains stable at 47 MTLUs from 2010 to 2050; pasture decreases by 20% from 92 Mha in 2030 to 73 Mha in 2050, in the FC scenario. Without the small farms amnesty, pastures drop to 65 Mha. Such loss happens because of increased pressure for cropland expansion in the Cerrado.

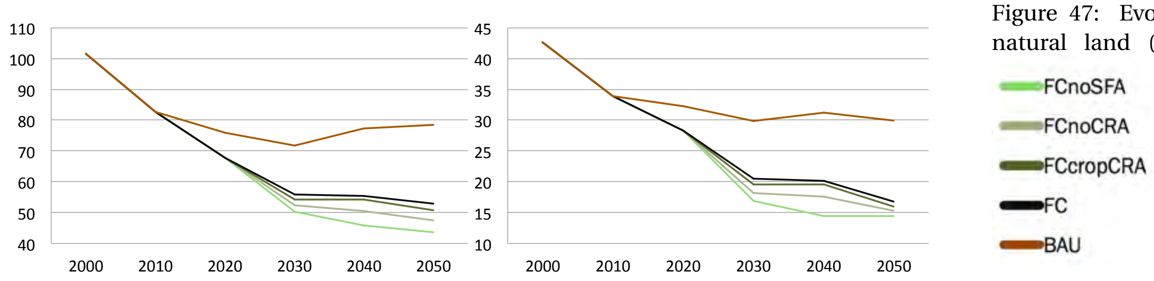
Trends in Mata Atlântica are similar to the Cerrado. In the Mata Atlântica, cropland expansion forces a drop in both pastures and bovine herd in all scenarios. Croplands grow from 24 Mha in 2010 to 37 Mha in 2030 and 42 Mha in 2050, while pastures decrease from 55 Mha in 2010 to 43 Mha in 2030 and 36 Mha in 2050(FC scenario). Cattle herd declines from 36 MTLUs in 2010 to 33 MTLUs in 2030.

Natural land

The largest land use change in GLOBIOM-Brazil scenarios is the decrease in natural land. In GLOBIOM, the 'natural land' class includes all natural vegetation classes, classified by the IGBP as 'open shrublands', 'closed shrublands', and 'non-forested savannas'. It also includes areas IBGE considers as 'secondary vegetation' and 'anthropic areas', already used by farmers[24]. In Brazil, the 'natural land' areas in 2000 are 102 Mha, with 36 Mha in Amazônia, 43 Mha in Cerrado, 6 Mha in Caatinga, and 14 Mha in Mata Atlântica. Most 'natural land' is areas where the Forest Code mandates a 20% protection of native vegetation.

[24] For matching between GLOBIOM land classes, IGBP land cover and the IBGE vegetation map, please see Table 2 above.

In GLOBIOM-Brazil scenarios, much crop expansion takes place over the 'natural land' class (Figure 47). In the FC scenario, the natural land decreases from 82 Mha in 2000 to 56 Mha in 2050, a loss of 32%. By 2050, we project 53 Mha of remaining natural land, out of which 29 Mha are protected areas (54%). The loss of natural land is particularly high in the Cerrado with a reduction of natural land by 13 Mha in 2050 with the forest code compared to BAU. The tighter the constraints on forest restoration needs are (FCnoCRA or FCnoSFA), the larger is the cut in natural land with the worse scenario being



(a) Natural land in Brazil

(b) Natural land in Cerrado

Figure 47: Evolution of natural land (in Mha).

the forest code without small farms amnesty. Since the area of natural land suitable for crop expansion will be limited from 2050 onwards, further pasture and cropland intensification will be needed for crop expansion beyond 2050.

Emissions from the LULUCF sectors: 2020-2050

Greenhouse gases emissions in Brazil: 1990-2012

To get a better context of projected greenhouse gases (GHG) emissions from land use change in Brazil, it is useful to consider how Brazil's emissions profile has evolved in recent years. In 2005, emissions in Brazil were 2.43 Gt CO_2e per year[25]. Two-thirds of these (65%) resulted from land use change, largely from deforestation in Amazônia. Emissions of GHG in Brazil fell to 1.58 Gt CO_2e in 2011, a drop of 35%, due to the decrease in deforestation [Boucher et al., 2014]. Emissions from land clearing fell from 1.57 Gt CO_2e in 2005 to just 0.57 Gt CO_2e in 2011. Emissions from energy and agriculture increased: energy-related emissions grew from 0.33 Gt CO_2e to 0.44 Gt CO_2e (an increase of 25%). Agriculture-related emissions grew from 0.42 Gt CO_2e to 0.44 Gt CO_2e (an increase of 4%), as shown in Figure 48.

[25] In our report, unless otherwise noted, GHG emissions are expressed in terms of their Global Warming potential (or GWP), one of the two options recommended by the IPCC for emissions reporting.

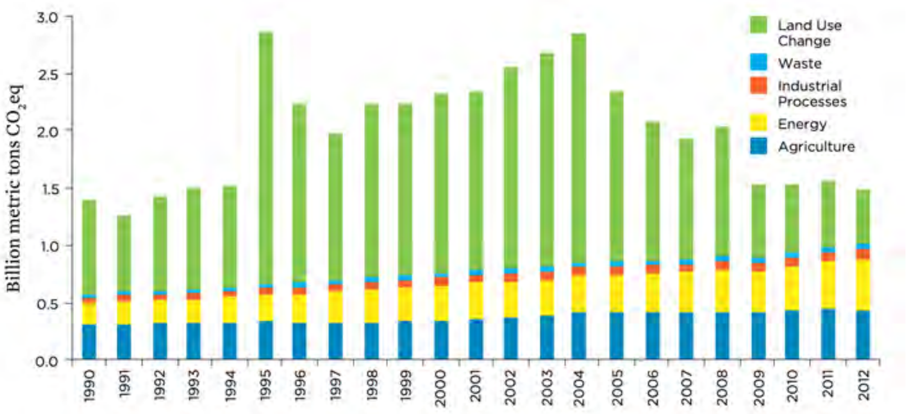


Figure 48: Brazil's GHG Emissions from 1990 to 2012 by Economic sector (source: SEEG–Observatório do Clima).

GHG Emissions from Land-Use Change and Forestry (LUCF)

GHG accounts of land use change actions use the carbon contents in the equilibrium states of the land cover classes[26]. Table 8 summarises the emissions related to land-use change transitions modelled by GLOBIOM-Brazil. Deforestation and other land-use change produce positive emissions, and afforestation from planted forests and reforestation by forest regrowth cause negative emissions, by removing CO_2 from the atmosphere.

[26] CO_2 coefficients for emissions and sinks are determined by the difference in the carbon content of the original class and of the new class.

Emissions		**Land Use Transition**	
Sign	**Action**	**From**	**To**
Positive	Deforestation	Mature Forest	Cropland
		Mature Forest	Pasture
	Other LUC	Pasture	Cropland
		Natural Land	Cropland
		Natural Land	Pasture
Negative	Afforestation	Cropland	Planted Forests
		Pasture	Planted Forests
		Natural Land	Planted Forests
	Reforestation	Cropland	Forest Regrowth
		Pasture	Forest Regrowth
		Natural Land	Forest Regrowth

Table 8: Land-use change transitions and associated emissions in GLOBIOM-Brazil.

Given the uncertainties on biomass data, the emission estimates use four biomass maps for Brazil. By default in GLOBIOM, carbon content in above- and below-ground living forest biomass and short-rotation plantations is taken from Kindermann et al. [2008]. For grasslands and other natural vegetation, GLOBIOM uses the biomass map of Ruesch and Gibbs [2008]. The Kindermann et al. [2008] map was adjusted to match FRA 2010 [FAO, 2010]. And we included two pan-tropical maps of above-ground live woody vegetation: Baccini et al. [2012] and Saatchi et al. [2011]. Baccini and Saatchi use data from the GLAS dataset, that provides systematic forest height and canopy structure estimates[27]. The authors use different ground datasets for calibration and different estimation methods, leading to significant differences in central Amazônia.

[27] GLAS is the Geoscience Laser Altimeter System instrument aboard the Ice, Cloud, and land Elevation (ICESat) satellite.

When natural vegetation is converted to agricultural use or to short rotation plantation, we consider that all below and aboveground biomass is released in the atmosphere. Litter, dead wood, and soil organic carbon are not accounted for. This is the approach that Brazil has adopted to compute the forest reference level submitted to UNFCCC. A more sophisticated approach is used in Aguiar et al. [2012], which we want to use in future studies.

The model accounts for carbon uptake from forest and natural land regeneration. In the model, forest regeneration on deforested areas varies from 20 to 75 years depending on the biome. In Amazônia and Mata Atlântica, mature forest regeneration takes 75 years. In Cerrado, Caatinga and Pantanal, it takes 20 years for forest to grow back to full biomass. As the Pampa has a grassland-based vegetation, regeneration of natural vegetation there takes 3 years. These regrowth periods per vegetation type are estimated using the annual increment from the G4M model[28], combined with carbon estimates given by Liu et al. [2015] for tropical forests, woody savannas and grasslands. For the Amazônia and Mata Atlântica forests, our vegetation growth curves assumes that tropical forests recover 70% of their original biomass in 25 years [Houghton et al., 2000] [Ramankutty et al., 2007]. However, forest under regeneration remains a separated class during the whole period of simulation to account for different impacts on biodiversity.

[28] G4M is a forest management model developed by IIASA, part of the integrated REDD model cluster together with EPIC and GLOBIOM.

Given the uncertainties of biomass maps, the net CO_2 emissions from land use change from 2010 to 2050 use an ensemble of estimates. We use four afforestation carbon uptake maps, and three different deforestation carbon emission maps. The ensemble has 12 cases and is summarised in Table 9.

Scenario	Action	Biomass Map
FC	Deforestation (3 cases)	Saatchi et al. (2011) Baccini et al. (2012) Kindermann et al. (2008) & FRA 2010
	Reforestation (4 cases)	Saatchi et al. (2011) Baccini et al. (2012) Kindermann et al. (2008) & FRA 2010 G4M Increment & Liu et al. (2015)
BAU	Deforestation	Saatchi et al. (2011) Baccini et al. (2012) Kindermann et al. (2008) & FRA 2010

Table 9: Ensemble of biomass maps and GLOBIOM-Brazil scenarios.

GLOBIOM estimates of emissions for CO_2 from LUCF for 2001–2010 are presented in Table 10, compared with Brazil's Forest Reference Emission Level (FREL), Aguiar et al. [2012] and Greenhouse Gas Emission Estimation System (SEEG)[29]. GLOBIOM-Brazil estimates for emissions from deforestation in Amazonia are within 3% of those of Brazil's FREL and of Aguiar et al. [2012]. Median estimates of our model for the whole Brazil are within 2% of the estimates given by the SEEG.

[29] Estimates from FREL, SEEG and Aguiar et al (2012) are their averages. Our estimates are median values for 2001–2010.

Study	Period	Coverage	Type	Emissions ($MtCO_2$)
FREL (MMA 2014)	2001 – 2010	Amazônia	Deforestation	872
Aguiar et al. (2012)	2000 – 2009	Amazônia	Deforestation	831
GLOBIOM-Brazil	2001 – 2010	Amazônia	Deforestation	862
SEEG (2014)	2001 – 2010	Brazil	LUCF	1326
GLOBIOM-Brazil	2001 – 2010	Brazil	LUCF	1404

Table 10: Comparison of GHG estimates from land use change. The GLOBIOM values shown are the median estimates for Amazônia and for Brazil.

We calculated the net CO_2 emissions from land use change for the whole Brazil and the Amazônia biome from 2000 to 2050. Emissions are broken down by emission type (deforestation, reforestation, afforestation and other land-use change). Release of carbon from the terrestrial biosphere to the atmosphere as CO_2 occurs in one 10 year simulation period for deforestation and other land use change. By contrast, CO_2 removal from the atmosphere by forest regrowth takes several decades. From 2010 to 2050, deforestation causes more emissions than absorption by forest regrowth. Planted forests remove small amounts of CO_2, compared to forest regrowth.

The Forest Code scenarios project low emissions in the decade 2020–2030 for Brazil (Figure 50(a)), and that net emissions from land use change will reach zero between 2030 and 2040. For Amazônia, the model projects a net sink after 2040 (Figure 50(b)). The avoided emissions from 2010 to 2050 for the FC scenario compared to the BAU one are 24.6 $GtCO_2e$. This is a significant contribution to GHG mitigation.

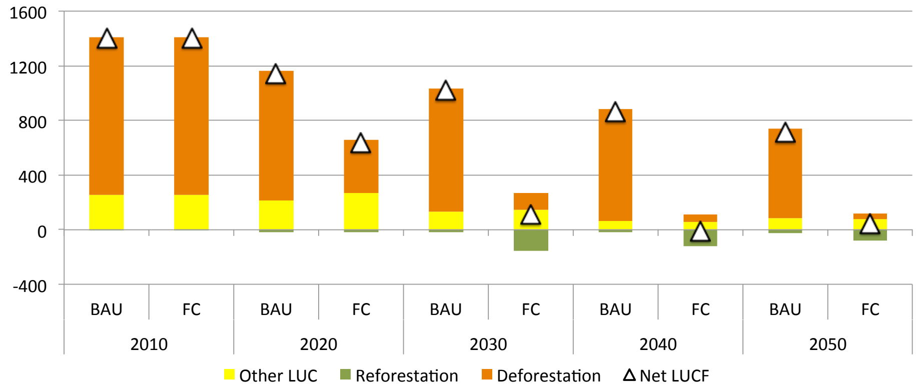
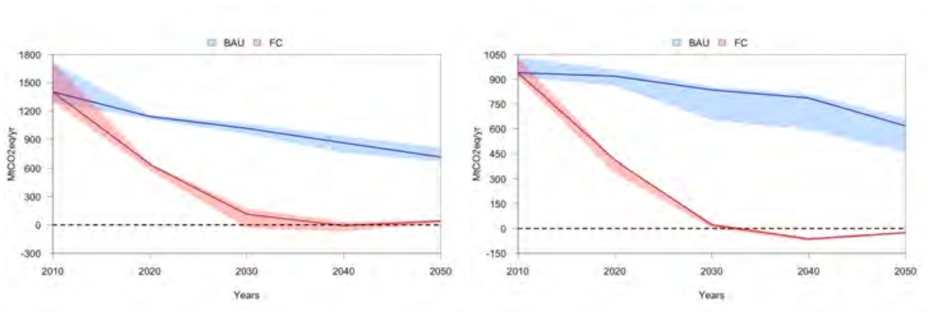


Figure 49: GHG emissions in Brazil from land-use change for different scenarios.



(a) Brazil (b) Amazonia

Figure 50: Net CO_2 emissions from land-use change and forestry in $MtCO_2e/yr$ for Brazil and Amazonia for BAU and FC scenarios. The solid line represents the median value and the shadow represents the range defined by the minimum and maximum values.

GHG emissions from the agricultural land use (LU)

As prescribed by the IPCC, emission estimates from agriculture include enteric fermentation, manure management, rice cultivation, field burning of agricultural residues, and agricultural soils. Agricultural soils include the emissions produced by synthetic and organic fertilizers [Cerri et al., 2009]. In GLOBIOM, the emissions from livestock are: CH_4 from enteric fermentation, CH_4 from manure management, and N_2O from excreta on pasture (N_2O from manure applied on cropland is reported in a separate account linked to crop production).

Emission estimates follow an IPCC tier 2 approach for each species, system and region, using the RUMINANT model[30][Thornton, 2010] [Herrero et al., 2013]. In brief, CH_4 from enteric fermentation is a simultaneous output of the feed-yield calculations in the RUMINANT model, nitrogen content of excreta and mass of volatile solids. The model emission coefficients takes into account different manure management systems, and manure uses.

[30] RUMINANT is a dynamic model for predicting feed intake, nutrient supply, and emissions associated to ruminants.

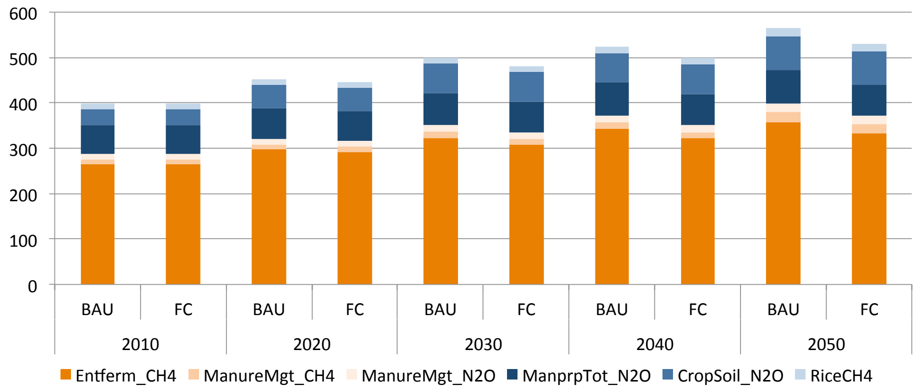


Figure 51: GHG emissions in Brazil from crop and livestock for different scenarios.

Crop emissions stem from N_2O fertilisation (synthetic and organic composts) and CH_4 emissions from rice cultivation. Estimates take data from the EPIC model on fertiliser use for each management system and emission factors from IPCC guidelines.

Synthetic fertiliser estimates use a bottom up approach. From the EPIC model, estimates of the quantity of phosphorous and nitrogen applied by hectare for each crop, each management system and each grid cell are used. Then, the total fertilizer use is adjusted at the national level based on International Fertiliser Association statistics. For rice, we apply a Tier 1 approach, where emissions are proportional to the cultivated area, given the emission factors from the US Environmental Protection Agency. To quantify organic fertiliser emissions, the RUMINANT model uses similar methods.

To validate our projections of emissions from land use, we compare baselines for 2000 to Cerri et al. [2009], and projections for 2010 with estimates from SEEG. For 2000, we found that GLOBIOM estimates and those from Cerri et al. [2009] differ by 21%. Our results tend to slightly overestimate emissions from enteric fermentation and underestimate emissions from fertilizer use (Crop soils), and emissions from field burning are not yet taken into account. For 2010, there is only 2% difference between land use emission estimates from GLOBIOM and those of SEEG.

GHG Emissions	2000		2010	
	GLOBIOM	Cerri	GLOBIOM	SEEG
Enteric Ferm.	213.05	204.8	266.22	234.32
Manure Mangmt	14.89	13.2	20.99	17.36
Rice Fields	11.68	5.0	12.89	9.75
Crop Soils	75.35	155.4	98.71	139.64
Field Burns	-	4.0	-	5.38
Total	314.97	382.4	398.81	406.45

Table 11: Comparison of GHG emissions estimates from land use (values expressed in $MtCO_2e$).

The projected emissions from land use in Brazil increase for the period 2020–2050. Emissions in the FC scenario grow from 400 $MtCO_2e$ in 2010 to 480 $MtCO_2e$ in 2030 and to 531 $MtCO_2e$ in 2050. Most land use emissions in Brazil (70%) come from range-fed livestock. To measure the effect of Brazil's agricultural emissions on global climate change, we follow the IPCC guidelines and convert them to GTP (Global Temperature Potential). In GTP measures, Brazil's emissions from agriculture are much smaller, ranging from 128 $MtCO_2e$ in 2010 to 154 $MtCO_2e$ in 2030 and to 170 $MtCO_2e$ in 2050.

According to Brazilian government estimates, emissions from LULUCF comprised 80% of the country's total in 2005, measured in GTP equivalentes. Considering the overall emission targets set by Brazil's INDC, which is 1.07 $MtCO_2e$ in GTP terms for 2030 (without mature forest removals), our results show that emissions from land use and land use change (LULUCF) represent 28% of total GHG country emissions. It means that emissions from energy, industry and residues will be more than 70% of Brazil's total. This is a major change compared the decades of 1980s, 1990s and 2000s when the LULUCF sector was responsible for most of the Brazilian emissions.

Impacts of land use change on biodiversity

Conversion of natural ecosystems for human use reduces their extent and harms their biodiversity, including through the loss and fragmentation of species habitats. These effects depend on the location and extent of the conversion, and on the new land uses. Each of the six different biomes of Brazil has unique ecological characteristics and has areas of especial importance for biodiversity. Using GLOBIOM-Brazil results, this assessment considers where land use change occurs in each biome compared to biodiversity priorities. Results show where biodiversity is under threat and point out the relative impact of each scenario. We also appraise how individual species ranges and habitats are affected.

The Brazilian Environment ministry (MMA) has identified biodiversity priority areas for Brazil[31] [Rosa et al., 2007]. Many of the areas identified as national priorities for biodiversity are under protection. Since GLOBIOM assumes protected areas stop land use change, its results are useful to assess pressures on unprotected biodiversity priority areas. Our study focuses on these areas and on broader impacts on species.

[31] They selected priorities based on importance and urgency. Biological diversity areas are identified as 'important', 'very important', 'extremely important' or 'having insufficient data'.

Biodiversity representation in GLOBIOM-Brazil

In the model, the 'natural land' class includes both areas of natural vegetation and abandoned farmland. Biodiversity impacts of converting natural land to production depends on whether agriculture expands on abandoned land or on natural areas. To assess this conversion, we used estimates of natural vegetation remnants in 2010 done from Soares-Filho et al. [2014], and compared them with the model results in the same year.

GLOBIOM works in 50x50km^2 cells; information on biodiversity priorities is at a finer resolution. We need extra assumptions to merge the two data sets. Consider a grid-cell with 100% forest cover and where 50% is a biodiversity priority area. The biodiversity impact of losing of 25% of its forest cover depends whether change occurs inside or outside the priority area. We assume different land classes in a grid-cell are evenly distributed, regardless of where biodiversity priority areas are located. The affect of this assumption is explored in relation to deforestation.

Overall impacts on biodiversity for different scenarios

The increase or stabilisation of forest cover in all scenarios at first glance appears to be positive for biodiversity. Forest areas are high in biodiversity and reductions of forest cover are linked to significant losses in forest-dependent biodiversity.

However, this trend in total forest masks a decrease in mature forests that has negative consequences. Although forest regrowth compensates the CO_2 emissions from forest cuts, biodiversity loss is not easily reversed. Regenerating forests support different species and communities compared to primary forests and it can take up to 300 years for biodiversity to recover when forest regenerates [Liebsch et al., 2008]. As the 'mature forest category in GLOBIOM covers all forest that was standing and not being used for timber in 2010, it will therefor include all of Brazil's primary forest.

The FC scenario leads to much smaller losses of mature forest compared to the BAU scenario. However, 11% of mature forests outside protected areas will still be cut by 2050. The scenario without environmental quotes (FCnoCRA) leads to an increase in loss of mature forest compared the FC scenario. Highlighting that how environmental quota are put into practice may affect forest conservation and biodiversity.

The overall stabilisation of total forest cover also masks an uneven distribution of deforestation across Brazil. In the Caatinga biome, the FC scenarios show increases in deforestation compared to the BAU, due to displacement of land use from the other more protected biomes.

The Caatinga experiences the largest relative loss of forest in all forest code scenarios: between 24% to 51% of dry forest is cut by 2050 depending on scenario. The Caatinga is a mosaic of shrubs and seasonal dry forests [Beuchle et al., 2015], a long dry season and irregular rainfall [Rosa et al., 2007]. In the past, it had been overlooked and described as a biodiversity poor area. More recent studies emphasise its biological richness (156 mammal species, 510 birds, 175 reptiles and 79 amphibians, along with over 1000 plant species) and the value of its endemic species [Albuquerque et al., 2012].

Natural vegetation remnants occur outside areas designated as forest in the model, classified as 'natural land'. Loss of these areas has potential negative effects on biodiversity as species of conservation concern occur outside forest areas. For the Cerrado and Pantanal biomes, Soares-Filho et al. [2014] estimate of natural vegetation remnants are over double the models projection for forest area. The implementation of the forest code scenarios lead to higher losses of natural vegetation, especially in Cerrado, which is likely to cause a negative impact on grassland and shrubland biodiversity in Brazil.

Impacts on biodiversity priority areas

Changes in priority areas for biodiversity outside protected areas mirror the wider changes across the different biomes. Figure 52 shows land use change in ‘extremely important’ unprotected biodiversity priority areas, for all model scenarios. Each bar stands for the change in one biome (as a percentage of the total biome area) for a scenario. The brown section of each bar is the decrease in mature forest, the yellow-brown section is for the change in natural land and the green section is reforestation.

The forest code implementation leads to significant improvements in preservation of biodiversity rich natural habitats in Amazônia; decreasing loss of unprotected ’extremely important’ biodiversity priority area from 26% in the BAU to 9% in the FC scenario. However, model projections show higher threats to forests in biodiversity priority areas of the Caatinga. The biome loses forest over 17% of the total area of biodiversity importance not in protected areas from 2010 to 2050 in the FC scenario compared to -9% in BAU. This represents a loss of over 50% of the forest remaining in unprotected biodiversity priority areas in 2010. The amount of other natural land in unprotected biodiversity priority areas is project to increase in the Caatinga as farmland is abandoned. These areas will have very different biodiversity from mature forests.

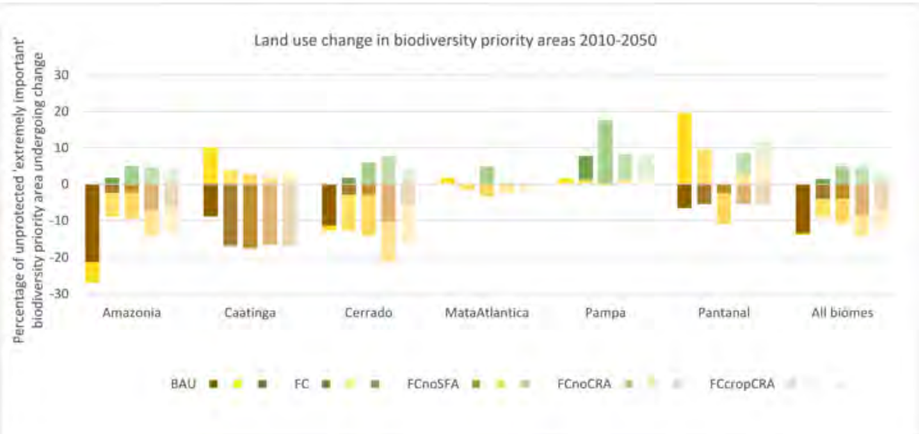


Figure 52: Projected change in area of mature forest (browns), natural land (yellows) and reforested land (greens) within unprotected biodiversity priority areas in each biome under different scenarios.

For the Cerrado biome, while the loss of forest within biodiversity priority areas decreases with the full implementation of the forest code, the model projects an increased risk of conversion of natural lands. In total 13% of the ‘extremely important’ unprotected biodiversity priority area in the Cerrado is at risk of conversion during 2010 to 2050 in the FC scenario. Although the conversion is project only over a minority of the total area of unprotected biodiversity priority, this conversion represents a loss of nearly %80 of the natural land remaining in 2010.

The removal of the small farms amnesty (FCnoSFA) leads to higher forest regrowth (Figure 53). Depending on how forest restoration is undertaken these areas may support biodiversity in the future, and although, there is an increase in loss of natural land in the FCnoSFA scenario compared to the FC scenario, this a small loss for all biomes except the Pantanal. To the contrary, the removal of environmental quotas seems to reduce the overall natural vegetation in biodiversity priority areas by 2050, in particular in Amazônia and Cerrado (FCnoCRA and FCcropCRA).

Figure 53 shows the distribution of biodiversity priority areas and the projected land use change inside them. In the BAU scenario, the greatest loss of priority forest areas is in the Amazon biome. The Caatinga loses more forest in biodiversity priority areas than any other biome in the FC scenario. The Cerrado shows the greatest loss of natural land.

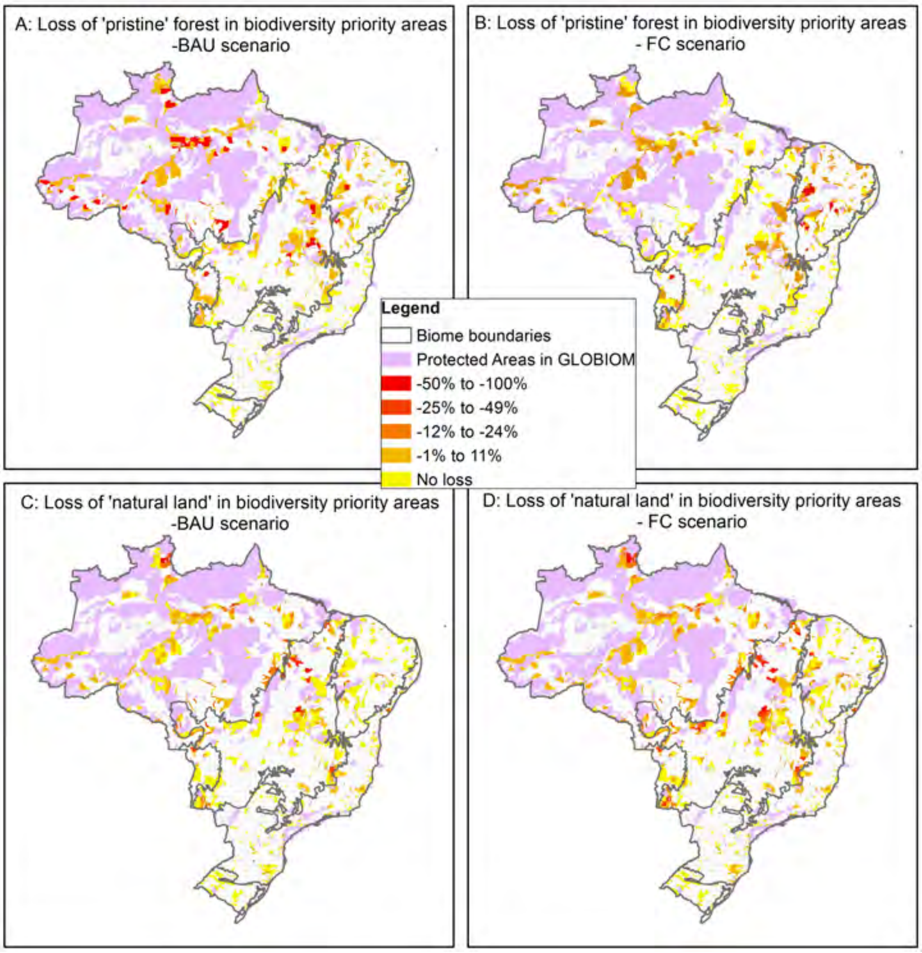


Figure 53: Change in mature forest (upper panels) and natural land (lower panels) in Brazil's biodiversity priority areas under two different scenarios: (A and C) business as usual, BAU; (B and D) forest code, FC. Protected areas are also highlighted. These areas are likely to be important for biodiversity but do not change in the simulations.

Figure 54 shows the uncertainty in projections of deforestation in biodiversity priority areas of Brazilian biomes in five scenarios. Under an assumption that initial forest area is evenly distributed across the gridecells, the difference between the scenarios is larger than the uncertainty on where deforestation occurs in relation to priority areas (the error bars in figure 54). However, an additional source of uncertainty is the precise location of initial forest cover in relation to the priority areas.

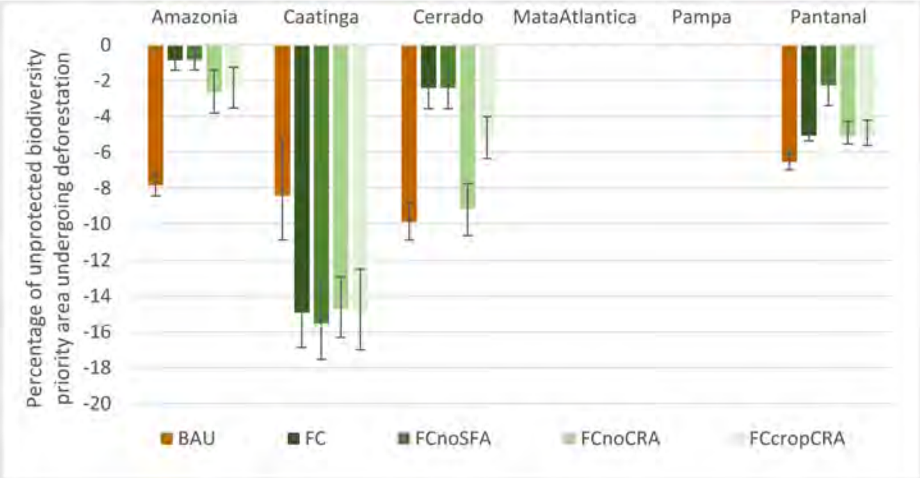


Figure 54: Variation in deforestation projected to occur in unprotected biodiversity priority areas; for each biome the bars represent different scenarios and the error bars show uncertainty due to local allocation.

Impacts of land use change on species

To assess how land use change affects species, we focus on species of particular interest (for example legally protected species, threatened species, specific taxa such as birds, mammals). To work out how land use change influences each individual species, we identify the expected loss of its potential habitat. The number of species that lose a large part of their habitat highlights the impact across species.

Patterns of species richness can differ between groups; selecting which species are of interest will influence the conclusions. To reduce the rate of species extinctions and so support Aichi and Brazilian biodiversity targets, information on how land use change influences threatened species is especially relevant. In Brazil, the Chico Mendes Institute for Biodiversity Conservation (ICMBio) evaluates species conservation status and identifies those that are at risk. Our assessment considers 311 mammals, birds and amphibians identified by ICMBio as endangered and for which IUCN has data available on its global Red List (http://www.iucnredlist.org/)[32].

For each species, we took its habitat needs from the IUCN database and matched them to the GLOBIOM classes[33]. Our assessment considers cases where land use change destroys a large part of one species' habitat and where land use change affects many species. To do this, we use a composite index of 'combined species habitat change'(Figure 55).

As shown in Figure 55, the index maps information on the range of species (A) to the grid (B), considering their relative endemism, based on how much of the species range is inside each cell. Higher weights on species with smaller ranges are shown in darker grey. We combine the result with the locations with changes in potentially suitable habitat (e.g. natural shrubland is lost) (C–red squares). This allows us to identify where each species loses (or gains) habitat (D) and the proportion of its habitat affected by the change (depth of red colour). Then, we add the information on habitat change for all species (E).

[32] Mammals, birds and amphibians are the groups for which the IUCN has more data.

[33] Matching is largely straightforward apart from the IUCN 'savanna' class, which includes species which need forest patches and those that need grasses and shrublands. We consider that savanna species occur in both GLOBIOM 'forest' and 'natural land' classes.

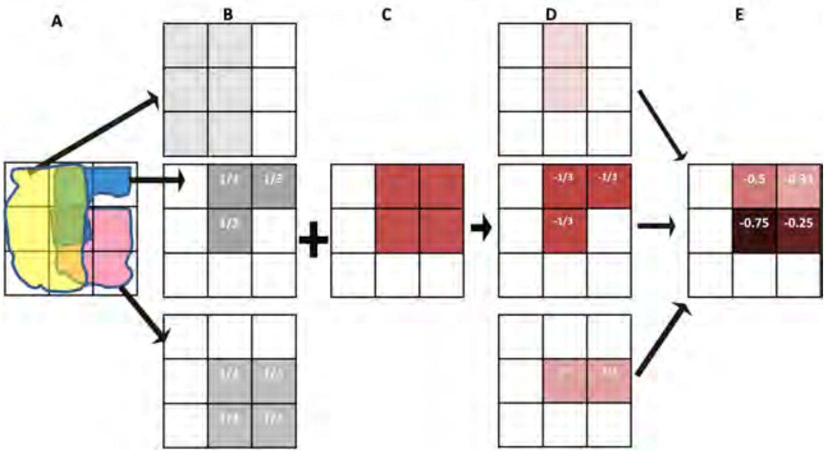


Figure 55: A spatially explicit index of combined species habitat change.

We analysed the impact of the scenarios on the 311 chosen species. Under the BAU scenario, over 41% of the species assessed lose over 5% of their potential habitat (Figure 56). This loss is limited to 24% in the FC scenario and the number of species losing over 25% of their potential habitat is smaller in the FC than in the BAU scenario (6 and 20 species respectively). Without environmental quotas, the number of species losing over 5% of their habitat is larger than with the FC scenario; the number of species that lose over 25% of their habitat is larger than both the FC and the BAU scenarios.

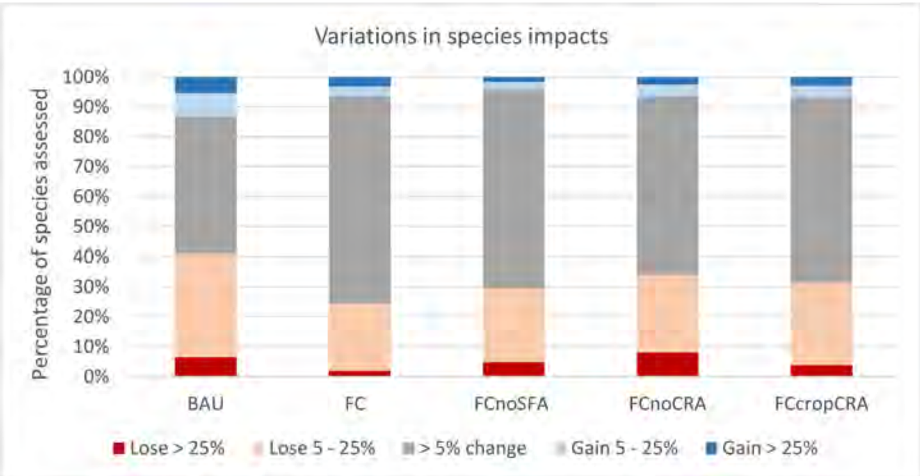


Figure 56: Impacts on species of modelled land use change under five scenarios, expressed as percentage of the assessed species projected to experience different degrees of net change in extent of potential habitat.

How forest regeneration is implemented matters. If regeneration occurs in ways that allow forest species to recolonise the areas faster, net habitat loss is reduced. Species may even increase their available habitats. We compared the case where regenerated areas are not suitable for forest species to the opposite situation, where forest regrowth favours recolonisation (see Figure 57). Differences can be significant. For the FC scenarios, how regeneration happens affects over 38% of the species, including 13 where it causes a gain of greater than 5% of their potential habitat. This is shown by the change in size of the blue section of the bars in Figure 57.

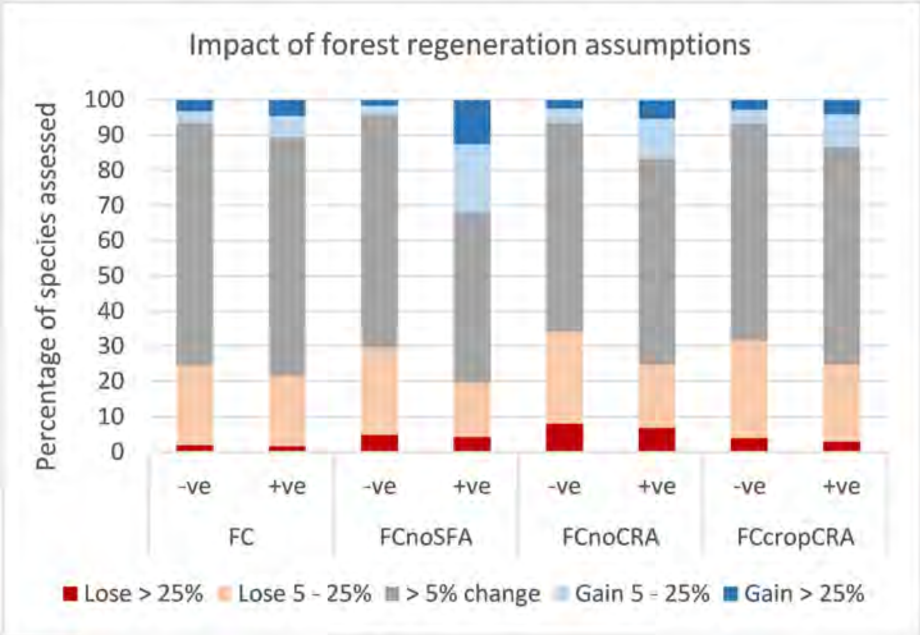


Figure 57: Variation in the impact of land use change on species depending on how forest regeneration happens. For each scenario, the left hand bar is the case when regenerated areas are not suitable for forest species (-ve) and the right hand bar represents the opposite assumption (+ve).

Land use change affects individual species in different ways, as shown in Figure 58. Loss of habitat for the Jaguar (*Panthera onca*) and Moustached woodcreeper (*Xiphocolaptes falcirostris*) is smaller in the FC scenario than in the BAU. For Cerrado and Caatinga species such as the Brazilian three-banded armadillo (*Tolypeutes tricinctus*) and the Golden-bellied capuchin (*Cebus xanthosternos*) their habitat loss is greater in the FC than in the BAU. Not having quotas or implementing them only for croplands leads to even greater habitat loss than the FC scenario. This shows the quota mechanism helps conserve biodiversity.

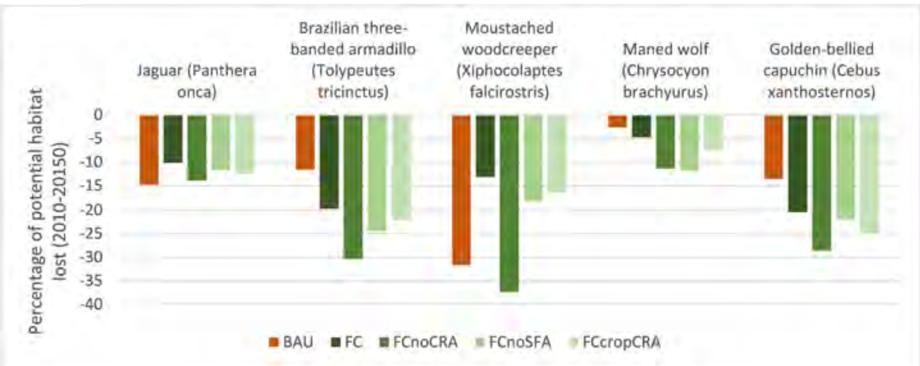


Figure 58: Impact of the policy scenarios on five different species. The five species were selected to illustrate the variability in impact between species.

We combined the expected influence of land use change on individual species for all assessed species. Impacts will be larger where land use change causes species to lose a large part of their habitat, due to the species having a small range. The resulting 'index of combined species habitat change' (Figure 59) shows that areas of the Cerrado and Caatinga suffer the greatest biodiversity losses in all scenarios. Loss in Amazônia is large in the BAU scenario, but is reduced in the Forest Code scenarios.

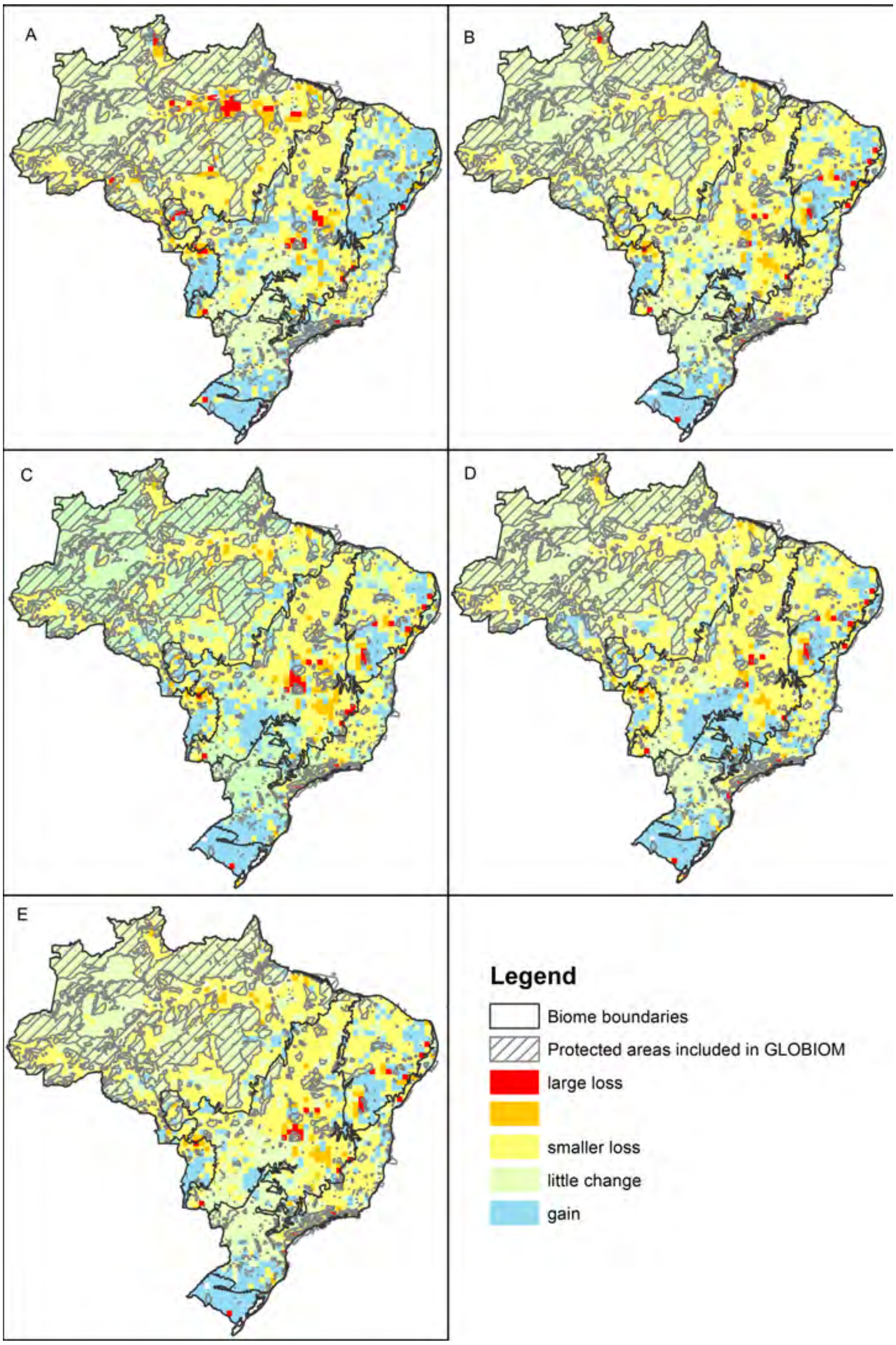


Figure 59: Map of combined species habitat change under the different scenarios: (a) BAU; (b) Forest Code; (c) FC without the small farms amnesty (FCnoSFA); (d) FC without the environmental reserve quotas (FCnoCRA); and (e) FC with the quota being used only by crop farmers (FCcropCRA). The maps shows the combined impact of land use change on biodiversity, considering both losses in a large proportion of a species' habitat and where places where land use change harms a large number of species. Potential gains in the Pampa and Caatinga need to be interpreted with caution. Changes from cropland to 'natural land', due to agricultural production becoming unprofitable, do not necessarily improve habitat needs of species, since it takes time for species to recolonise areas.

Discussion of model results

Production and deforestation

The trend in all Forest Code-related scenarios modelled by GLOBIOM-Brazil for 2000-2050 is that total forest area stabilises while agricultural production keeps increasing. This expansion takes place outside of Amazônia, most of it in the Cerrado and Mata Atlântica, with focus in the MATOPIBA. Scenarios show that enforcing the Forest Code does not prevent cropland expansion.

Most of the cropland expansion occurs in natural land, whose availability will be limited from 2050 onwards. Thus, farmers will need to further improve yields and promote pasture intensification beyond 2050.

In the Cerrado and Mata Atlântica, improvements in cattle diet and cropland expansion lead to intensification of cattle production. Cattle herds in these biomes decrease by 5%, while pasture area gets smaller by 20%. Amazônia is the only biome where cattle herds increase and pasture area does not decrease. Brazil needs to continue to commit large resources for law enforcement in Amazônia, given the challenge of controlling expanding cattle ranching.

Small farms amnesty

The small farms amnesty reduces forest regrowth. Without this rule, the model projects an extra 33 Mha of forest regrowth by 2050. Within Brazil's public debate on REDD+ it has been proposed that finance from REDD+ be used to help small farmers restore their legal reserve deficits. This policy would promote forest regrowth without damaging mature forests.

The policy of REDD+ payments to small farmers faces legal and practical challenges. Large farmers can bring about judicial action for equality of rights. Such incentives are likely to induce large-scale farmers to break their large farms in small ones. Payments could lead to leakages; REDD+ money given to protect one area finances deforestation elsewhere. Over-burdened public institutions would find it hard to control such opportunistic behaviour.

Environmental reserve quotas

Model results point out quotas have mixed outcomes. As more quotas are used to offset legal reserve deficits, less forest is restored and more mature forest is protected. When both crop farmers and cattle ranchers use quotas, and all quotas are used, the model projects 11 Mha of forest regrowth by 2050. If crop farmers are the only ones to buy quotas, forest regrowth increases to 24 MHa by 2050. If no quotas are available, regrowth reaches 35 Mha by 2050. Without environmental quotas, results point to an extra loss of 15 Mha of mature forest in Brazil (4%) and 6 Mha in Amazonia (2%), compared to the Forest Code projections.

Implementation of quotas has important implications for biodiversity. Secondary and regenerating forests support different species and communities than primary and mature forests. Mature forests have higher biodiversity value than areas of regrowth; it can take up to 300 years for biodiversity to come back when forest regenerates [Liebsch et al., 2008]. Since the model scenarios show that quotas prevent loss of mature forest, use of quotas supports Brazil in achieving the REDD+ safeguards[34]. The more quotas are used, the better for biodiversity conservation.

[34] All parties to the UNFCCC, including Brazil, agreed to "promote and support" the REDD+ Cancun Safeguards. These include safeguard 'e', which calls on countries to make sure that [REDD+ actions are] *"consistent with the conservation of natural forests and biological diversity, ensuring that [actions] are not used for conversion of natural forest, but are instead used to incentivise the protection and conservation of forests..."*.

In Brazil's public debate there has been a suggestion that the government should, using REDD+ funds, buy all (or most) available quotas. This would force all farmers and ranchers to restore forest. This action would put strong pressure on crop farmers, who have less margin than cattle ranchers to reduce their productive areas.

Government intervention in the quota market leads to price distortions and needs large investment of public funds. At most this would preserve 5% of forest across Brazil (and 2% of Amazonian rainforest) that is projected to be lost in the Forest Code scenario. Based on the available data, using REDD+ finance to buy quotas does not seem likely to bring a large benefit to Brazil[35].

[35] This recommendation should be revised if the implementation of the rural environment cadastre shows that our legal reserve estimates were not accurate.

Policy balance

Overall, a REDD+ strategy for Brazil needs to balance conserving mature forests, promoting forest regrowth, reducing emissions, and conserving biodiversity.

The modelled scenarios show that in the 2030–2040 decade, Brazil can reach zero emissions from land use change if the Forest Code is fully applied. The share of Brazil's total emissions that come from land use change will also decrease. Emissions from land use, land use change and forestry (LULUCF) were 80% of total GHG Brazilian emissions in 2005 in GTP measures[36]. Model results project LULUCF emissions from Brazil to be 28% of the total in GTP measures by 2030, a major drop in 25 years.

[36] source: MMA - Brazilian Ministry for the Environment

Land use change will affect biodiversity in Brazil. The Forest Code limits the overall impacts of land use change on biodiversity, including the total number of species that lose habitat. This general picture does not hold across all biomes or land cover types. In all scenarios, the Caatinga loses forest. Crop expansion in the Cerrado is likely to remove remnants of non-forest natural vegetation, including both shrublands and grasslands housing important biodiversity. Since the Caatinga is an area with many endemic species and the Cerrado is one of the world's biodiversity hotspots, more protection measures are needed for both biomes.

The overall message from modelled scenarios is positive: Brazil's Forest Code has achieved a compromise between protection and production. It enables economic gain from agriculture, without significant loss of mature forests, and with zero emissions from land use change. The Forest Code is the centrepiece of Brazilian land policy and its enforcement should be the major focus of Brazil's approach to REDD+.

Uncertainty on current results and planned evolution of GLOBIOM-Brazil

To put our results in context, we need to consider the major sources of uncertainty in the GLOBIOM-Brazil model. We present our hypothesis, consider alternatives and point out how we plan to deal with these issues in future versions of the model.

Our scenarios will continue to be developed with stakeholders at Brazil's Environmental Ministry. We will place particular emphasis on scenarios that lead to zero net emissions resulting from the land use change and forest sector.

Legal reserve deficits and surpluses

The deficits and surpluses of legal reserve are the basis for Forest Code enforcement. Since implementation of the rural cadastre is still ongoing and data is not available, we do not have the data on boundaries of rural properties. Legal reserve deficits and surpluses were computed inside 50 km x 50 km cells, using land use data from IBGE as the basis for legal reserve estimation[37].

[37] Soares-Filho et al. [2014] used another approach by using drainage basins as their basic spatial units and combined their limits with land cover maps derived from remote sensing.

In most cases, a 50 km x 50 km cell contains many rural properties. To quantify legal reserves debts and surpluses, we compute the overall surplus or deficit per cell, ignoring internal differences. Consider a grid with two properties of the same size inside the Amazônia biome, which requires an 80% legal reserve. If one farm has a 100% forest cover and the other has a 60% forest cover, in our estimates this is the same as two farms with 80% forest cover each. The cell has neither surplus nor deficit of legal reserve. This approach underestimates the needs for forest restoration. We will replace the current assumption as soon as data from the rural cadastre will become available.

Implementation of the environmental reserve quota market

Due to the lack of detailed data, we made simplifying assumptions for the environmental quota market. Simulation cells with larger deficits are compensated first; cells with larger surpluses are used first to offset the debts. This simplification is justified because locations with higher deficits are more likely to have higher opportunity costs. In these areas, landowners are more inclined to buy quotas instead of reforesting. Places with higher surpluses are more likely to have lower opportunity costs. The corresponding landowners are more willing to sell their available quotas, instead of suppressing the excess of vegetation for productive use.

These assumptions are exploratory. It is not yet clear how the quota market will work, and how accessible it will be for farmers. Depending on the transaction costs, landowners with less economic means might find it hard to offer quotas in the market. A detailed representation of the quota market, based on property data, land prices and transaction costs, will be part of future development in GLOBIOM-Brazil.

Destination of public lands in the state of Amazonas

Public lands in Amazônia are a second source of uncertainty on the calculus of legal reserves. These are lands not yet destined for protection, nor have been claimed as private properties. The lack of information is acute in the big state of Amazonas, which has an area of 1.571 million km^2 where large regions are yet to be destined. A large part of these areas are in places with difficult access and have limited commercial value per se. Registering these areas as private farms creates a large offer of environmental reserve quotas, distorting the market.

The Brazilian Ministry for the Environment (MMA) knows these risks and is pushing for new land regulations that prevents these areas of being used for speculation. Our assumption that only 20% of the unclaimed public lands in the state of Amazonas will be part of the rural cadastre is based on consultation with stakeholders at MMA. The hypothesis reflects their expectations on how the quota market will be regulated. In the coming years, we will follow how the federal and state authorities deal with public lands in the state of Amazonas and will update our model.

Costs of forest restoration in private lands

Landowners with legal reserve deficit need to decide between reforesting or keeping productive land by acquiring quotas. To do this, they will consider the costs of forest restoration; estimates vary from US$1,000 to US$20,000 per hectare. In Mata Atlântica and the Cerrado, different species of *Brachiaria* grass are spread over the biome due to the cattle grazing. This makes forest restoration hard in these biomes, without preparing the soil for regrowth. In the current version, the model does not account for the costs of forest restoration. We plan to include restoration costs and assess compensation programs that promote regrowth in future versions of the model.

Crop production in the Caatinga

The model projects a drop of 11 Mha of dry forests in the Caatinga from 2000 to 2050, due to cropland expansion. This result needs to be taken with care, given the likelihood of current and future impacts on global climate change in the region. Yields in the Caatinga have been low since 2010. Recent surveys point out that smallholders already report a shift of the rainy season, warmer temperatures, and more concentrated rainfalls [Nasuti et al., 2013]. Yields are projected to decrease even further as less water will be available under future climate change [Salazar et al., 2007].

Although productivity is low, there are incentives for expanding crop production in the Caatinga biome. Farmers expect to be compensated by the government in a case of droughts. The productive systems in the Caatinga are thus part of a patronage system that encourages farmers to plant, regardless of climate predictions [Nelson and Finan, 2009].

The way GLOBIOM-Brazil handles water availability is one of the main causes of uncertainties in the Caatinga. We limit agricultural expansion in the Caatinga to a 10% increase per period, since the model is likely to underestimate water constraints faced by farmers. In future work, we plan to improve representation of the Caatinga to capture its unique vulnerability, with special focus on water issues. The EPIC model outputs will be compared with current observations and climate change impacts will be included in GLOBIOM-Brazil.

Scale of the IBGE vegetation map

The IBGE vegetation map is our primary source of information on natural vegetation in the Cerrado and Caatinga biomes. This is the authoritative source of classification of Brazilian vegetation and is used as the reference for Brazils FREL (Forest Reference Emissions Level) to the UNFCCC. Its temporal reference is the year 2000, the same starting date chosen for the GLOBIOM model. It would be desirable to use a reference map with a more detailed scale than the IBGE one (1:5,000,000), if one were available.

We tested other data sources: the Global Land Cover (GLC) map by the EC Joint Research Centre [Bartholomé and Belward, 2005] and the PROBIO map by different Brazilian institutions[38]. Using the IBGE vegetation map enabled us to get better results in 2010 compared to observations than using either

[38] PROBIO data is avaliable at http://mapas.mma.gov.br/mapas/aplic/probio/datadownload.htm.

GLC or the PROBIO maps[39]. For forest remnants in Mata Atlantica, we used SOS Mata Atlantica maps, to complement IBGE vegetation map data - this allowed us to capture small patches of forest in that biome.

[39] We relied on advice from INPE experts.

For future work on GLOBIOM-Brazil, we plan to use new land use maps being developed by INPE and EMBRAPA for the Cerrado. We expect those new maps will improve our estimates of forests, natural land and productive land in the biome.

Pasture productivity gains

We had to make assumptions on current and future pasture productivity, due to lack of data on carrying capacity of pasture. Significant productivity gains are included in the model through pasture intensification and transition to mixed livestock systems.

Our hypothesis was based on current trends. However, the extent of degraded pasture and the investment cost required to increase pasture productivity are uncertain and need further research. Cattle feed in Brazil is based on pasture. To model the transition to mixed intensive-extensive production systems, we need to improve the cattle supply chain in the model. We plan to collect data to better simulate pasture productivity under different management systems for Brazil.

Crop productivity gains

Double-cropping has enabled large productivity gains in Brazil over the last decade. In Mato Grosso, more than half of the cultivated area used double-cropping in 2011 [Spera et al., 2014]. GLOBIOM-Brazil does not include this productive system, leading to a likely overestimation of cropland expansion. Including double-cropping in our estimates will be one of the priorities for future model improvements.

Protected areas

The current version of the model allows no productive land use inside protected areas. As land use within protected areas is in most cases at low intensity, its impact on removal of forests and natural lands is limited. In some protected areas, especially extractive and sustainable development reserves, uses such as collecting of non-timber forest produces (NTFPs) provide an important source of income. Since these products are not included in GLOBIOM-Brazil, the model does not capture the full economic value of standing forests, or of protected areas. A future aim in model development is to include productive uses inside protected areas.

In 2003, Brazil set up the Amazon Region Protected Areas Program (ARPA), to invest in the creation, consolidation, and financial sustainability of the Brazilian Amazon Conservation Units. The ARPA program created 63 Conservation Units with close to 340,000 km^2, investing US$ 105 million. In the future, we plan to develop scenarios related to new protected areas planned in the ARPA program.

Impacts on biodiversity

Our evaluation points out how different scenarios affects biodiversity both in terms of biodiversity priority areas and species. The assessment of impacts on biodiversity priority areas was based on areas identified by MMA in 2007. MMA is currently undertaking a process to review and update the list of priority areas. We plan to update the assessment with the new areas once they become available.

To assess the impacts on species, we had to make assumptions about how the habitat preferences of species relate to the model's land use categories. Some species are associated to specific habitats, e.g., tropical dry forests. As the model has a limited number of land use classes, we had to make things simpler. Species were assigned as having broad habitat preferences corresponding to the model land use classes.

To reduce the effect of this assumption, we combined habitat preference information with species potential range. The range of vegetation types that are considered suitable for any given species is thus reduced. When more than one sub-type of forest or other natural land occur within one cell it could lead to under- or over-estimations of habitat loss. A second simplification was that species were either considered as occurring or not occurring in different land uses, in reality there is likely to be continuum of suitability. This is especially the case in terms of regenerating areas, when over time the area may become increasingly suitable for species, the impact of this uncertainty was explored by comparing the two extremes.

In addition, there are also other potential impacts of land use on biodiversity that are not addressed by our results, including those associated with fragmentation, land degradation and different cultivation practises. We need to combine the potential effects of land use change with information on changes due to other pressures, such as illegal hunting, pollution and climate change. Such analysis will help to build a more thorough understanding of the future of biodiversity in Brazil.

Biofuels

Biofuel demand in Brazil depends on oil price and thus is uncertain in Brazil. Despite Brazil being the second-largest bioethanol producer in the world, the sector has faced problems since 2009. Most of the cars in Brazil are flex cars that can switch from oil to ethanol. In future work, we intend to consider alternative biofuel use according to different oil prices. We will consider possible European and US regulations on biofuels that could increase sugarcane production.

International trade

Brazil has become a major player on international agricultural markets over the last decade. Our results show that this trend can even reinforce in the next decades, with large Brazilian exports to China, Africa and the Middle East. External demand for Brazilian products is major driver of land use chance. Future work on GLOBIOM-Brazil has to consider factors that will affect Brazil competitiveness on international markets.

If multilateral trade liberalisation has made little progress, bilateral discussions could lower tariffs faced by Brazil in key regions. For instance, a trade agreement between the EU and MERCOSUR that would cover agricultural commodities is under discussion. It is important to consider not only trade agreements in which Brazil is a member. The Trans-Pacific Partnership (TPP), involving the USA, Japan, Mexico, Peru, Chile, Canada, Malaysia, Singapore, Vietnam, Brunei, Australia and New Zealand could have indirect impacts on Brazil.

Another source of uncertainty is how exchange rates will evolve. Brazil is going through a major exchange rate adjustment, with a 81% raise in the dollar value against the Brazilian real in two years. The yuan devaluation could slow down Chinese imports from Brazil. We plan to run scenarios to investigate how changes in exchange rates could affect our results.

Conclusions

This report shows possible trajectories of land use change in Brazil from 2020 to 2050, using the GLOBIOM-Brazil model. The model considers environmental policies, agricultural production and external trade. In model scenarios, forest area stabilises while agricultural production keeps increasing. A compromise between environmental protection and agricultural production results from the full application of Brazil's Forest Code. Results show the proposed cuts in emissions from land use change in Brazil's INDC are achievable.

The Forest Code allows zero net deforestation in Amazônia, where agricultural production will be dominated by cattle raising. Major cropland expansion occurs in the Cerrado and in Mata Atlântica, using both natural lands and spare land from pasture intensification. Such pressures on natural vegetation suggest that, to avoid significant biodiversity losses in Caatinga and the Cerrado, Brazil needs extra preservation measures in these biomes.

Brazil could become a net carbon sink in the next decades. Forest regrowth due to implementation of Forest Code rules offsets emissions resulting from legal deforestation in the 2020–2030 decade, reducing the net emissions by 90% compared to 2005. In the 2030–2040 decade, Brazil reaches zero emissions from land use change in the Forest Code scenarios.

The overall message of this report is the crucial importance for Brazil of implementing the Forest Code. To do so, the country faces major challenges. Building a high quality rural environmental cadastre is key to monitoring forest restoration. Brazil needs to set up a monitoring system for the whole country as powerful as the one in place for Amazônia. Legal reserve amnesty should be limited to small farmers, avoiding illicit break-up of large farms. The market for environmental quotas needs to be regulated to avoid leakages and enhance forest conservation. Strong action to avoid illegal deforestation in Amazonia must continue to be enforced. The right incentives for efficient production must be in place, including the Low Carbon Agriculture plan. If Brazil overcomes these challenges, there will be multiple benefits for its citizens, including biodiversity protection, emissions mitigation, and positive institution building.

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Annex 1: Full list of model refinements implemented in GLOBIOM-Brazil

(1) Inclusion of protection areas: Brazil's federal, state and municipal networks of protected areas defined by the Brazilian Ministry of the Environment (MMA) were incorporated in the model. Conversions and productive activities are not allowed inside these areas.

(2) New land use class for forest regrowth: To implement the Brazil's Forest Code, a new land use class named 'ForReg' was incorporated in the GLOBIOM model. This new class allows for transitions from cropland, pasture and natural land areas. No conversions are allowed from 'ForReg' to other land use classes. The non-linear land conversion costs (SLOPE and INTERCEPT) are the same for all allowed transitions to 'ForReg'.

(3) Modifications in planted forests: Representation of short rotation tree plantations was improved in GLOBIOM to cover charcoal, logs, pulp and paper production, and not only bioenergy production as defined in the standard GLOBIOM.

(4) Coefficients used for land conversion costs: The standard GLOBIOM coefficients for non-linear land conversion costs were reduced by 2 orders of magnitude (from 10^{-3} to 10^{-5}).

(5) Expansion constraint coefficients for cropland: The coefficients related to expansion constraints for cropland by crop, and cropland by management system, at simulation unit level, have been changed due to the small expansion observed in initial 2010 results.

(6) Replacing EPIC data: Corrections in the EPIC data have ben made and the new data were replaced in the model. The old EPIC data was not defined for the whole Brazilian territory, specially Amazônia, because it used cropland land cover from GLC 2000 to define its outputs. Croplands from GLC 2000 are not defined for all Brazilian territory. The new EPIC data has its outputs defined for all Brazilian simulation units.

(7) IBGE data used for harmonisation: Data harvested area and output from IBGE PAM were incorporated in the model for harmonisation.

(8) Livestock numbers from census: GLOBIOM has a detailed representation of the livestock sector. Distinctions are made among dairy and other bovines, dairy and other sheep and goats, laying hens and broilers, and pigs. Several production systems are defined in the model. We used data from IBGE census and surveys to update the original data from GLOBIOM.

(9) Pasture productivity: The pasture productivity maps in default GLOBIOM obtained from EPIC do not present good results for livestock production, especially bovines, in 2010. We improved data on pasture productivity using data from IBGE and from Brazil's Ministry for Agriculture.

(10) Adjustments on data from G4M forestry model: We adjusted data from G4M to account for selective loggings in tropical forests.

(11) Definition of carbon uptake for regenerated forest: We used increment data from G4M to account for carbon uptake from forest regrowth.

(12) Internal transportation cost: We built a new detailed and up-to-date representation of Brazil's transport infrastructure, including transportation costs per product type (solid, liquid and grain) and destination (internal or external markets).

(13) Representation of Brazil's regions: The six legally defined Brazilian natural biomes as well as other administrative divisions such as the 26 states and the Federal District, and the Legal Amazônia were incorporated in the model. These regions are necessary to implement Brazil's Forest Code.

(14) Changes in soybean trade: Tariff changes in 2010 have been introduced in the model for China to capture the Chinese trade liberalisation. Chinese soybeans imports increased from 2000 to 2010 while Brazilian soybean exports to China have increased in the same period.

(15) Mata Atlântica Law: Federal Law 11428/2006 that protects the Mata Atlântica biome was included in the model; no transitions from mature forests on the biome are allowed.

(16) Legal reserves: The Legal Reserve (LR) system defines the minimum percentage of forest to be preserved or restored at the landowner's expense; this percentage is defined in the Forest Code and included in the model, for each 50 x 50 km^2 cell.

(17) Small farms amnesty: As defined in the Forest Code, the small farms amnesty (SFA) exempts small farmers from the obligation to restore the legal reserve in their properties. We included the small farms amnesty in the model, for each 50 x 50 km^2 cell.

(18) Environmental Reserve Quotas: The environmental reserve quota is a tradable legal title of native vegetation surpluses. Forest surplus on one property may be used to offset a legal reserve deficit on another property within the same biome. Deficits and surpluses are calculated for each biome for each 50 x 50 km^2 cell. To implement the quotas, the cells with deficits are ranked in decreasing order for each biome and discounted, in sequence, from the legal reserve requirement while the surplus stock of their biome is positive. This strategy allows cell with larger deficits to be compensated first by the quota mechanism.

(19) Calculation of forest deficits and surpluses: The legal reserve requirement is calculated for each 50 x 50 km^2 cell. If the amount of forest inside a cell is below the legal reserve requirement, then this deficit should be restored. If the amount of forest inside cell is above the LR requirement, then this surplus is available to be deforested or used as an environmental reserve quota in the biome.

(20) Illegal deforestation ban: In the grid cells where the forest area is less than the legal reserve requirement, conversions from mature forest to croplands or grasslands are not allowed.

(21) Inclusion of avoided cost for forest regrowth: The forest restoration requirement is incorporated directly in the welfare equation by means of a penalty function weighted by a Lagrange multiplier, representing the local level of enforcement.

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