



Landscape Restoration

RESTORE+

RESTORE+ Project

Output V

July 2019

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

Project Support

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Executive Summary

During the period covered by this report (01 March 2017 to 01 July 2019), there has been excellent progress towards the attainment of Output V overarching and specific goals, particularly those concerning activities V.1.1, V.1.4, V.1.6, V.1.7, V.2.1 and V.2.2. These activities are scheduled to be partially or totally completed by 01 July, according to the RESTORE+ Work Plan. Below follows a list of the main achievements of the RESTORE+ Brazilian team, described in detail in the rest of the document.

- Activity V.1.1: Several rounds of meetings were held in Brasília with relevant public and private stakeholders, such as the MMA, the MAPA or WWF-Brazil; the take away messages emphasized the importance of taking into account Brazil's NDC and the federal environmental legislation in framing RESTORE+ goals in Brazil; the need to produce realistic scenarios that include the impact of climate chance in the dynamics of land use change in Brazil was also highlighted.
- Activity V.1.4: Novel annual land use and land cover maps for the Cerrado and the Amazon biomes were produced for the period 2001-2016, using an innovative deep learning approach to identify natural vegetation, pasture, and individual (single and double) crops; maps are freely available at http://bit.ly/2RD6e9C. The family of software packages developed to generate these maps are open source tools also freely available to any researcher interested in building and analyzing land use and cover maps for any country or region of the globe.
- Activity V.1.6: Maps of Legal Reserve deficits and surpluses were created combining three different sources of information: the self-declaratory data from the 2018 Brazilian Environmental Rural Cadastre (CAR), the 2014 TerraClass land cover classification map produced by INPE for the Brazilian Amazon, and the Brazil-wide 2017 MapBiomas land cover map; different strategies were used to combine these data sources in order to generate estimates of maximum and minimum deficit and surplus per municipality, per state or per biome; results are available at http://bit.ly/2ZKaRl2.
- Activity V.1.7: Estimates of the economic cost (from 2010 to 2030) of the implementation of Brazil's Forest Code under different scenarios have been produced, at the country and state level; to this end, GLOBIOM-Brazil

spatially-explicit production and land use results have been introduced into TERM-BR, a computer general equilibrium (CGE) macroeconomic model, developed by the Luiz de Queiroz College of Agriculture of the Univeristy of São Paulo (ESALQ/USP) in Brazil; cost estimates range from 0.12% to 0.51% of the GDP, depending on the scenario; this approach permits to estimate the aggregated cost of any specific policy within the Forest Code, for example, the application of the CAR mechanism or the restoration of illegally deforested areas.

- Activities V.2.1 and V.2.2: A set of scenarios were designed through stakeholders consultations to investigate the policies that would contribute to achieve Brazil's international commitments of emissions reductions and forest restoration such as the Nationally Determined Contributions (NDC) of the Paris Agreement, the Bonn Challenge, the New York Declarations on Forests and the Initiative 20x20. Scenarios that evaluate the impacts of climate change on Brazil's agriculture and the land-use implications of future demand of ethanol were also implemented. To this end, a series of adaptations and improvements were performed in GLOBIOM-Brazil model in order to run realistic scenarios as requested by the stakeholders. Our simulation with the improved GLOBIOM-Brazil model found that the rigorous enforcement of the 2012 Forest Code (FC) is key for Brazil to fulfill its NDC commitments. A potential way for the country either to achieve zero emissions from the land-use and forestry sector or to transform the Amazon biome into a carbon sink is the implementation of zero deforestation agreements for the cattle sector combined with a restoration target larger than 12 million hectares, in addition to the full enforcement of the FC. Different ethanol demand scenarios have little direct or indirect impact on other crops and on native vegetation, including forests in the Amazon. Climate change impacts the production of Brazil's major agricultural commodities, decreasing its production and shifting its geographic span.

Introduction

Restoration of degraded land is a significant contributor to the global effort of enhancing land use sustainability. Restoration of degraded and destroyed ecosystems is a proven measure to fight the climate crisis and enhance food security, water supply and biodiversity. Brazil aims in its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) under the 2015 Paris Agreement to attain zero illegal deforestation and zero net emissions from the Amazon rain forest by 2030. The forest emission balance will be achieved by restoring and reforesting 12 million hectares of forests. Brazil's NDC also makes a firm commitment to promote low-carbon agriculture and to increase biofuel use for transportation. Overall, achieving the emission reduction goals Brazil set in its NDC will depend on how the country meets the targets associated with the land use sector.

The RESTORE+ project is a five-year partnership that aims at enhancing land use planning capacity related to restoration or utilization of degraded land in Indonesia and Brazil. In Brazil, the project will enhance established land monitoring and modelling capabilities and support Brazil's contribution to meeting the "Bonn Challenge". The project will identify degraded areas, assess restoration options and explore trade-offs associated with implementation of the Brazilian Forest Code.

Approximately halfway into the project, this technical report describes the activities undertaken by the RESTORE+ Brazilian team from 01 March 2017 to 01 July 2019. It focus on Activities V.1.1, V.1.4, V.1.6, V.1.7, V.2.1 and V.2.2. Other RESTORE+ activities described in the project's work plan, and also pertaining to the Brazilian team, are to be started after the period covered by this document, and, thus, will not be described here.

Activity V.1.1

Activity V.1.1: Stakeholder consultation (including MMA, MCTI, MAPA and their supporting agencies) on policies and definitions on degraded land in Brazil. The project will explore how the definitions of degraded lands are currently used and may be used in the future, including to help ensure that the UNFCCC's Cancun Safeguards for REDD+ are accounted for (especially on natural forest), and to identify to what extent bio-energy development can be consistent with these and other safeguards. This will also feed into the scenario selection process for the modelling exercise.

On 13 and 14 September 2017, and on 27 March 2018, Brazil's RESTORE+ team held a series of technical meetings with representatives of Brazil's Ministry of Environment (MMA), Ministry of Science, Technology, Innovation and Communications (MCTIC), Ministry of Planning (MPDG), Ministry of Foreigner Affairs (MRE), Ministry of Agriculture (MAPA), Ministry of the Economy (ME) and the Staff of the Presidency of the Republic (Casa Civil). Contacts also included chief directors of national agencies such as IBAMA and EMBRAPA; chief directors of private sector associations such as ABIOVE; researchers from universities and research institutes such as USP/ESALQ, Unicamp and PUC-RIO; and of NGOs like WWF-Brazil, the TNC-Brazil, IPAM and IMAZON.

The meetings, held in Brasília, are part of several rounds of consultations and engagement with relevant stakeholders, planned to explore policies and definitions on degraded land in Brazil, and provide the Brazilian government with national scenarios of restoration and sustainable food/energy crop production on degraded lands.

The events emphasized the synergy between RESTORE+ project activities and the implementation of Brazil's NDC. Discussions included the definition of priority areas for restoration within Brazil's National Plan for the Recovery of Native Vegetation (PLANAVEG) context, and how corresponding carbon removals will impact Brazil's GHG emissions reduction targets. Issues like the impact of climate change on the dynamics of land use change in Brazil, and the relevance of supply-chain agreements like the Amazon soy and beef moratoria were also explored.

The Forest Code and the Plan ABC (National Plan for Low Carbon Emission in Agriculture) were presented as the major policies to mitigate climate change in the agricultural sector, which is the second largest GHG emitter within Brazil's emissions budget. The enforcement of the Forest Code is well supported by the sector and some researchers emphasized the importance of the Forest Code as an instrument to promote the technological changes the sector needs toward a more sustainable agriculture.

Summarizing, the take away messages of all these meetings were:

- Area, timing and location of forest and other native vegetation restoration initiatives shall be framed by the existing federal environmental laws and programs (basically, 2012 Forest Code and PLANAVEG) and Brazil's international commitments, such as the country's NDC and the Bonn Challenge.
- GLOBIOM-Brazil (and related models) shall take into account in its simulations the future impacts of climate change on land use change in Brazil, in order to be able to generate realistic scenarios for policy makers up to 2050 and beyond.
- The impact on native vegetation targets (and related positive/negative carbon emissions) of supply chain agreements, such as the soy and beef moratoria, and large federal programs, like the Renovabio on the expansion of the use of sugarcane bioethanol, shall be investigated and incorporated into GLOBIOM-Brazil.

Although this activity has been formally concluded, considering that a populist right wing president with a strong anti-environment platform has recently been elected, we continue with our efforts to keep the channels open with the relevant stakeholders in Brasília.

Activity V.1.4

Activity V.1.4: Identify degraded lands according to each definition. This include mapping degraded land with innovative methods for analyzing big Earth Observation data.

Introduction

Brazil is one of the top agricultural producers and exporters, being home to an estimated 15% to 20% of the world's biodiversity and the largest extent of tropical rainforest. Such a unique position leads to the need for balancing agricultural production and environmental protection [Martinelli et al., 2010]. Without substantial investments in productivity and strong land policies, the expansion of agricultural production can be a significant factor of environmental degradation. For this reason, it is important to understand the impact of environmental policies on the expansion of tropical agriculture.

Cerrado and Amazon biomes are of particular interest for understanding the balance between production and protection. Covering more than 70% of the Brazilian territory (shown in Fig. 1), these two biomes are responsible for most of the land change dynamics along the last decades. The objective of this activity is to generate a consistent multi-year land use and cover maps for these biomes using machine learning techniques. These maps constitute our Collection 1 product and provide information on crop production systems and pasture expansion into natural vegetation.

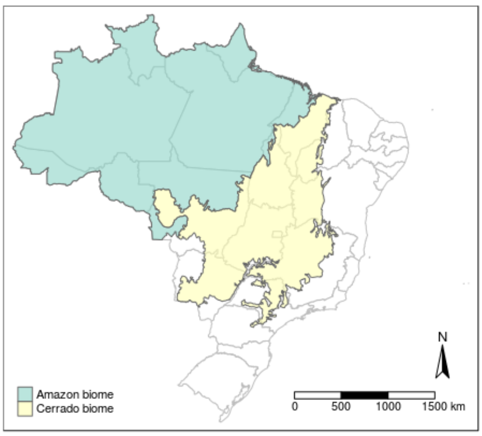


Figure 1: Cerrado and Amazon biomes.

Methodology

Earth observation satellites provide a regular and consistent set of information about the land and oceans of the planet. Recently, most space agencies have adopted open data policies, making unprecedented amounts of satellite data available for research and operational use. The approach taken in the current work is to develop data analysis methods that handle satellite image time series, obtained by taking calibrated and comparable measures of the same location in Earth at different times. If obtained by frequent revisits, the temporal resolution of these data sets can capture important land changes.

Time series of remote sensing data show that land cover can occur not only in a progressive and gradual way, but also show discontinuities with abrupt changes [Lambin et al., 2003]. The analysis of multiyear time series of land surface attributes, their fine-scale spatial pattern, and their seasonal evolution leads to a broader view of land cover change.

The complete methodology used in this work is shown in Figure 2. It uses a set of samples to train a machine learning model. This model is used to classify unlabeled data to produce land use and cover maps using satellite image time series (big data). Such classification can be validated using other data sources or subsets of the input samples to estimate consistency and accuracy. Also, the classifications can be post-processed to generate new maps according to some spatial or temporal constraints to obtain higher consistency.

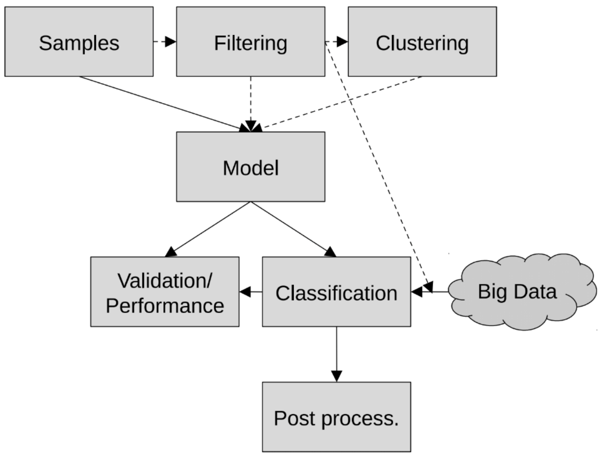


Figure 2: Overview of the methodology to produce land use and cover maps.

Input Data

Our method classifies yearly time series data using Moderate Resolution Imaging Spectrometer (MODIS) product. The land use and cover maps are based on time series analysis of over 24,000 images covering Amazon and Cerrado biomes, with spatial resolution of 250 meters per pixel. This represents more than 440 millions time series that were classified into land cover classes.

The input time series data are based on MODIS product MOD13Q1 (collection 6), provided by NASA/LPDAAC [Didan, 2015]. MOD13Q1 is a vegetation product composed by the best available pixel from all the acquisitions from within a 16 days period. It provides four layers of spectral reflectance, blue, red, near-infrared (NIR), and mid-infrared (MIR), as well as two vegetation layers, the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). The imaging acquisition started in 2000-02-18 and is still operational.

We organize a set of MOD13Q1 images that cover Cerrado and Amazon biomes from 2000 to 2016. This data set builds up a data cube of satellite images representing two spatial and one temporal dimensions. The samples and their time series follow the Brazilian crop season interval, which begins on September 1st of one year and ends on August 30th of next year.

To train the classification model, we use two samples datasets consisting of geographic location (longitude and latitude), one year time interval (start and end dates), and a class associated to a land use or cover. The first data set is used to create the Cerrado classification model, shown in Figure 3. It contains more than 64,000 samples divided into thirteen classes from which five are natural savanna formations: (1) *Savanna-Araguaya*, (2) *Savanna-field*, (3) *Savanna-forest*, (4) *Savanna*, and (5) *Savanna-rock*; six are cropping classes: (6) *Fallow-Cotton*, (7) *Millet-Cotton*, (8) *Soy-Corn*, (9) *Soy-Cotton*, (10) *Soy-Fallow*, and (11) *Soy-Millet*; plus two remaining classes (12) *Pasture*

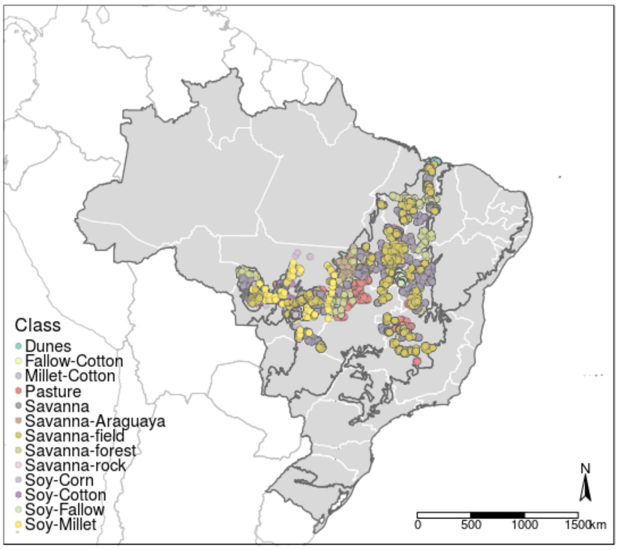


Figure 3: Spatial distribution of samples to train a classification model for Cerrado biome.

and (13) *Dunes*. Names of the cropping classes are the concatenation of the crops of first season followed by the second season. Classes with “Fallow” label refer to single cropping classes.

The second data set consists of 45,000 samples and is used to generate the Amazon classification model, shown in Figure 4. It is divided in eleven classes: (1) *Forest*, (2) *Savanna-field*, (3) *Pasture*, (4) *Pasture-dirty*, (5) *Sugarcane*, (6) *Fallow-Cotton*, (7) *Millet-Cotton*, (8) *Soy-Corn*, (9) *Soy-Cotton*, (10) *Soy-Fallow*, and (11) *Soy-Millet*.

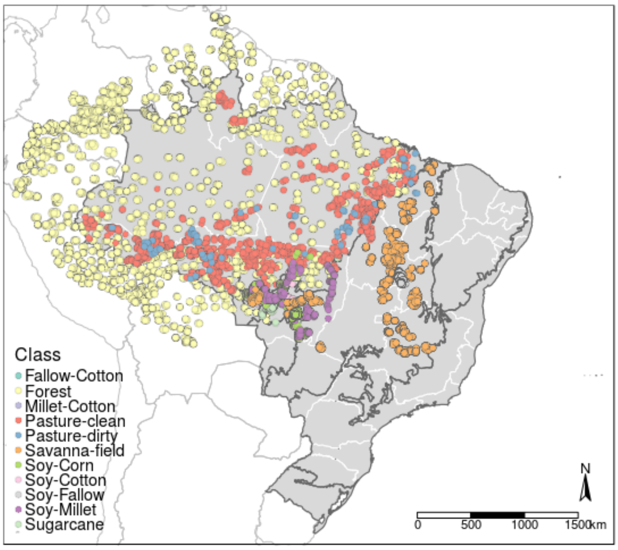


Figure 4: Spatial distribution of samples to train a classification model for Amazon biome.

The samples of *Savanna-field* and cropping classes *Fallow-Cotton*, *Millet-Cotton*, *Soy-Corn*, *Soy-Cotton*, *Soy-Fallow*, and *Soy-Millet* are the same for both data sets. These cropping classes were collected through field observations and farmer interviews by Arvor et al. [2011] and EMBRAPA/CNPTIA. Pasture samples for Cerrado biome also were provided by EMBRAPA research team. Samples of natural vegetation in Cerrado biome, including the *Savanna-field* of Amazon biome, as well as *Forest*, *Pasture-clean*, and *Pasture-dirty* classes in Amazon biome, were collected and provided by INPE’s researchers by interpreting high resolution images.

Classification Method

We use Deep Learning algorithm to generate the vegetation maps. Deep Learning is a technique that uses layers of neurons to associate an input data with a limited set of outputs values (labels). The first and last layers are interface layers (input and output layers) and between them we can construct hidden layers of neurons. In this work, we create four hidden layers with 512 neurons. We connect two consecutive layers using the complete network architecture. Each neuron is associated with the exponential linear activation function that speeds up the learning process and precludes the vanishing gradient problem [Clevert et al., 2015].

Once we define the network architecture, we explore the learning parameters (1) dropout rates, (2) gradient descent optimization, (3) batch gradient descent size, and (4) number of epochs. In this work, we set the dropout rates to 0.5 for the first hidden layer, 0.4 for the second, 0.35 for the third layer, and 0.3 for the last hidden layer; the optimization strategy used to train the models is the Adaptive Moment Estimation with a batch size of 128; and the number of epochs is 400.

To generate the Collection 1 maps, only NIR, MIR, NDVI, and EVI layers provided by MOD13Q1 product were used. This give us four time series per sample, each one consisting in 23 values over one year of observations. Thus, the number of neurons of input layers both of Cerrado and Amazon Deep Learning models is 92. The output layers differ between the models as the number of classes diverge between the samples data sets. For Cerrado biome the output layer consists of 13 neurons, and for Amazon biome, 11 neurons.

To evaluate the training process, we use 25% of the samples of each data for validation. At the final epochs, the models showed a good convergence between training and validation accuracy between 94% and 98%. The models were then applied on the respective biome region, generating two layers of data for each year: (1) a vector layer with the probabilities associated with all classes for each pixel and (2) a single layer with the most probable class (categorical value) for each pixel which consists the map output.

Post-processing steps

In the first post-processing step, we use a spatial Bayesian smoothing filter to reduce the “salt-and-pepper” noise from the maps, mainly induced by cloud interference on time series. The main rationale is to change the class of those pixels with high uncertainty (high variance in the probabilities vector) to the class with the lowest uncertainty in its neighborhood using a Bayesian inference. The neighborhood consists in a square window around a central pixel. When the variance of the neighborhood is too high, the smoothing algorithm gives more weight to the pixel value and ignores the neighborhood classes likelihood, and vice versa.

The smoothing algorithm has only one parameter, the “global noise”, which mediates the importance of the weights in deciding to update or not the pixel value. We can choose the global noise arbitrarily, however higher values will result in larger spatial smoothness. In this work, we defined the neighboorhood as a 3×3 window around the central pixel, with a global noise value of 10, which results in more updates of the pixel values whenever its uncertainty is high compared to the neighboorhood’s uncertainties.

After this, three masks were applied on Cerrado maps: sugarcane, urban area, and water. The masks of sugarcane from 2003 to 2016 were obtained from the Canasat project, which maps sugarcane areas in south-central region of Brazil using Landsat images [Rudorff et al., 2010, Adami et al., 2012]. The mask of urban area are from Sparovek et al. [2015] and the mask of water surface are from Pekel et al. [2016], which used Landsat satellite images to quantify changes in global surface water over the past 32 years (1984 to 2015).

On the Amazon maps, only two masks were applied: urban area and water. Both urban areas and water masks were obtained from the TerraClass project [Almeida et al., 2016], that uses Landsat and MODIS images to generate land use and land cover maps for Amazon biome. The product used for the sugarcane mask was not available in the North region of Brazil. Thus, we decided to produce our own class by providing samples of sugarcane to train the model.

The pre-analysis of the classifications of Cerrado biome identified that the largerst confusion was between *Pasture* and *Savanna* classes, resulting form the similarities between the temporal profiles of these classes. To reduce this confusion, we applied a mask consisting of clear-cut areas generated by PRODES-Cerrado [INPE, 2018] as follows: *Pasture* areas outside the mask were converted into *Savanna*, while *Savanna* areas inside the mask were converted to *Pasture*. Thus, our classifications actually overestimate the total pasture area of Cerrado biome, since it can include areas of secondary vegetation within the deforested area of Cerrado. Additionally, the following post-processing rules were applied to Cerrado biome maps:

- Areas not classified as *Pasture* in year n, but classified as *Pasture* in years $n-1$ and $n+1$, were converted to *Pasture*;
- Areas not classified as *Soy-** in year n, but classified as *Soy-** in years $n-1$ and $n+1$, were converted to *Soy-Fallow*;
- Areas not classified as *Cotton-** in year n, but classified as *Cotton-** in years $n-1$ and $n+1$, were converted into *Fallow-Cotton*.
- Areas classified as *Savanna-forest* (a class of tree phytophysiognomy) within the PRODES-Cerrado mask were converted into a new class called *Planted-forest*.

Figure 5 presents a general overview of the post-processing and validation steps adopted in generating and analyzing the land use and cover maps. The highlighted purple area correspond to those steps explained in this section. The other steps are related to the maps validation and are explained in next sections.

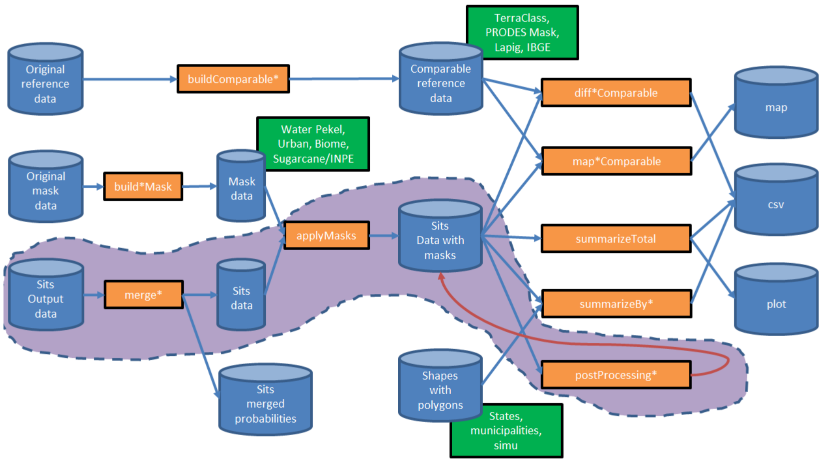


Figure 5: Diagram of post-processing and validation of classifications.

Software tools used to generate land use and cover maps

To produce the Collection 1 land use and land cover maps of Cerrado and Amazon biomes, we followed a variety of steps that demand different analysis methods. To provide a unified support to theses activities, we have developed an open source software for R language called *sits*.

The package includes time series data retrieval from many services and providers such as the Web Time Series Service (WTSS) [Queiroz et al., 2015] and the Simple Storage Services (Amazon S3). It also includes time series data visualization tools and provides an unified way to test and generate classification models of different machine learning techniques such as Support Vector Machine, Random Forest, and Deep Learning. The package also incorporates temporal and spatial smoothing algorithms that can be used to attenuate cloud coverage noise in time series and "salt-and-pepper" noise effect on classified maps. It also manages the computer resources (process and memory) to be able to work with a large amount of data.

The development of *sits* package is associated with the development of other packages: *WTSS*, *EOCubes*, *lucCalculus*, and *sits.validate*. These packages provide tools to access samples time series, to access MOD13Q1 data cube, to compute temporal trajectories post-processing, and to validate maps according to other data sources, respectively.

Assessment of agricultural dynamics in Cerrado biome

This section presents results of the Collection 1 of land use and cover maps produced with *sits* for Cerrado biome. The maps are available from 2000/2001 to 2016/2017. Two of them can be seen in Figure 6, which clearly shows the expansion of agriculture in several parts of the biome, mainly in the southward part, which is closely connected to more developed regions of the country.

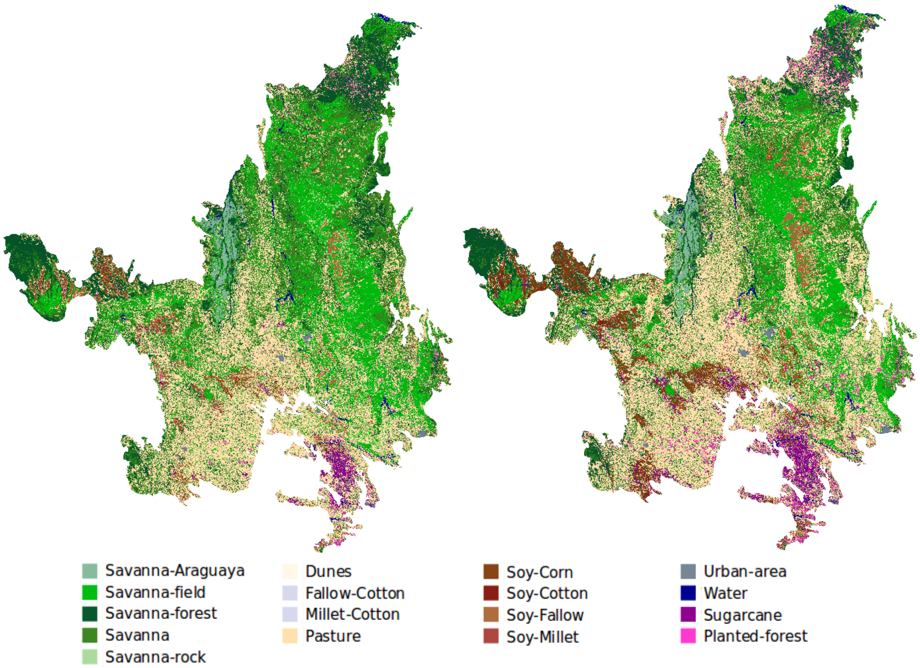


Figure 6: Cerrado biome land cover and use maps for years 2000/2001 (left) and 2015/2016 (right).

The results indicate that, from 2000 to 2015, there was a reduction of 26.8Mha of natural *Savanna*. This deforestation is associated with an increase of 10.3Mha in the area of agriculture, 12.4Mha in the pasture area and 3.5Mha in the planted forest area (the remaining area, about 0.6Mha, is related to other classes, such as urban areas). The evolution of these areas over time can be seen in Figure 7.

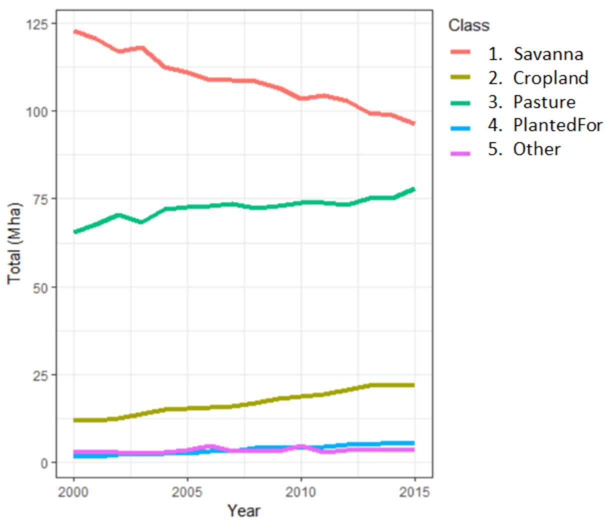


Figure 7: Evolution of the main classes over time.

For the validation of the agriculture and livestock classes, the main sources of data are IBGE agricultural census and Municipal Agricultural Production (PAM). As IBGE data are available by municipality, it was necessary to consider only areas consisting of those municipalities entirely within Cerrado. This area encompasses 799 municipalities, or 70% of the total Cerrado area. Figure 8 shows this cutout. As this region covers a significant area of the Cerrado, it can be assumed that the results inside and outside will be statistically close. From this perspective, the results presented below consider only this region.

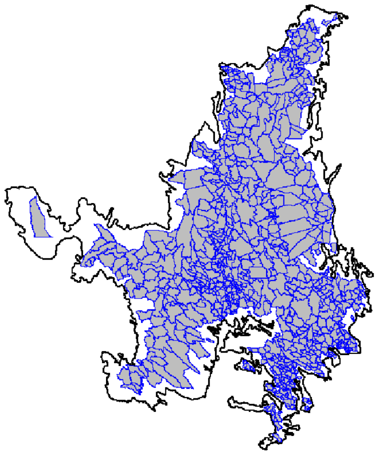


Figure 8: Municipalities completely within Cerrado.

With regard to agriculture, the main crops in the region are soybeans, corn, and cotton, corresponding to about 70% of the region's agricultural area in the year 2000/2001. Figure 9 shows the evolution of the three crops area from 2000 to 2015 according to *sits* classification in comparison with IBGE data. We can see that, for cotton and corn the results were very similar. In the case of soybeans, there was an overestimation of the area. This difference may be related to other agricultural crops with similar phenology, disregarded by the classification model due to the absence of other crop classes, such as beans and corn. Possibly such areas are being classified as soybeans, creating this gap. This point requires further investigation in the future.

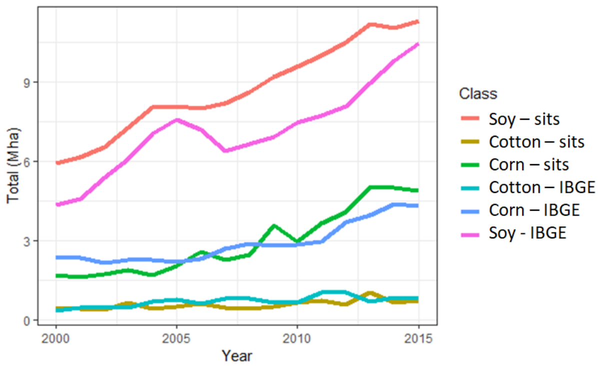


Figure 9: Evolution of the main crops in Cerrado biome.

Figure 10 shows the result of soybean area aggregated by the 799 municipalities for 2000. In the x-axis, we have the area of the municipality classified as soybean and in the y-axis the area declared by the producers of the municipality in the IBGE data. The axes are in logarithmic scale in order to disregard the impact of the size of the municipalities in this analysis. Note that there is a large correlation between these classifications and IBGE data, especially for the large producers (top-right points). Only three municipalities have declared soybeans production in IBGE but had no area in the classification, while 450 municipalities have soybeans in the classification but not in IBGE data. This difference may also be related to the absence of other crop classes, such as beans and corn. In addition, there may exist some errors in the declared data, and also neighborhood effects related to rural properties that belong to more than one municipality but all its production is declared in only one of them.

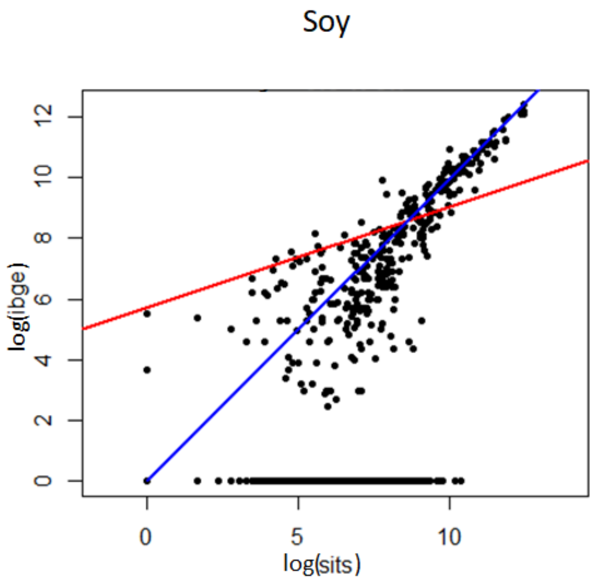


Figure 10: Soy per Cerrado municipalities.

Assessment of agricultural dynamics in Amazon biome

This section presents results of the land use and cover maps (Collection 1) produced with *sits* for Amazon biome. The maps are available from 2000/2001 to 2016/2017. The Figure 11 depicts the maps for years 2000/2001 and 2009/2010. We can note how crop areas are almost insignificant in 2000/2001 and grows significantly in the southeast in ten years.

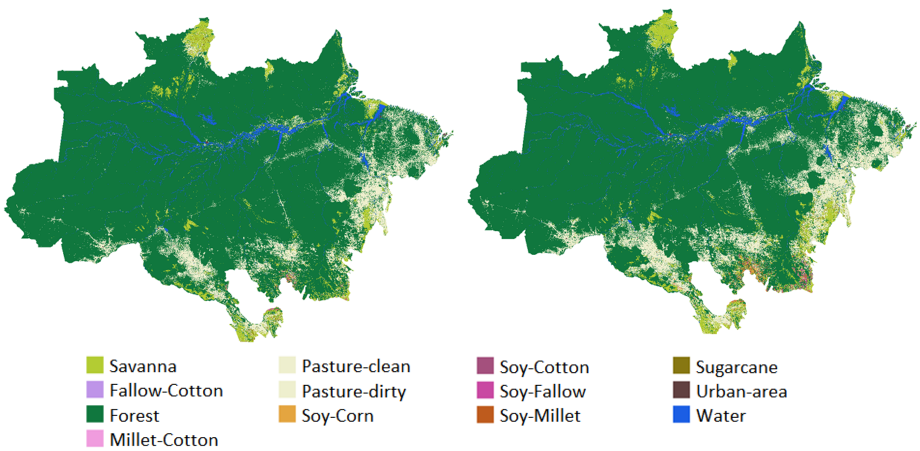


Figure 11: Amazon biome land cover and use maps for years 2000 (left) and 2010 (right).

The main source of information to validate sits classifications for Amazon biome is TerraClass [Almeida et al., 2016]. It provides land cover maps for Amazon based on visual interpretation, with a careful field validation. Terra-

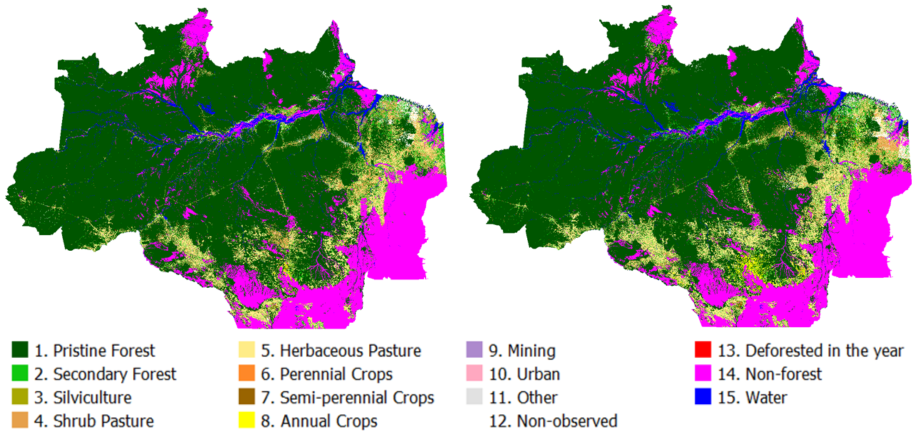


Figure 12: TerraClass maps for years 2000 (left) and 2010 (right).

Class identifies what happened with clear-cut deforestation areas classified by PRODES project. The maps of TerraClass for 2000 and 2010 are shown in Figure 12. The areas in magenta were never pristine forest, and therefore they are ignored in TerraClass. Additionally, parts of east and southeast areas of TerraClass maps are not considered in sits, because they belong to Legal Amazon but not to the Amazon biome. Most of these areas are classified as Non-forest because they belong to Cerrado biome.

Considering the areas of *Forest*, *Pasture-** and crops (in general) of the years 2000/2001 and 2009/2010, *sits* correctly reproduces 94.9% and 93.3% of the corresponding years in TerraClass maps. In the TerraClass areas classified as "Non-forest", which cover around 7% of Amazonia biome in 2000, *sits* identified 9% as *Pasture-** and 2% as crops.

Concluding Remarks

The Collection 1 of *sits* land use and cover maps for Cerrado and Amazon biomes showed reasonable accuracy for modeling purposes. The results enable an informed assessment of the interplay between production and protection in the Brazilian Amazon and Cerrado biomes, being relevant to support land use and cover planning and public policies, such as the calculation of grennhouse gas (GHG) emissions for the implementation of Brazil's NDCs. Additionally, they are temporally consistent and provide information on deforestation and changes in natural vegetation and on agricultural expansion and productivity increase. *Sits* maps also have specific advantages regarding to modelling issues, mainly for GLOBIOM-Brazil:

1. *sits* identifies crop types, specially double cropping areas, which are consistently expanding in Brazil.
2. *sits* is available for all years from 2000 to 2016, and will also be updated as new data is collected and made available in the data cube.

As a first collection, we consider that our innovative methodology to generate land use and land cover maps has potential to be improved in the near future. For example, the overestimation of areas classified as soybean can be reduced as new samples of other crops are made available. Additionally, future efforts will be made to produce new collections for the other Brazilian biomes.

Along the development of this activity, considerable effort was made to develop the family of software packages to cover the whole process for creating land use and cover maps, which are *sits*, *WTSS*, *EOCubes*, *lucCalculus*, and *sits.validate*. These packages can be found in the e-Sensing's GitHub repository at https://github.com/e-sensing. They can be useful to other researchers interested in building and analyzing land use and cover maps for any country or region of the globe.

The land use and cover maps are available at http://bit.ly/2RD6e9C. They will be made public as soon as the scientific results are published.

Activity V.1.6

Activity V.1.6: Use new data from land tenure cadastre to determine the extent of deforested areas that should be restored according to the new Forest Code.

Introduction

The legal basis for land policies in Brazil is the Forest Code. Since its creation, in 1965, it establishes general rules on the protection of vegetation and use of rural properties by defining a proportion of rural properties that must be permanently maintained as native vegetation, called Legal Reserve. These areas have the purpose of ensuring the sustainable use of the natural resources and promote the conservation of biodiversity by protecting wildlife and native flora.

Forest Code also forbids clearing vegetation in sensitive areas such as steep slopes and along riverbanks and streams. These areas, called Area of Permanent Preservation, might be covered or not by native vegetation. They have the environmental function of preserving water resources, landscape, geological stability and biodiversity, facilitate the genetic flow of fauna and flora, as well as protect the soil, ensuring the well-being of human populations. Figure 13 illustrates the definitions of Legal Reserve and Area of Permanent Preservation within a rural property.

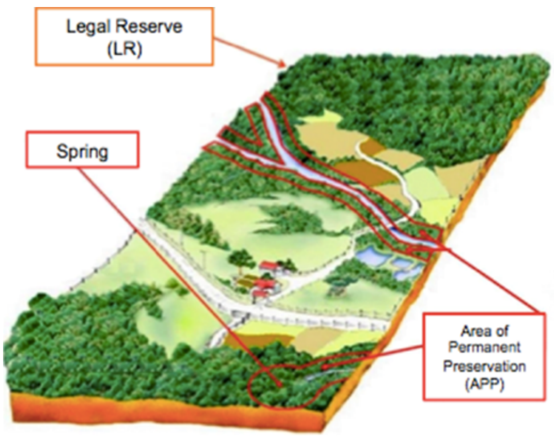


Figure 13: Illustration of Legal Reserve and Area of Permanent Preservation within a rural property. Source: based on [Schaffer and Prochnov, 2002].

Forest Code establishes a mandatory percentage of Legal Reserve that must be preserved within each rural property. The percentage depends on the definition of Legal Amazon, which comprises the whole Amazon biome and parts of Cerrado and Pantanal biomes, covering around 61% of the Brazilian territory. Outside Legal Amazon, rural properties must preserve 20% of the area as Legal Reserve. Within Legal Amazon, rural properties located in forest areas must have 80% of Legal Reserve; those located in Cerrado biome (within Legal Amazon) must preserve 35% of their area while those in general fields must preserve 20% of their area. Additionally, the public authority may reduce Legal Reserve from 80% to 50% in the following situations:

- When a given municipality has more than 50% of its area occupied by protected areas in the public domain as well as ratified or homologated indigenous lands.
- States that have 65% of their territory occupied by regularized conservation units and approved indigenous lands might reduce Legal Reserve within Ecological-Economic Zones.

Figure 14 illustrates the current requirements of Legal Reserve within the Brazilian territory. As described previously, areas with Legal Reserve larger than 20% belong to the Legal Amazon. If, the area of Legal Reserve in a given rural property exceeds the mandatory percentage, it is considered a surplus of Legal Reserve. Likewise, if the percentage of Legal Reserve is lower than the established, it is assumed a deficit of Legal Reserve.

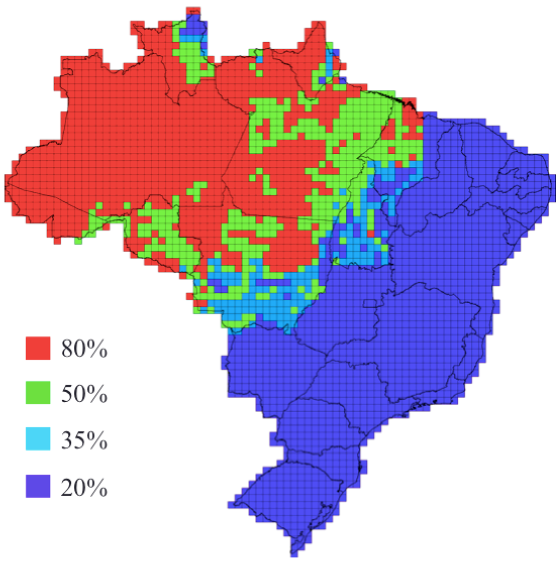


Figure 14: Spatial distribution of the Legal Reserve (LR) requirements from Soares-Filho et al. [2014] downscaled to 50 km x 50 km pixels.

In 2012, the Brazilian Congress approved the latest revision of the Forest Code (Law 12.651/12). This law sets up the general rules for those that illegally deforested their Legal Reserve areas, allowing their regularization in the Environmental Regularization Program (in Portuguese, *Programa de Regularização Ambiental*, or PRA), as long as they restore their Legal Reserves and declare the location of their properties in a system called Rural Environmental Registry (in Portuguese, *Cadastro Ambiental Rural*, or simply CAR). Rural properties with deficits might alternatively compensate for their areas by buying the surpluses of other properties within the same biome through a market of Environmental Reserve Quotas (in Portuguese, *Cotas de Reserva Ambiental*, or CRA).

The new Forest Code also establishes amnesty for small properties, which are those with up to four fiscal modules. A fiscal module is an agrarian measure that represents the minimum area required for rural properties to be economically viable, ranging from 5 ha to 110 ha. This way, a property with up to 440 ha might have amnesty. Figure 15 shows the map of fiscal modules for the Brazilian municipalities.

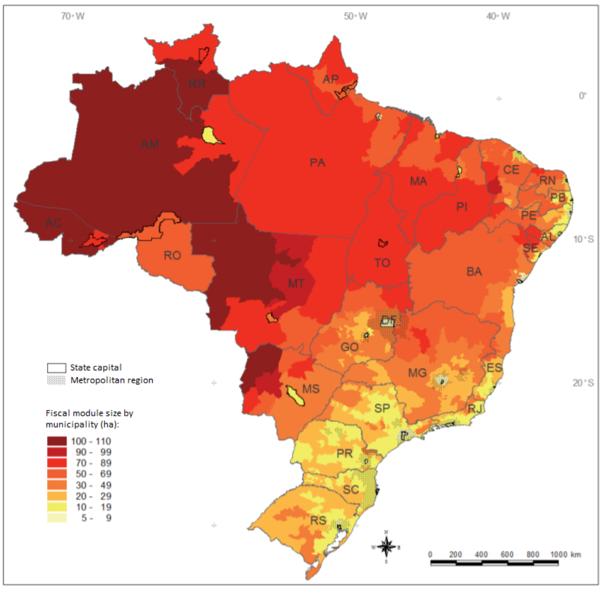


Figure 15: Fiscal module size by municipality. Source: [Landau et al., 2012].

Computing deficits and surpluses of Legal Reserve is an important step to study restoration scenarios in Brazil. However, the data available to estimate such debits or surpluses have great uncertainty. The objective of this activity is to combine CAR with the best data currently available to estimate scenarios of deficits and surpluses of Legal Reserve in Brazil, according to Forest Code.

CAR data

CAR is an electronic record of rural properties implemented to control, monitor, and combat deforestation of any native vegetation in Brazil. It can also be used as a tool for environmental and economic planning of rural properties. Figure 16 shows an example of CAR data for the municipality of Sorriso, in Mato Grosso state.

CAR contains self-declared data and it is publicly released a couple of times each year, as long as new data arrives. The version of CAR data used in this work is dated from October 2018. It has 4,819,574 rural properties,

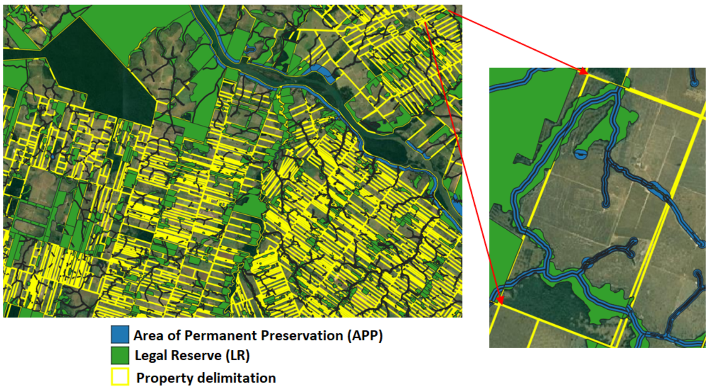


Figure 16: Rural properties for the municipality of Sorriso, in Mato Grosso state, as published in CAR. Properties are drawn on top of Google Earth.

5% less than reported in the last agricultural census for Brazil. By law, State governments are in charge of verifying the correctness of CAR data, in a process that will possibly take years to be concluded. Notwithstanding this fact, CAR data was publicly released without a careful validation, which requires a thorough check in order to be properly handled.

A careful analysis of CAR data has found some inconsistencies in the data available. In addition to geometric errors, such as lines that do not exist, a visual observation has detected many overlapping rural properties, mainly in Legal Amazon. Figure 17 shows an example for the municipality of Lábrea, in Amazonas state: a property of more than 1.5 Mha (in yellow) has a considerable overlay with other property of 1.3 Mha (in red). Both properties also have several other overlaps with smaller properties (in orange), being impossible to infer their real shape.

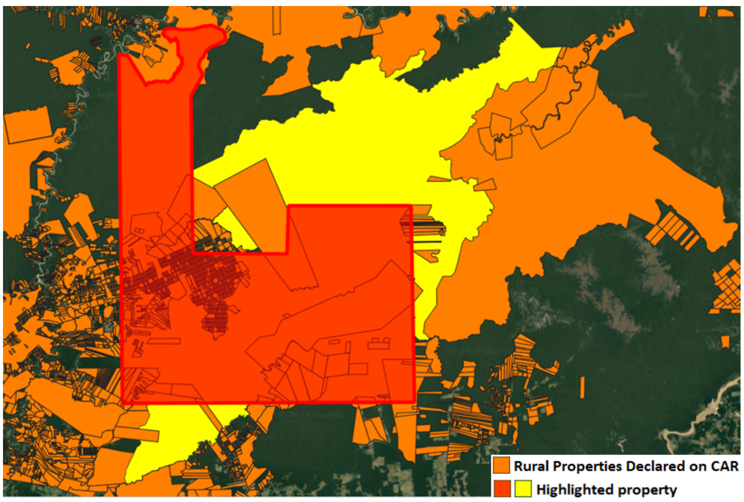


Figure 17: Example of overlapping properties within the municipality of Lábrea, in Amazonas state. In yellow, a property of 1.5 Mha, overlapped with a property of 1.3 Mha in red.

Another problem observed mainly in Amazon biome was the lack of Legal Reserve in very large properties. Figure 18 shows the case of Amazonas state, with a large number of rural properties (in orange), but with very few declared Legal Reserves (in green). Deeming such data as accurate, the Legal Reserve deficit for Amazonas state alone would be 28 Mha, an area three times larger than Austria. This lack of Legal Reserve is implausible, since most of these areas are covered with pristine forest, which suggests inconsistencies in Legal Reserve information from CAR data. Thus, this data should be carefully handled to properly estimate deficits and surpluses for Amazon biome.

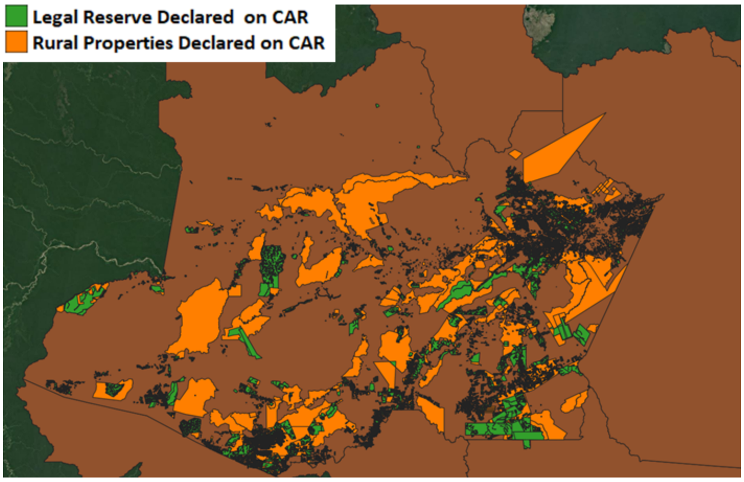


Figure 18: Rural properties and declared Legal Reserve in Amazonas state.

Methodologies and Scenarios

The methodology to estimate deficits and surpluses is divided in two parts, as shown in Figure 19. In the first part, pre-processing algorithms prepare the CAR data that, in the second part, are used to compute deficits and surpluses. The first part includes the following procedures:

1. Fixing geometry errors that prevent the estimation of deficits and surpluses;

2. Removing all properties with less than four fiscal modules, as they are amnestied;

3. Removing all cancelled properties, as well as settlements (but not the individual properties within settlements) and conservation units.

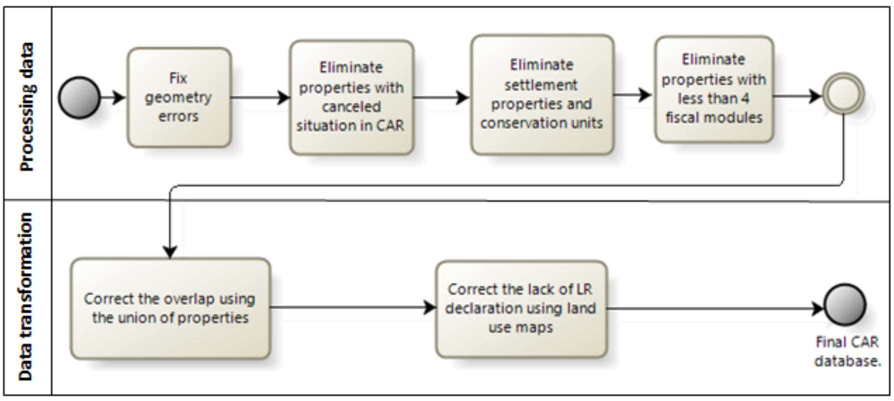


Figure 19: Steps to estimate deficits and surpluses.

The second part handles CAR data to compute deficits and surpluses. In order to solve the problems described in the previous section, some decisions have been made. The first one aims to solve the overlap of rural properties by changing the resolution of study from rural property to municipality. All properties within the same municipality are grouped into a single property, as if the municipality would have only one rural property.

In the next step the lack of Legal Reserve declaration in CAR is solved by using natural vegetation categories from maps of land cover and use. In this case, the Legal Reserve is estimated as the percentage of natural vegetation within a property. Properties with less (more) natural vegetation than the mandatory percentage have a deficit (surplus). In Brazil, there are two consolidated land use and cover maps suitable for this purpose: TerraClass and MapBiomas.

TerraClass[1] is a project lead by INPE that characterizes land cover and use of clear-cut areas in Legal Amazon. It is the Brazilian government official data used for public policies. The main advantage of TerraClass is its classification of abandoned areas that became secondary vegetation, raising an important point of analysis regarding the quality of the forest composition used as Legal Reserve. However, this data is only available for the Legal Amazon. This work uses the most recent TerraClass data, available for year 2014.

[1] https://www.terraclass.gov.br/

The second source of data used by this work, MapBiomas[2], is an initiative of the Greenhouse Gas Emissions Estimation System from the Climate Observatory. It is developed by a collaborative network of co-creators from NGOs, universities, and technology companies.The main advantage of MapBiomas is its national coverage. However, it overestimates the forest class, at least in Amazon biome, as pointed out by [Maurano and Escada, 2019]. Additionally, MapBiomas does not have a secondary vegetation class as in TerraClass dataset. In this work we use MapBiomas collection 3.0.

[2] http://mapbiomas.org/

Hence, the in-depth analysis of the Brazilian area available for restoration was based on three different methodologies to estimate Legal Reserve deficits and surpluses. All three methodologies use CAR data to represent the rural properties. The difference between them consists on the form of estimating Legal Reserve. In the first methodology (M_1), CAR data is used to estimate deficits and surpluses for the entire country except in the Amazon biome, where this information is derived from TerraClass. The second methodology (M_2) also uses TerraClass to estimate Legal Reserve deficits and surpluses in the Amazon biome, but for the rest of the country, it uses MapBiomas. Finally, in the third methodology (M_3), deficits and surpluses are estimated using MapBiomas for the entire country.

Due to the expected differences among the three methodologies, it was also analyzed two scenarios to estimate possible ranges of deficits and surpluses. Scenario S_A uses the lowest deficit and highest surplus among the three methodologies in each municipality, estimating the upper bound of surplus for Brazil. Scenario S_B estimates the lower bound of surplus by computing the highest deficit and the lowest surplus among the three methodologies. The use of scenarios with ranges of deficits and surpluses ensures that the reality is within this interval. The difference in the outcomes will then point out the importance of this uncertainty.

Results

The results of methodology M_1 are spatially illustrated in Figure 20. The total deficit was 25.6 Mha, with the largest Legal Reserve deficits spread over Amazon biome. Also, there was a large area of deficit that covers almost entirely the state of Mato Grosso do Sul. However, after investigating the input data, it was concluded that this occurs due a lack of reliable Legal Reserve data for this state. The total Brazilian surplus of M_1 was 54.2 Mha.

The states located in the border between Amazon and Cerrado biomes did not have Legal Reserve deficit due a limitation on the classification of natural vegetation. TerraClass maps differentiate land use classes only within the Amazon biome. States in the border between Amazon and Cerrado do not have discriminated classes of natural vegetation and other uses inside of Cerrado biome.

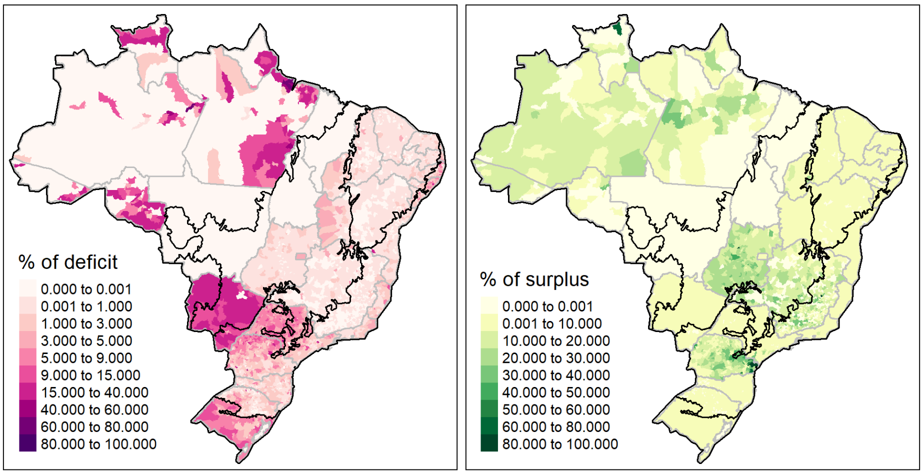


Figure 20: Percentage of deficits (left) and surpluses (right) by municipality according to the methodology M_1.

The result of Legal Reserve deficit estimated by methodology M_2 is shown in Figure 21. The total deficit for Brazil in this methodology was 24.0 Mha. It differs from the previous methodology only in the region outside Amazon biome. Note that the deficit of Mato Grosso do Sul was reduced if compared with M_1 since the unreliable Legal Reserve data from CAR for this state was not considered here. Additionally, one of the largest deficits occured in Mato Grosso state, one of the Brazilian states with the largest agricultural production. It can also be highlighted the large deficit in the Cerrado part São Paulo state. Significant surpluses occur in Caatinga, Pantanal, Pampa, and parts of Mata Atlântica biomes.

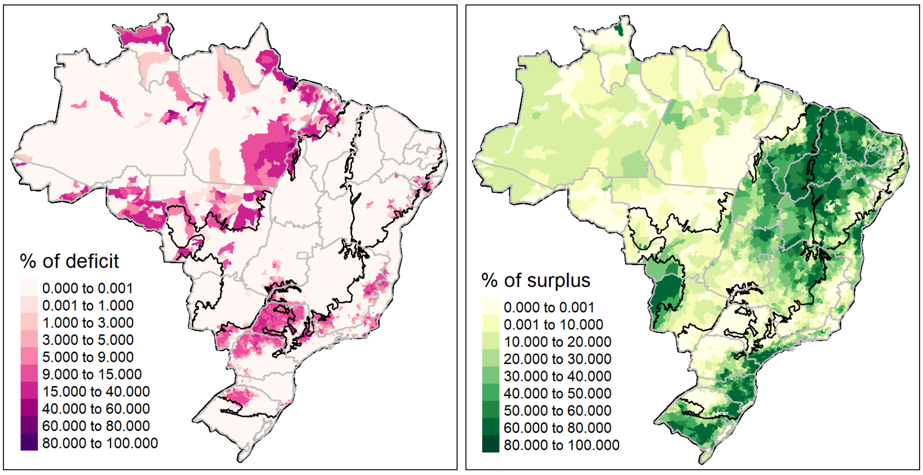


Figure 21: Percentage of deficits (left) and surpluses(right) by municipality according to methodology M_2.

Using methodology M_2, the total Legal Reserve surplus was 174.8 Mha, more than three times the surpluses found in methodology M_1. This high difference might be related to the under-reporting Legal Reserve in CAR combined with the overestimation of forest areas in MapBiomas, as verified by [Maurano and Escada, 2019].

Finally, Figure 22 shows the percentages of deficit by municipality obtained through methodology M_3, in which the total deficit for Brazil was 15.7 Mha. Since the reference map for states outside the Amazon biome is the same as in methodology M_2, the difference of 8.7 Mha between these methodologies occurred exclusively in the states of Amazon biome.

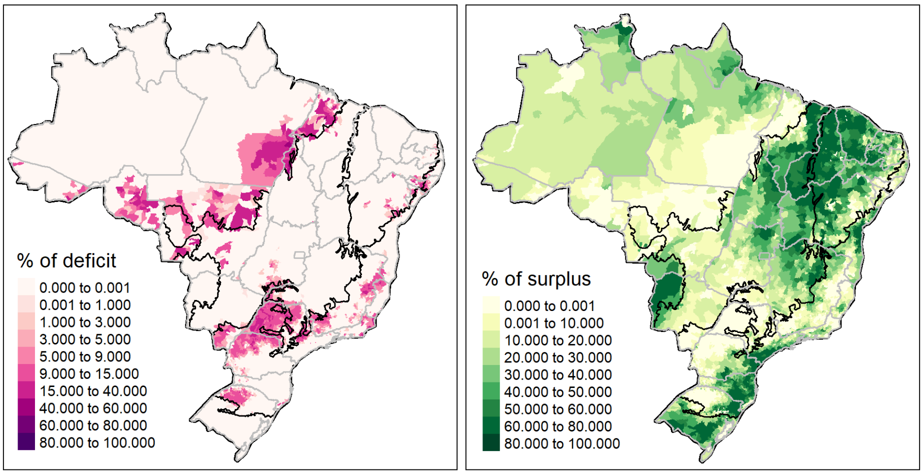


Figure 22: Percentage of deficits (left) and surpluses (right) by municipality according to methodology M_3.

The total surplus of Legal Reserve calculated in this methodology was 204.8 Mha, showing also an increase in the states of Amazon biome. Since MapBiomas land use maps estimate more natural vegetation than TerraClass, it was expected that the surplus calculated using this reference would be higher than the one with TerraClass. It is worth mentioning the importance of the surplus calculation since this value represents the unprotected native vegetation that, according to Forest Code, can be legally deforested.

Scenarios defining the upper and lower limits of deficit and surpluses in each Brazilian municipality were created by combining the three methodologies. These scenarios, denominated S_A and S_B, are shown in Figures 23 and 24, respectively.

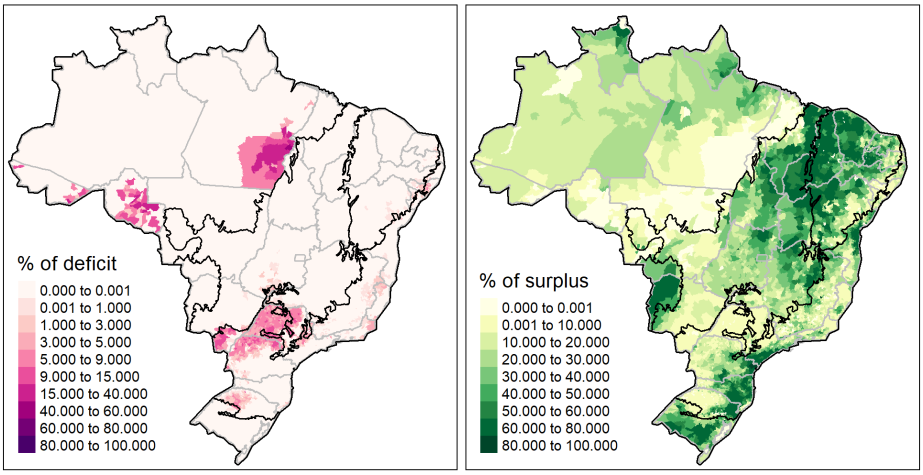


Figure 23: Percentage of deficits (left) and surpluses (right) by municipality in scenario S_A.

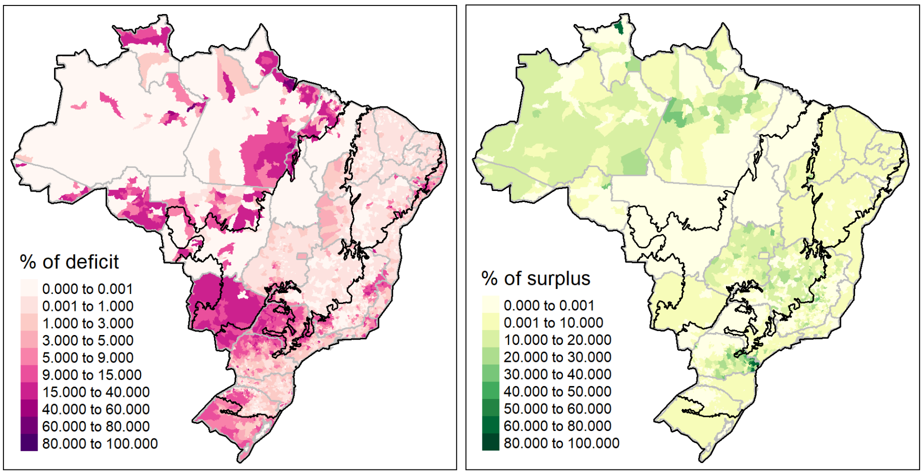


Figure 24: Percentage of deficits (left) and surpluses (right) by municipality in Scenario S_B.

These results indicate that, even in the scenario with the lowest deficit (S_A), the municipalities of Pará and Rondônia states along the border between Amazon and Cerrado showed the largest deficits of the country. In S_B, with the upper limit of deficits, all the border between Amazon and Cerrado, also known as deforestation arch, has large deficits. Additionally, large deficits can be found in the region covered by North of Paraná, West of São Paulo and Mato Grosso do Sul, as well as the extreme south of the country. The total deficit for Scenario S_A is 6.9 Mha and for Scenario S_B is 34.5 Mha.

On the other hand, analyzing the surpluses, Amazon biome has considerable surpluses in both scenarios, excluding the deforestation arch. Note that the maps are drawn as a proportion of the municipality area. As the average area of the municipalities within Amazon biome is significantly greater than in the rest of the country, the overall surplus of this biome will also be significantly greater than the other biomes. Since a high surplus means an unprotected native vegetation, these results highlight the importance of protection of the Amazon biome, which contains the world's largest rain forest and biodiversity. The total surplus for scenario S_A is 212.9 Mha and for scenario S_B is 46.1 Mha.

Comparison with Other Methodologies

The results of the three methodologies and two scenarios were compared to those of Guidotti et al. [2017], in which the authors also computed Legal Reserve deficits based on CAR. The methodology used in this previous study differs from the current methodology in two points. First, Guidotti et al. [2017] use CAR data from December 2016, when there were only 3,923,689 registered properties, equivalent to about 81% of the properties available in October 2018. Because of that, the authors simulated the allocation of the remaining 20% rural properties using additional data. Second, the land use map used as Legal Reserve proxy in [Guidotti et al., 2017] was produced by [Sparovek et al., 2015] while in this work we used MapBiomas and TerraClass.

The results aggregated by biome are shown in Tables 1 and 2. It is observed that the Amazon biome has the largest deficit and surplus among all methodologies, and with values greater than those presented by Imaflora. In the Atlantic Forest biome, the deficit values calculated in the three methodologies are lower than the Imaflora results. However, the methodology M_1 and Imaflora present practically the same values of surplus. For the other biomes, Imaflora values of deficits in Caatinga, Pampa, and Pantanal are similar to those obtained here using methodologies M_2 and M_3. In Cerrado, Imaflora deficit is closer to the values estimated by methodology M_1. Surpluses calculated by Imaflora in these four biomes are similar to those estimated by methodologies M_2 and M_3.

Biome	M_1	M_2	M_3	S_A	S_B	Imaflora
Amazon	13.6	18.2	9.9	4.8	18.7	4.0
Atlantic Forest	3.5	4.2	4.2	1.7	6.0	6.7
Caatinga	0.3	0.3	0.3	0.0	0.5	0.9
Cerrado	5.2	1.4	1.4	0.4	6.2	6.0
Pampa	1.6	0.0	0.0	0.0	1.6	0.7
Pantanal	1.5	0.0	0.0	0.0	1.5	0.0

Table 1: Comparison of deficits by biomes, in Mha.

Table 3 shows the summary of aggregated results for Brazil along with the results of [Soares-Filho et al., 2014]. It is worth mentioning that CAR data was unavailable at the time of the analysis of Soares-Filho et al. [2014]. In the absence of a unified land registry, the authors used 12^{th}-order watersheds provided by ANA (Brazil's National Water Agency) as a proxy for rural properties. To estimate deficits and surpluses of Forest Code, they quantified the total area where Forest Code is applicable in each microwatershed.

Biome	M_1	M_2	M_3	S_A	S_B	Imaflora
Amazon	32.5	34.8	64.8	64.9	32.4	11.6
Atlantic Forest	8.5	24.4	24.4	28.4	4.6	8.3
Caatinga	0.6	38.2	38.2	38.2	0.6	34.9
Cerrado	12.5	59.6	59.6	63.8	8.4	43.8
Pampa	0.1	9.1	9.1	9.2	0.1	4.2
Pantanal	0.0	8.3	8.3	8.3	0.0	7.9

Table 2: Comparison of surpluses by biomes, in Mha.

Methodology	Deficit	Surplus
M_1 (CAR + TerraClass)	25.6	54.2
M_2 (TerraClass + MapBiomas)	24.0	174.8
M_3 (MapBiomas)	15.7	204.8
S_A (min deficit/max surplus)	6.9	212.9
S_B (max deficit/min surplus)	34.5	46.1
Guidotti et al. [2017]	18.7	111.1
Soares-Filho et al. [2014]	21.0	88.0

Table 3: Comparison of Legal Reserve deficits and surpluses for Brazil, in Mha.

Final Remarks

Estimating deficits and surpluses for Legal Reserve in Brazil is a tough task due the size and complexity of the country. In this activity, we developed a methodology to combine CAR data with other sources to improve the existing estimates. Modeling studies usually try to consider the uncertainty of data and projections by developing scenarios. The results presented in this chapter can be used directly as input for different scenarios that investigate impacts of Forest Code and its possible changes.

In the current Brazilian scenario, it is important to monitor estimates of Legal Reserve deficits and surpluses in order to protect the natural vegetation. The current Brazilian government is trying to reduce the mandatory percentages of Legal Reserve (according to the proposal, the percentages within Legal Amazon could go down from 80% to 50% in forest areas and from 35% to 20% in Cerrado areas). The consequences of this action must be emphasized. Even in the Scenario S_A, which presents a somewhat optimistic result, there are large areas with deficits to be recovered, and a large area of unprotected native vegetation.

Due to time constraints, the classifications for Cerrado and Amazon biomes presented in last chapter were not included in the analysis presented in this chapter. Additionally, it is possible to include the results of other methodologies available in the literature into scenarios S_A and S_B. The next step of this work includes performing such analysis.

The methodologies developed to compute deficits and surpluses were implemented in PostGIS using SQL scripts. This way, it is possible to easily recompute deficits and surpluses as new CAR or land cover data is released. The results as well as the scripts are available at http://bit.ly/2ZKaRl2.

Activity V.1.7

Activity V.1.7: Conduct econometric analysis of historical forest gains to better estimate opportunity costs of forest restoration, focusing on key regions.

Introduction

The last version of Brazil's Forest Code (or Native Vegetation Protection Law - NVPL) went into effect on May 25, 2012, and became thus the main environmental regulatory mechanism established by Law No. 12.651/2012 [Brasil, 2012]. The Forest Code regulates exploration, conservation, and recovery of native vegetation nationwide. However, this legislation faces direct opposition of powerful groups of the agricultural sector as well as from their representatives in the Brazilian Parliament. These opposition groups point to environmental damages because of flexibility of the new rules regarding permanent preservation areas, reduction of legal reserve, and amnesty for environmental degradation before July 22, 2008. Therefore, it is necessary to know the potential economic impacts of the Forest Code (FC) nationally and regionally in Brazil.

This activity assess the economic impacts of changes promoted by the New Forest Code on economic sectors and regions of Brazil, considering three scenarios and integrating two models: GLOBIOM-Brazil and TERM-BR.

Methodology

In this study, we integrate two models: i) GLOBIOM-BRAZIL and ii) TERM-BR. The former brings projections of land use change, based on geophysical information, and the latter presents projections of the economic scenario through Computer Generic Equilibrium (CGE) simulations for Brazil, with regionalized variables. This integration between the two models is shown in Figure 25.

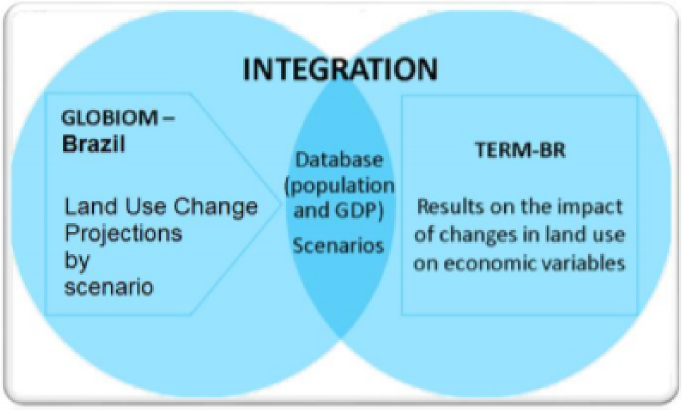


Figure 25: Integration between GLOBIOM-BRAZIL and TERM-BR.

Thus, the integration of both models provides results based on physical variables that detail land use and implications on the economic and social variables representing the reality of each Brazilian region. This approach captures the heterogeneity of impacts caused by the three mechanisms on which the scenarios mentioned in the FC are based. This subsection details the operation of the input database from GLOBIOM-Brazil and compatibility with the general equilibrium model, TERM-BR.

For the TERM-BR model simulations, a database of 38 sectors was aggregated into sectors, focusing on the agricultural sector and 15 regions. The model further details 10 types of land use and a stratification of household income in 10 groups. In all sectors, the most important products (commodities) are affected by the production constraint simulated by the GLOBIOM-BRAZIL model, namely rice; corn; wheat, sorghum and barley; sugar cane; soybean; cassava; cotton; and others.

Other sectors, such as commerce, industry, and services were not listed, because they were not affected directly. In each of the simulation scenarios, as well as the base scenario, there is an average annual growth projection of each crop. These variations affect economic variables differently in each region and the impacts are shown by the TERM-BR model.

The regions were grouped as follows: Amazon (Part of North, including the states Acre, Amazonas, Roraima, and Amapá), Rondônia (Rondônia state only), ParaToc (Para and Tocantins states), MarPiaui (Maranhão and Piauí states), Brazil, Bahia (only Bahia state), MtGrosso (Mato Grosso states), Central (Goias state and Distrito Federal), PernAlag (Pernambuco and Alagoas states), RestNE (Rest of the Northeast, including the states of Ceará, Rio Grande do Norte, Paraíba, and Sergipe), MtGrSul (Mato Grosso do Sul state), MinasG (Minas Gerais state), RioJEspS (Rio de Janeiro and Espírito Santos states), SaoPaulo (São Paulo state), Paraná (Paraná state), SCatRioS (Santa Catarina and Rio Grande do Sul states).

The scenarios considered in GLOBIOM-Brazil and in this research are based on the baseline (less restrictive scenario from the productive viewpoint) model, according to [Soterroni et al., 2016]:

- FC – Base scenario: considered the broad implementation of the Forest Code, as approved in 2012, with the effective functioning of all its instruments. The application of the Atlantic Forest Law is also considered. This scenario is less restrictive than the others, since it is possible to compensate for deforestation in other areas, without the need for recovery in a productive area. The amnesty of small properties also allows the maintenance of cultivable area. Thus, the total interference of the FC on land use was projected. This law will be implemented from 2020 until 2050 under the hypothesis of effective implementation of all the instruments of the legislation: forest restoration as legal reserve; amnesty for small properties (SFA) and environmental reserve quotas (CRA).

- Scenario 1: FC crop CRA – In this scenario, the partial use of the Environmental Reserve Quota (CRA), according to the FC, is considered. It is used to offset deficits in rural properties or possessions with agricultural production, except for livestock areas. This scenario considers that the opportunity cost of the cattle growers is lower compared to that of the CRA market entry. Therefore, they do not use CRA to offset their legal reserve liabilities. Agricultural producers, in turn, are more inclined to buy quotas of environmental reserve in order to not lose arable land.

- Scenario 2: FC without CRA– This scenario traces the FC without CRA mechanism to offset legal reserve deficit. Thus, without the possibility of offsetting liabilities in the rural property, the owner is obliged to restore vegetation within their property. There are discussions based on the inefficacy of the quota market, since the biome that has large supply also has little demand. Therefore, there are certain difficulties in negotiating quotas for certain biomes. Another concern about this mechanism is the legal possibility of not compensating for deforested area in the same micro basin, that is, near the ecosystem with suppression of native vegetation, which would lead to losses of plant and animal species and other recurring environmental problems.

- Scenario 3: FC without SFA – This last scenario simulates the FC without the amnesty of fines and sanctions to denominated small landowners (possessions with less than four fiscal modules). This scenario is based on the hypothesis that there is an obligation to recompose the environmental deficit from before July 22, 2008. There is still a debate about this issue due to the large number of properties that falls into this category. Fine exemption depends on court decision. Likewise, there is also a debate about amnesty due to the definition of "small property" in the law, with up to four fiscal modules, due to the large range in size variation of the property area according to its location, since the fiscal modules (scenarios 1, 2 and 3) are compared to the base scenario. This scenario simulates changes in land use resulting from requirements of the FC, considering the effective implementation of all legislation instruments after 2020: forest restoration as legal reserve, small property amnesty and reserve quotas.

For simulations on TERM-BR, we used GLOBIOM-BRAZIL projections of land use changes in every scenario. The production structure of TERM-BR is defined by a Leontief function, which indicates fixed proportions between the productive factors in the production of each activity. On the other hand, the primary factors (land, labor, and capital) and the origin of goods, whether domestic (DOM) or imported (IMP), are guided by the Constant Elasticity of Substitution (CES) function. Consumers minimize their expenditures based on a CES function [Fachinello and Ferreira Filho, 2010].

In the demand structure of this model, vectors of investment and government spending are exogenous. Exports follow a constant elasticity function, while household demand follows a linear system of expenditure [da Silva, 2015]. Changes in land use are treated exogenously, with the support of a matrix in which land use restrictions are imposed, according to existing boundaries. In this version of TERM-BR, data changes on the use of the primary factor Land were adjusted by state and crop in the agricultural sector.

Results

Simulations of the TERM-BR model present the impact for three scenarios: i) Crop CRA; (ii) Without CRA; and iii) Without SFA. The information from these scenarios is compared with those of a baseline scenario, which includes all these mechanisms of the 2012 Forest Code.

The results can be compared in the cumulative version of the period, or every period, between 2010 and 2030, according to land use database restricted by FC, from 2010 to 2030. The score evaluation in the national regional extension period compares the deviations of the three simulation scenarios with those in the baseline scenario.

The three main steps are based on policies of land use reduction to improve environmental regeneration, reducing the productive area. This reduction of the decision-making capacity is a structure that aggregates and reaches each scenario distinctly, since the territory and agents involved are distinct in each simulation.

The quota mechanism is more interesting to cattle growers than to farmers, since the former have a lower opportunity cost to recover native vegetation in their properties, provided they can improve the total yield factor. Still, areas for cattle farming in Brazil have been increasingly pressured by the recovery of APP and Legal Reserve (LR) imposed by the Forest Code, in addition to the pressure to increase the crop areas, as reported by [Sparovek et al., 2011] and [Soterroni et al., 2016].

The national reference values indicate the percentage deviation for selected macroeconomic variables in relation to the base scenario (Table 4). Note the similarity of the results in scenarios 1 and 2. The economic impact

Selected Variables	Scenario1 FC crop CRA Δ%	Scenario 2 FC without CRA Δ%	Scenario 3 FC without SFA FC crop CRA Δ%
Consumption	-0.11	-0.11	-0.44
Employment	0.01	0.00	0.01
Capital Stock	-0.19	-0.17	-0.66
Export (Vol.)	0.44	0.43	1.89
Government Expenses	-0.09	-0.11	-0.45
Import (Vol.)	-0.13	-0.14	-0.40
Real investment	-0.79	-0.84	-3.09
Real GDP	-0.12	-0.14	-0.51
Real salary	-0.27	-0.28	-1.15

Table 4: Percentage deviation, between the base scenario in relation to scenarios 1, 2 and 3, of the selected macroeconomic variables, accumulated in the period 2010 - 2030.

in scenario 3 is higher, compared to the previous ones. This last scenario is more restricted from the productive perspective, mainly because of a greater regenerated area.

The macroeconomic equilibrium re-established after land use restriction occurs with GDP decrease in the scenarios (1, 2 and 3) and, in the long-term, there is a reduction in the real salary of 0.27%, 0.28%, and 1.15% for each scenario, respectively. This reduction affects mainly household consumption, which, in turn, decrease 0.11% when the CRA mechanism was totally or partially disregarded. By disregarding the amnesty of fines and sanctions, the impact on national consumption is four times higher, or a 0.44% decrease. Government expenditures follow the same trend of family consumption, with a decrease of 0.09%, 0.11%, and 0.45% in scenarios 1, 2, and 3, respectively.

Nevertheless, at the national level, the employment variable does not show a significant decrease in the accumulated period between 2010 and 2030, which means the re-absorption of employees by less impacted sectors. The sectors directly affected are labor intensive thus it is important to observe the regionally disaggregated values. The general equilibrium model takes into account the substitution effect that can occur between the primary factors (land, capital, labor) through the elasticity of substitution. Thus, if labor is less expensive, it is also more absorbed. Besides, labor force can move between regions and sectors, depending on the relative wage.

Capital stock shows a larger decrease compared to consumption, which results in a reduction of 0.19% (partial CRA), 0.17% (FC without CRA), and 0.66% (FC without SFA) compared to the base scenario.

Despite the GDP reduction, the volume of exports is projected to remain above the baseline scenario. In case of non-use of the CRA partially or totally, there is a reduction of the productive area for LR compensation, even though exports increase by 0.44% and 0.43% for scenarios 1 and 2, respectively. In case of amnesty, exports increased 1.89% in the accumulated for the analyzed period. This is explained by consumption decrease in the domestic market, causing change in trade. The impact depreciates the exchange rate, devaluing local currency, increasing the comparative advantage of the Brazilian product in international trade.

Investment is the variable with the largest drop in the three scenarios. In the case of a change in environmental policy according to scenarios 1 and 2 (partial CRA or non-CRA), the actual investment accumulated between 2010 and 2030 decreases 0.79% and 0.84%, respectively. In scenario 3 (FC without SFA), in turn, this deviation shows a reduction of 3.09%. The result is a reduction of crop area and a consequent decrease in the production value of sectors. These results are in line with the study of [Diniz, 2013], when restriction of the land variable also showed an increase in exports and a GDP drop, as well as in other variables.

Without CRA for LR compensation, the grower is obliged to produce in a restricted area, although there is still the possibility of legal deforestation in other areas. In the scenario disregarding the amnesty to owners with consolidated areas, there is only loss of area for environmental recovery of the liabilities recorded before July 2008.

By disregarding the partial/total CRA mechanism or amnesty, the accumulated real GDP is projected to remain below the baseline throughout the period. However, at the end of the period (2030), in scenarios 1 and 2, real GDP decreases 0.12% and 0.14%, respectively, while in scenario 3, the reduction is 0.51%. The retraction is greater in scenario 3, with a greater variation decrease, since it is the impact of the scenario with greater regeneration of native vegetation. Still, the decrease does not reach 1% of the value accumulated in the baseline, that is, it is a small variation because it is only a mechanism of the Forest Code. This study is similar to [Diniz, 2013], who evaluated the impact of the 2012 Forest Code in relation to the previous Code and obtained impacts below 1% (between 0.17% and 0.19% in GDP with the current Environmental Law).

Similar to GDP, production is affected differently in each economic sector. Products related to agriculture and agribusiness are more negatively impacted by land restriction. Tables 5 and 6 show the percentage deviation of the total output of selected products in scenarios 1, 2, and 3 compared to the baseline, for the most negatively impacted products.

Brazil is an important producer of sugarcane, soybean, and meats, which are mostly affected by a change in the environmental policy. Nevertheless, other products had their production increased, regardless of the scenario. This may occur in exporting sectors that benefit from the devaluation of the Brazilian currency. Therefore, in the three simulations, there were not only losses. Some products with expressive positive variations in their production: rice (scenario 3), except for the South of Brazil; soybean grain (scenarios 1 and 2), except for the Midwest), coffee beans in northern Brazil (scenarios 1, 2, and 3).

Industries	North			Northeast			State of São Paulo		
	Δ% by scenario			Δ% by scenario			Δ% by scenario		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Rice	-8.51	-4.67	62.12	1.87	-7.33	3.48	0.31	-1.21	0.05
Sugar cane	-19.16	2.81	7.28	-0.97	0.35	-1.08	0.78	-1.07	-3.74
Soybean	1.17	2.41	2.92	3.19	4.50	3.04	2.53	6.83	-2.62
Cassava	-16.93	-9.94	-4.73	1.60	5.14	-2.45	56.50	-9.17	48.35
Tabacco	7.96	22.63	-6.65	-3.06	-3.05	-1.09	-0.32	-0.25	0.98
Coffee	45.54	22.91	19.80	-1.63	-2.11	-0.74	-0.31	-0.27	-0.47
Forestry	-12.06	11.64	14.15	-5.80	7.45	5.03	1.95	0.45	-1.90
Cattle	-5.26	-1.17	-1.20	0.48	1.90	2.87	2.41	-0.46	-2.63
Milk	-4.85	0.03	-0.66	-0.23	1.05	3.03	1.00	-1.18	-2.33
Sugar	4.05	3.48	-0.50	-0.95	-2.14	-5.27	-0.57	-1.96	-6.65

Table 5: Percentage deviation of the total production of the industries (selected products) by scenario and region: North, Northeast and São Paulo State, in Brazil, in the accumulated period of 2010-2030.

Industries	Southeast*			South			Midwest		
	Δ% by scenario			Δ% by scenario			Δ% by scenario		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Rice	0.79	5.88	5.75	-0.14	1.53	-12.10	-0.22	1.77	3.17
Sugar cane	-0.77	0.30	1.73	-1.38	-0.27	10.77	-0.56	2.82	3.12
Soybean	7.04	12.72	-0.14	1.08	7.45	5.13	-9.21	-13.90	-10.31
Cassava	5.17	5.49	-7.96	8.75	-15.70	5.61	-23.10	3.75	6.64
Tabacco	0.20	-0.15	0.64	0.05	0.28	1.51	-0.01	0.53	1.14
Coffee	-061	-0.46	-0.64	-0.39	-0.28	-0.52	-0.82	0.33	-1.03
Forestry	1.47	-1.76	-4.50	0.02	-0.45	-2.16	2.91	-13.5	-4.73
Cattle	2.40	1.89	-5.58	2.49	-8.43	-14.60	-1.95	-5.82	-16.89
Milk	1.31	1.53	-4.69	1.49	-8.74	-13.80	4.68	-4.57	-37.37
Sugar	0.15	-0.16	-2.96	0.03	-2.67	-6.81	-0.50	-0.67	-7.13

Table 6: Percentage deviation of the total production of the industries (selected products) by scenario and region, Southeast* (without São Paulo State), South and Midwest of Brazil, in the accumulated period of 2010-2030.

Regionally, employment follows a production structure of the sectors. The difference between employment levels at the national level at the end of the period analyzed points to a decreased demand for employment, especially in the agricultural sectors with a reduction in production.

Similar to Table 6, the main sectors that had 10% in the request for employment were in the regions: Midwest, for cassava production, forest exploration, and milk (scenarios 1,2, and 3, respectively); in the North, for the sugarcane industry (scenario 1); in the state of São Paulo for a sharp demand in the industries of wheat and other cereals (scenario 3); and in the South, with a drop for rice production (scenario3).

The consequences were not harnessed with land yield gains. The northern region suffered most productivity loss of the land in agricultural products. We highlight the greatest negative impacts: i) in scenario 1, to Part of North of Brazil (sugarcane) and Rondônia (coffee beans); ii) in scenario 2, to Part of North (sugarcane and coffee beans) and Minas Gerais (soybean) also lost productivity in scenario 2; iii) in scenario 3, to Tocantins and SCatRioS (soybean).

On the other hand, some states showed gain in land use yield. We highlight that in scenario 1, Pará and Tocantins (sugarcane and soybean). In scenario 2, the larger gains in output per cultivated area occurred in the states of Mato Grosso do Sul (sugarcane) and Pará and Tocantins (soybean). In scenario 3, we highlight Mato Grosso do Sul (sugarcane); Goiás and Distrito Federal (soybean).

The regional macroeconomic results show the impact of policies in each Brazilian state. Figure 26 shows a variation of real GDP per state, not accumulated from 2010 to 2030, between simulated and baseline policy results.

The results of this research show that, nationwide, forgiveness of penalties cause greater negative impact on the real GDP compared to the system of quotes of environmental reserve, as discussed earlier. Regionally, such changes in transport legislation have minor impact on states with large areas with environmental assets. Regions with larger deficits of LR and APP will need support to reduce their economic losses due to reduction of productive area. This is a great challenge, without mentioning existing inequalities issues in a rural environment. The most diverse agricultural producers will suffer impacts in scenarios 1 and 2 (FC partial CRA and without CRA, respectively). Regions with numerous small businesses, typically concentrated in the Northeast and South of the country, will probably be more impacted according to the simulation in scenario 3 (FC without SFA), although interference on regional GDP refers to the added value of the production of large crops, such as soybean and sugarcane, for example.

Thus, Figure 26 shows GDP from every state in every simulation, although the state of Minas Gerais was not different in the first two simulations. The states with the highest casual reality, which was refined in the Brazilian market, were: PA-TO (-2.5%), in scenario 1; Mato Grosso (-4.5%) in scenario 2; and Goiás and Distrito Federal (-4.3%).

	RO	Parte do NO*	PA-TO	MA-PI	PE-AL	BA	Parte do NE**	MG	RJ-ES	SP	PR	SC-RS	MS	MT	GO-DF
■ Scenario1: FC crop CRA	1.3	0.9	-2.5	-0.6	-0.3	-0.1	-0.2	0.0	-0.1	0.0	-0.1	-0.1	-0.1	-1.9	-0.1
□ Scenario2: FC without CRA	1.5	0.9	-0.9	0.3	-0.4	-0.1	0.1	0.0	-0.1	-0.1	-0.1	-0.2	-0.6	-4.5	-0.1
■ Scenario3: FC without SFA	0.0	-0.4	0.4	0.1	-0.8	-0.1	0.0	-0.6	-0.3	-0.3	-0.4	-0.6	-1.4	-0.9	-4.3

Figure 26: Percentage deviation of real GDP, per Brazilian state, in scenarios 1, 2 and 3, related to the base scenario, in the accumulated period between 2010 and 2030.

Conclusions

The New Forest Code has generated one of the biggest debates in the Brazilian legislative scope since rights are discussed democratically. In addition, in 2018, specific provisions of the law are being considered, among which the CRA, referring to the LR compensation mechanism, and the granting of amnesty to rural producers and squatters under the crime law according to Decree No. 6,514 of July 22, 2008.

The macroeconomic results, generated from the TERM-BR model, showed a GDP reduction of 0.12% (scenario 1), 0.14% (scenario 2), and 0.51% (scenario 3). This impact should not generate major concerns for the national economy, since it is a reduction of less than 1%, as this reduction is due to the substitution of productive area for an area of environmental recovery. This result is in line with other studies, cited in the literature review of this research, which present mild economic impacts when considering total or partial reduction in deforestation.

The reduction in the productive area has stronger negative economic impacts in scenario 3, compared to scenarios 1 and 2, mainly in the labor-intensive sectors of the agriculture and food industry. The impact on scenario 3 is mainly on small properties, with up to four minimum rural area module, which correspond to about 90% of private rural properties in Brazil. Production decerases due to a reduction in the production frontier, thus, there is a reallocation of productive factors during the period. Based on the neoclassical theory, employment tends to the natural rate at the end of the period. The variables that follow the GDP behavior, such as Consumption, Government Expenditures, and Imports (vol.) show a decline with a retraction of 0.1% (scenarios 1 and 2) and about 0.5% (scenario 3). Investment decreased 0.8%, 0.8% and 3.1% in the respective scenarios 1, 2 and 3. The percentage decrease in real salary is even higher than in consumption, where there was a reduction of 0.3% (scenarios 1 and 2) and 1.2% (scenario 3). Exports increased 0.4% in scenarios 1 and 2, while in scenario 3, the increase reached 1.9%. The downturn in the domestic market pressures the agro-export sectors for trading in the international market. Possibly, there is an improvement of trades due to the devaluation of the Brazilian currency, boosting sales in foreign markets.

Regionally and sectorally, the imposed constraint of land use affects the productive structure in the agricultural sector. There is a natural tendency to replace crop products according to their relative prices. The results showed a positive variation of soybean yield, for example, in at least two of the simulation scenarios in all major regions except for the Center West.

In sum, concerns regarding the socioeconomic situation should be related to the states with the greatest GDP losses, which, according to scenarios 1, 2 and 3, are respectively: PA-TO (2.5%); Mato Grosso (4.5%); and Goiás and DF (4.3%). These states lost the largest area for growing soybeans. The same states also suffered great losses of pasture areas. The state of Mato Grosso had a large reduction of exports due to a reduction in soybean production, unlike most states.

From the environmental perspective, under the hypothesis of scenario 1, where CRA market cannot be used, it is possible that producers with environmental assets are discouraged from maintaining them and legally clear areas for cultivation. Even though there is questioning about the compliance of rural producers with this law, the New Forest Code is being implemented as reflected by the registration of producers in the Rural Environmental Registry (CAR) (100% in the North, Southeast and South of Brazil).

This reinforces the compliance of rural owners and squatters to the mechanisms of the Forest Code, which means an important step towards the implementation of environmental legislation in support of the three pillars of sustainable development: environmental, economic, and social. Despite controversies about legitimacy in protecting the environment, the new legislation extends the possibility of economic sustainability, especially on small farms.

Although this research presents mild economic losses, we suggest the development of compensatory policies, mainly for the states with greater losses and that present other socioeconomic problems.

The economic cost of any of the changes in the 2012 Forest Code are outweighed by a social and environmental gain, considering the need to ensure preservation of the ecosystem to mitigate emission of greenhouse gases and climate change. There are also gains in diplomatic terms because Brazil can maintain an environmental profile that confers a good negotiating position at forums that debate the topic. The government, however, should be cautious with the most affected regions and economic sectors.

It is necessary thus to investigate in a microeconomic way the needs of the most affected players and impose greater efficiency to the current environmental policy. There is a need for more adequacy on the part of landowners to increase their land production over time. It is a long way to go until we reach the ideal situation, but a first step is already possible. Further analyses of changes within the livestock sector related to yield increase under restrictions of the 2012 Forest Code are valid suggestions for future research.

Activity V.2.1 and V.2.2

Activity V.2.1: Develop scenarios, including through stakeholder consultations (conducted inter alia through R+ Labs), that: (a) cover policies that would reach zero emissions from deforestation at the earliest possible time, (b) cover policies that would transform the Amazon rain forest into a carbon sink, (c) consider REDD+ impacts from improvements on crop and livestock production systems, and (d) consider scenarios for biofuels demand and production.

Activity V.2.2: Refined analysis for alternative scenarios.

Introduction

In the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), Brazil pledged to cut its greenhouse gas (GHG) emissions by 37% below 2005 levels by 2025 and to reach a 43% reduction by 2030 [Brazil, 2015]. As can be seen in Fig. 27, the largest source of emissions in Brazil is by far the land-use change and the forest (LUCF) sector. In 2015, emissions from agriculture and LUCF sectors accounted for almost 70% of the country's emissions.

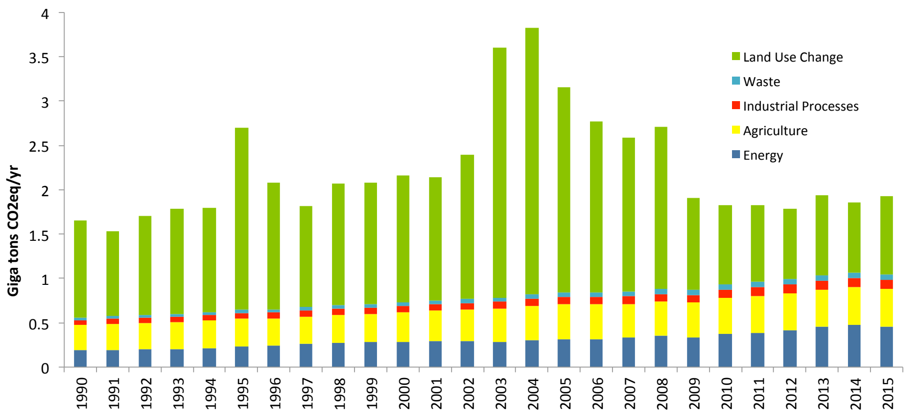


Figure 27: Brazil's emissions by sector. Source: [SEEG, 2019].

Between 2004 and 2012, the emissions from land-use change sector declined following the same decreasing trend observed in the deforestation in the Brazilian Amazon (see Fig. 28). Environmental protection measures that were implemented after 2005 let to an 83% reduction in the Amazon's deforestation, from 27,772 km^2 in 2004 to 4,656 km^2 in 2012 according to the Program to Calculate Deforestation in the Amazon (PRODES) from the National Institute for Space Research (INPE) [INPE, 2017]. This reduction resulted from a combination of improved satellite monitoring systems, the creation of new protected areas, interventions in critical supply chains (soy moratorium and the terms of adjustments of conducts for beef), the enhanced enforcement of existing laws, and the imposition of fines, restricted access to credit and even prison sentences for lawbreakers [INPE, 2017, MMA, 2013a,b, NATURE, 2015, Nepstad et al., 2014]. Still, Brazil remains one of the countries with the highest deforestation rates in the world. Since 2012, the deforested area in the Amazon has been increasing and last year it reached 7,900 km^2, the worst annual deforestation figures in a decade (see dotted line in Fig. 28).

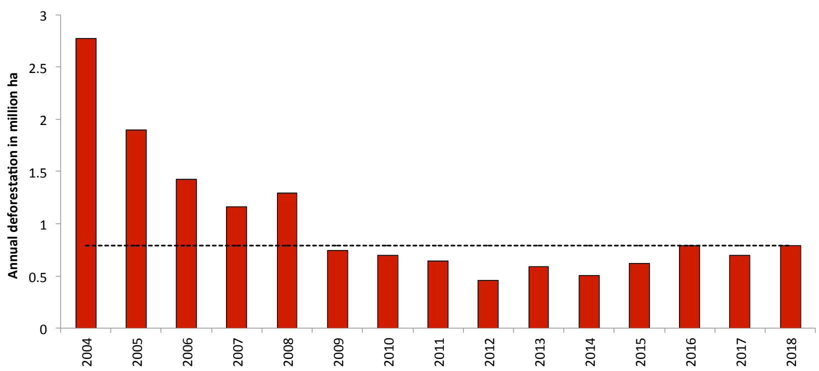


Figure 28: Amazon's annual rates of deforestation. Source: [INPE, 2017].

Private properties cover approximately 572 million hectares (Mha) or 67% of Brazilian territory [MDA, 2011], and contain more than 50% of Brazil's native vegetation [Soares-Filho et al., 2014]. The most important environmental law that regulates land use and environmental management on private properties in Brazil is the Forest Code, which dates from 1965 and underwent a major revision in 2012. The Forest Code sets a minimum percentage of native vegetation to be preserved or restored on each property. It is not a coincidence that among the key measures of the Brazil's NDC is the enforcement of the Forest Code and the control of illegal[3] deforestation in the Amazon biome (see box below).

[3] Illegal deforestation is the clear cut of forests or native vegetation not allowed according to the Forest Code. On the other hand, legal deforestation is the removal of vegetation permitted by this law.

The main program to restore the 12 Mha of forests by 2030, as committed in Brazil's NDC, is the National Plan of Native Vegetation Restoration (PLANAVEG) jointly launched in 2017 by the Ministry of the Environment and the Ministry of Agriculture. In addition to the goals of the LUCF sector, the Brazil's NDC targets for the agricultural sector include the enhancement of the Low Carbon Emission Agriculture Plan (ABC Plan) with the restoration of 15 Mha of degraded pastureland by 2030, and the expansion of 5 Mha of

Brazil's NDC commitments of the LUCF sector
• 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 Amazon, zero illegal deforestation by 2030 • restoring and reforesting 12 Mha 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 curb illegal and unsustainable practices

integrated cropland-livestock-forestry systems (ICLFS) by 2030. In the energy sector, the goals of the National Biofuels Policy (RenovaBio), which aims to reduce the carbon footprint of the national fuel mix, are underpinned by the Brazil's NDC targets. Brazil's national plans and international commitments such as the Paris Agreement, the Bonn Challenge, the New York Declarations on Forest (NYDF), the Convention on Biological Diversity (CBD), the Initiative 20x20, among others, will be benefited from the rigorous enforcement of the Forest Code.

When governance is weak, supply-chain agreements can play an important role. Particularly for soybeans – a Brazilian commodity-driven deforestation – such agreements have the potential to curb forests and native vegetation clear cut. In 2006, the Greenpeace started a campaign to clean Brazil's soy supply chain from Amazon's deforestation. The NGO exposed to the world's public opinion large companies that were consumers of soybeans produced in the Amazon, such as McDonald's. Brazil's soy producing and processing sector responded quickly by signing, in the same year, the so-called "Soy Moratorium" (SoyM). The Amazon SoyM is a zero-deforestation agreement between civil society, industry, and government that prohibits the buying of soybeans grown on recently deforested land in the Brazilian Amazon. In May 2016, the SoyM was renewed indefinitely. A recent study has shown that 65% of soybean farms surveyed in the Amazon's Mato Grosso region do not comply with the Forest Code, but comply with the soy moratorium [Azevedo et al., 2015]. According to the Soy Working Group (GTS), between 2008 and 2015, only 1.2% of the area cleared in this biome were not compliant with the moratorium.

Soybeans are Brazil's most important cash crop, with approximately 70% of Brazilian soybean production being exported worldwide [TRASE, 2015]. In 2015, only 13% of Brazil's soybean production was harvested in the Amazon while 48% came from the Cerrado biome [PAM/IBGE, 2019]. Inside the Cerrado, the Matopiba – a region that includes portions of Maranhão, Tocantins, Piauí and Bahia states – is at the forefront of agricultural expansion, with the soybean area increasing by 253% between 2000 and 2014 [Carneiro-Filho and Costa, 2016]. Brazil's soybean production is expected to continue to grow in the coming decades [OECD/FAO, 2017], and Cerrado is likely to be the main location of this expansion. Because only 19.8% of undisturbed native tropical savanna remains in Brazil's Cerrado [Strassburg et al., 2017], conversion of the remaining habitat is a major threat to biodiversity. Under Brazil's Forest Code, there is a requirement to conserve 80% of the native vegetation on private lands in the Amazon biome but only 20% in the Cerrado (35% for the portion of the Cerrado located in the Legal Amazon). Moreover, the government's regulatory measures that, together with supply chain initiatives, were responsible for reducing deforestation in the Brazilian Amazon [Nepstad et al., 2014] are historically ineffective in the Cerrado for lack of political will.

For Activities V.2.1 and V.2.2, we developed scenarios through stakeholders consultations that highlight the importance of enforcing the Forest Code for Brazil to achieve its emissions reduction goals and contribute to global climate change mitigation. The rigorous enforcement of the Forest Code is a key policy for the country to reach zero emissions from deforestation and to transform the Amazon rain forest into a carbon sink. To this end, we considered scenarios where the main Forest Code measures are implemented in different starting dates, different biomes and different levels of compliance. We also developed scenarios with different biofuels demand in Brazil that take into account different GDP and population growth, fleet composition, blending policies, fuel prices and energy efficiency.

In addition to being critical to future projections of environmental and agricultural impacts of policies that would reduce emissions from deforestation and increase the use of biofuels, the evaluation of the impacts of climate change in future projections of Brazilian agriculture was also a demand from Brazilian stakeholders. In GLOBIOM-Brazil, the impacts of climate change are estimated by introducing biophysical shocks that modify crop (and grassland) productivity at the beginning of each time step. These biophysical shocks are estimated through changes in potential productivity projected by crop models forced by projections of future climate change.

This chapter contains a description of the improvements and adaptations performed in GLOBIOM-Brazil model in order to implement the scenarios of this study. A validation of the business-as-usual scenario is performed regarding deforestation trends and the major agricultural outputs for the historical period. The refined analysis of our scenarios focuses on land-use changes, agricultural production and emissions reduction regarding the most relevant public and private policies in Brazil. Additional analysis for the impacts of different biofuel demands and climate change on Brazil's agriculture are also addressed. The key messages from the results are highlighted in the conclusions of this chapter.

Adaptations of GLOBIOM-Brazil model

GLOBIOM-Brazil, which is based on the IIASA's GLOBIOM [Havlik et al., 2011], has been adapted to incorporate Brazil's specificities and local policies. GLOBIOM-Brazil is a global bottom-up economic partial equilibrium model that focus on the main sectors of the land use economy (agriculture, forestry and bioenergy). The production of 18 crop products, 5 forestry products and 7 livestock products are adjusted to meet the demand for food, feed, fibers and bioenergy at the level of 30 economic regions. International trade representation is based on the spatial equilibrium modeling approach, where individual regions trade with each other based purely on cost competitiveness because goods are assumed to be homogeneous. Mathematically, the model simulates the competition for land at the pixel level by solving a constrained linear programming problem: the maximization of welfare (i.e.,the sum of producer and consumer surplus) subject to resources, technology and policy restrictions. As in other partial equilibrium models, prices are endogenously estimated. Figure 29 shows GLOBIOM (and GLOBIOM-Brazil) land use and production structure.

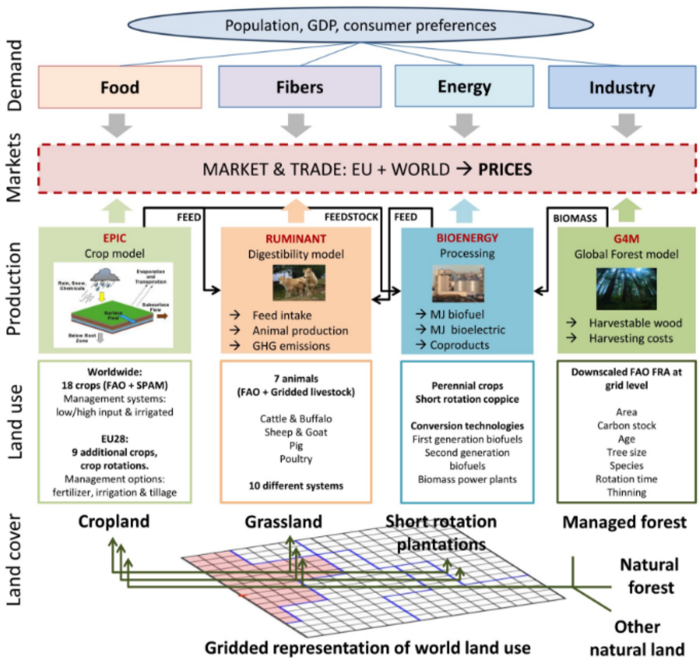


Figure 29: Overview of GLOBIOM model. SOURCE: www.globiom.org

5-year time step

The default version of GLOBIOM is recursively run with 10-year time steps, starting at the baseline year 2000 through 2050. The GLOBIOM-Brazil version used in RESTORE+ has been adapted to run with 5-year time step. A shorter simulation time step allows for more flexibility/accuracy in defining the starting dates of Brazil's local policy.

Forest regrowth land use class

The model optimizes over six land-use classes: 'Cropland', 'Pasture', Unmanaged forest', 'Managed forest', 'Planted forest' (or short-rotation tree plantation) and 'Non-productive land' (mosaic of natural vegetation and areas previously converted from agriculture but not currently under production). Given the total area of Brazil, we do not consider transitions in 'Wetlands', 'Not related lands', 'Other agricultural land' and 'Protected Areas'. The land conversion possibilities for the six land-use classes are restricted through biophysical land suitability and production potential, and through a matrix of endogenous land-use change (see Fig. 30).

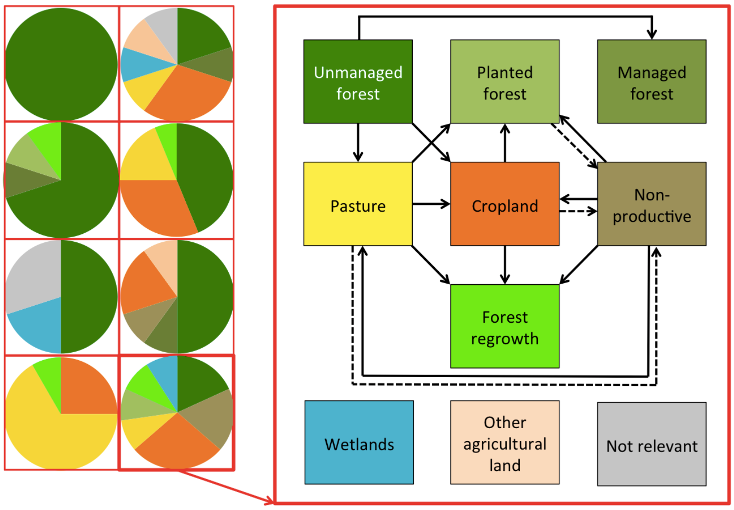


Figure 30: Matrix of endogenous land-use and land-cover changes allowed in GLOBIOM-Brazil and an illustration of possible model grid cell land use compositions. Source: Soterroni et al. [2018].

A new land-use class named 'Forest regrowth' was created in GLOBIOM-Brazil to simulate the obligatory native vegetation restoration of Brazil's Forest Code. Transitions from 'Cropland', 'Pasture' and 'Non-productive land' to 'Forest regrowth' are allowed in order to compensate for eventual environmental deficits, but no transitions are allowed from 'Forest regrowth' to any other land-use class. Land conversion cost is represented by a non-linear function. The cost per converted hectare increases with the total converted area. If production is no longer profitable, land can also be abandoned (see dotted arrows in Fig. 30). 'Forest regrowth' areas are set aside only for passive regrowth and the costs of active forest restoration are not considered in the competition for land.

Soy as a new land use class

In order to be able to control the direct conversion of land into soybeans, we separated this crop from the other 17 crops by creating a new land use class named 'SoyLnd'. Originally, the land use class 'Cropland' comprised 18 crops, including soybeans, corn, sugarcane, among others. In the default version of the model, the conversion from any land use to soybean necessarily involves the land use class 'Cropland' (see Fig. 30). In the latest version of the model used in this project, soybean has a separated class and, naturally, the total crop area simulated in GLOBIOM-Brazil is the sum of 'Cropland' and 'SoyLnd'. Other aspects of soybean production are unchanged from the previous version of GLOBIOM-Brazil.

Double cropping soy-maize

According to the official statistics, between 2003 and 2015, the area of single crop maize decreased approximately 4 Mha, whereas the area of double crop maize (or *safrinha* maize) jumped more than 6 Mha. Most of the *safrinha* is cultivated with soybeans. A remote sensing data study concludes that all maize harvested in Mato Grosso state in 2001 and in 2010 was produced using the double cropping system with soybeans [Spera et al., 2014]. The double cropping system for soybeans and maize in Brazil has also been included in the GLOBIOM-Brazil version used here. In GLOBIOM, the EPIC model is used to estimate yields and fertilizer needs for each crop in four management systems (subsistence, low-input rain-fed, high-input rain-fed, and high-input irrigated). In double cropping system, both soybeans and maize are cultivated in the same area during the same season. Fertilizer needs in the double cropping system are assumed to be equal to those in high-input single crop estimated by the biophysical model EPIC [Williams, 1995]. Yield values for soybeans in double cropping system are the same as those for high-input single crop whereas values for maize yield are assumed to be 20% lower than those in high-input system estimated by EPIC. The costs of growing soybeans and maize in double cropping system are the costs of soybeans plus 50% of the costs of maize already defined in GLOBIOM for the high-input system. The initial area for soy and maize in double cropping is derived from the Municipal Agricultural Survey (PAM, Portuguese acronym) of the Brazilian Institute of Geography and Statistics (IBGE). The representation of double cropping soy-maize in the model is important since it has become a well established crop system in Brazil [IBGE, 2008, CONAB, 2016, Spera et al., 2014, Pires et al., 2016].

Agroecological zoning for sugarcane

The model version used in this project also includes the agroecological zoning (AEZ) for sugarcane in Brazil established by a federal law in 2009 [Manzatto et al., 2009]. The AEZ for sugarcane identifies the areas where sugarcane crops can take place, and areas with restrictions regarding soil, climate, topography, water and others. It also prohibits sugarcane expansion in ecological sensitive areas, like the Amazon and the Pantanal biomes. The AEZ for sugarcane was implemented in GLOBIOM-Brazil as an economic incentive by reducing production costs proportionally to the AEZ suitability level. This incentive is implemented from 2010 onwards at a given grid cell. Unsuitable areas do not have any economic incentives. The model also restricts sugarcane expansion after 2010 in the Amazon and the Pantanal biomes.

Scenarios description and methodology of implementation

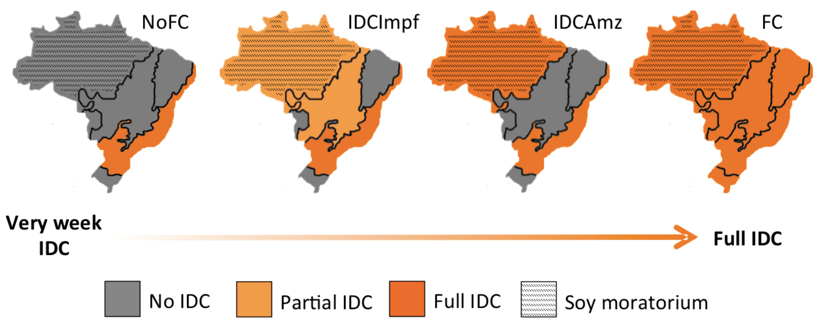
Brazilian policies with focus on emissions reduction, such as the goals of the Paris Agreement, must be necessarily connected to LUCF and agricultural sectors. In this context, the Forest Code is the key public policy to be investigated. Thus, the major scenario of this study is the Forest Code (FC): a command-and-control scenario that attempts to capture the future impacts of all key provisions of a rigorously enforced 2012 Brazil's Forest Code. It includes the full control of illegal deforestation (IDC) after 2010, the amnesty of LR debts that happened before 2010 in small farms (SFA), the environmental reserve quota (CRA) mechanism after 2020, and the mandatory restoration of LR and APP debts after 2020. Legal deforestation or conversion of LR surpluses is allowed at all times in all biomes, with the exception of the Atlantic Forest, which is protected by more restrictive legislation. The LR debts not waived by the SFA are fully paid by the farm owner, either by purchasing CRA quotas from the LR surpluses in the same biome or by taking illegally converted areas out of agricultural production for native vegetation restoration. Five additional scenarios were designed to investigate a gradient of governance and restoration around the Forest Code as can be seen in Table 7. All scenarios consider the full compliance with the SoyM in the Amazon biome from 2006 onwards.

Measures	NoFC	IDCImpf	IDCAmazon	FC	FCnoCRA	FCnoSFA
Full IDC	Atlantic F	Atlantic F	Atlantic F Amazon	Brazil	Brazil	Brazil
Partial IDC	-	Amazon Cerrado	-	-	-	-
Restoration	-	-	-	Brazil	Brazil	Brazil
CRA	-	-	-	Brazil	-	Brazil
SFA	-	-	-	Brazil	Brazil	-
SoyM	Amazon	Amazon	Amazon	Amazon	Amazon	Amazon

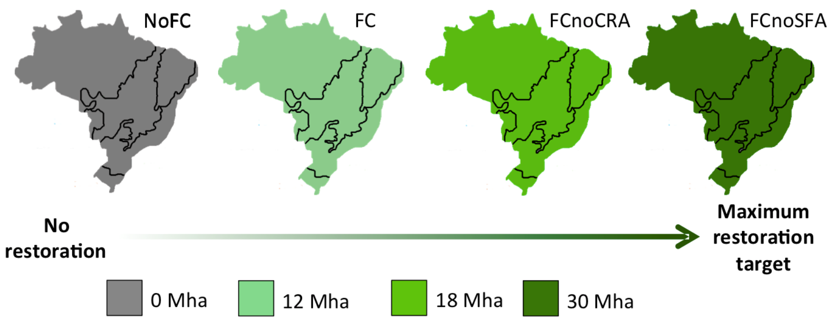
Table 7: Overview of the measures included in each scenario, and the location where those measures are applied. Abbreviation: 'Atlantic F' means Atlantic Forest biome.

The counterfactual analysis is a scenario without control of illegal deforestation in all biomes – except for the Atlantic Forest and deforestation for soybean in the Amazon biome after 2006 – and without any requirement for forest restoration (NoFC scenario). The land-use changes are driven by the demand for agricultural commodities. This type of scenario is important for evaluating the losses and gains of an unsustainable future without the enforcement of the Forest Code.

Building upon the NoFC scenario, illegal deforestation control is extended from the Atlantic Forest to the Amazon biome (IDCAmazon). To test a different level of compliance with the Forest Code, a scenario with a partial illegal deforestation control in the Amazon and the Cerrado biomes was also designed (IDCImpf). In this scenario, the probably of enforcement is based on the enforcement strategy of the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) as shown in Fig. 35. It is increased by 50% and kept constant during the period 2010-2050. Finally, we investigated the role of obligatory forest restoration with IDC and SFA but without any compensation mechanism from the environmental reserve quota system (FCnoCRA), and with IDC and CRA but without the amnesty of small farms (FCnoSFA) in Brazil. Figure 31 shows an overview of the scenarios in terms of governance and restoration targets.



(a) Governance gradient



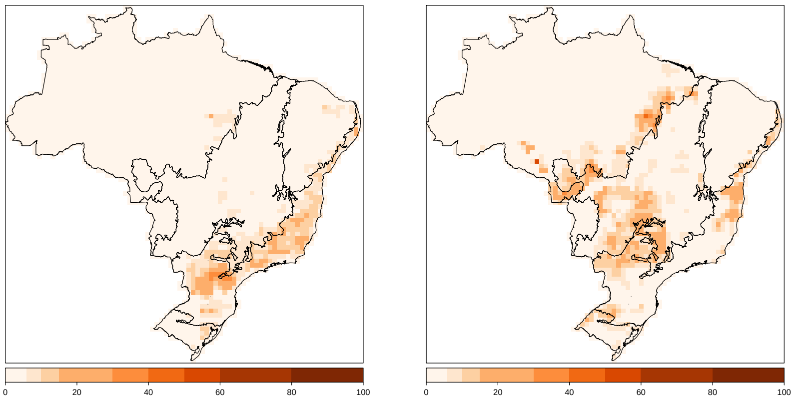
(b) Restoration targets

Figure 31: Gradient of governance and restoration targets of the various scenarios.

Environmental debts and surpluses

Due to the lack of information on property boundaries, we calculate the LR surpluses for each pixel (roughly 50 km by 50 km) as the amount of native vegetation that exceeds the legal reserve requirement. The LR is calculated by multiplying the amount of land in a pixel by the percentage of the LR requirement in that pixel. We thus obtain the total number of hectares of native vegetation which should be protected in each pixel according to the LR. Enforcement costs are not considered. We assume passive forest restoration as well as no direct costs (including the opportunity cost of taking land out of production) imposed on the farm owners in terms of legal reserve restoration.

Environmental debts are based on CAR data downloaded in December 2016 [Guidotti et al., 2017] and upscaled to 50 km by 50 km pixels. The total environmental debts amounts to 18.7 million hectares (Mha) in Brazil: 10.8 Mha of LR debts and 7.9 Mha of APP debts. This number already considers the amnesty of small farms (see Fig. 32). In the near future, maps of deficits and surpluses developed in Activity V.1.6 will be used in GLOBIOM-Brazil, and replace data from IMAFLORA or estimated computationally at the pixel level, as described above.



(a) APP debts (b) LR debts

Figure 32: Environmental debts of (a) Areas of Permanent Preservation (APP debts) and (b) Legal Reserves (LR debts) based on CAR [Guidotti et al., 2017]. Values are expressed in thousands of ha per pixel.

Forest regrowth curve

The scenarios FC, FCnoCRA, and FCnoSFA estimate different amounts of APP and LR debts to be paid by landowners. The forest regrowth in these scenarios follows the restoration curve from PLANAVEG [MMA, 2014b]. The restoration target areas are expected to be achieved by 2030 as shown in Fig. 33. The cumulative annual increase rate is approximately 38,73%, and the area to be restored in the first year is 50,000 hectares.

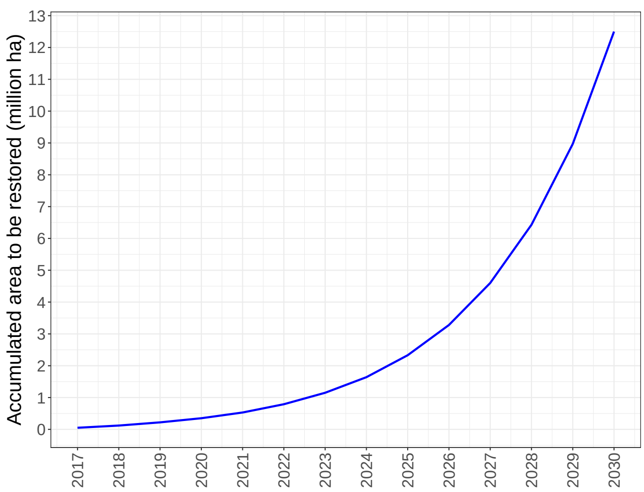


Figure 33: Forest restoration evolution as defined in PLANAVEG. Source: MMA [2014b]

In GLOBIOM-Brazil, the forest regrowth areas are not restored in one time step. As defined in PLANAVEG's curve, it is expected to be small in the beginning and increase geometrically as the large scale restoration programs and infrastructure are implemented in the country.

Environmental reserve quotas

The provision of a CRA system – tradable legal title of forest surpluses that can be purchased to offset environmental debts in the same biome – could make it less costly to conserve forests in areas with less agricultural return and less fragmented conservation of the remaining native vegetation [May et al., 2015]. In our implementation of the CRA mechanism, we assume that environmental debts will be compensated by the quota system only in pixels with deficits overlapping soybean and sugarcane production; this assumption is due to the profitability of these crops [Soares-Filho et al., 2016] and the agroecological restrictions of sugarcane expansion.

We also assume that pixels with larger deficits are compensated first, and those with larger surpluses are used first to offset the debts within the same biome. This assumption can be justified by the fact that areas with larger deficits are more likely to have higher opportunity costs. In these areas, landowners are more inclined to buy quotas and keep their land in production, rather than converting them to restored forest. On the other hand, areas with larger surpluses are more likely to have lower opportunity costs, and the corresponding landowners are more willing to sell their available quotas rather than suppress the production of excess vegetation. Given the uncertainties regarding the future use of public areas in the state of Amazonas, we assume that only 20% of the unclaimed public lands in this state will be designated as private properties and, thus, be part of the CAR database. Then, only 20% of forest surpluses in this region are considered in our environmental reserve quota stock estimates. Without this assumption, the amount of forest surpluses in the Amazonas state alone would be more than enough to compensate all the LR debts within the whole Amazon biome, which could distort the CRA market. Note that the functioning of the CRA market, described above and implemented in GLOBIOM-Brazil, will be completely reviewed in the light of the results to be produced by Activity V.1.7.

Amnesty of small farms

The small farms amnesty is a disposition included in the 2012 revised Forest Code that exempts landowners from the need to recover legal reserves in small properties. The size limit for small farms is defined by municipality, ranging from 20 ha in the southern Brazil to 440 ha in the Amazon. Based on CAR data downloaded in December 2016 [Guidotti et al., 2017], the total area of environmental debts coming from small properties sum up 18.82

Mha in Brazil. This area was prevented from restoration due to the amnesty disposition. Figure 34 shows the spatial distribution of the area of small farms amnesty upscaled to 50 km by 50 km pixels.

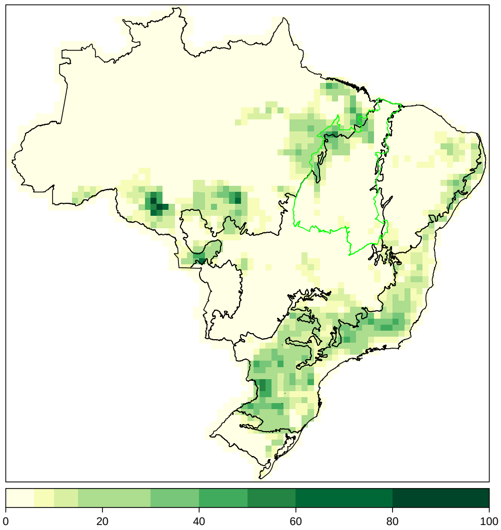


Figure 34: Spatial distribution of the area of small farms amnesty from Guidotti et al. [2017]. Values are expressed in thousands of ha per pixel.

Probability of enforcement

Given the historical lack of enforcement of the Forest Code, it is important to test in our scenarios different levels of compliance with the illegal deforestation control, the most important measure of the this law. In order to have an imperfect or partial compliance, the illegal deforestation control is modeled by using the Becker's standard model of enforcement [Becker, 1968] and the IBAMA's decision problem as defined in Börner et al. [2015] in a grid cell of 20 km x 20 km. In our IBAMA's decision problem, or IBAMA's enforcement strategy, we are taking into account: the Amazon and the Cerrado biomes as the target area; the historical IBAMA's embargoes occurrence in a grid cell during the period 2000-2014; the cost of visiting a grid cell given by a transportation costs equal to R$8,780 [Börner et al., 2014] multiplied by the transport time to visit that cell; the IBAMA's administration cost for each embargo, which is equal to R$2,165 [Börner et al., 2014]; the IBAMA's annual operation budget between 2003 and 2008 with 80% (R$40M) allocated to the Amazon biome, 9.34% (R$4.67M) to the Cerrado biome, and 10.66% (R$5.33M) to the rest of Brazil; and the official historical deforestation in a grid cell for the period 2005-2013 from PRODES/INPE. The IBAMA's enforcement strategy "seeks to minimize illegal deforestation by maximizing area of inspected illegal deforestation" [Börner et al., 2015]. For the Becker's standard model of enforcement, the cost of punishment is given by the official deforestation fine equal to R$5,000 per ha.

This approach assumes that farmers are aware of the approximate likelihood of getting punished for illegal deforestation, with their expectation based on historical enforcement. In areas with low deforestation rates, the perceived probability of enforcement (p) is low; if deforestation rates spike, the farmer's perceived p increases. Figure 35 shows the spatial distribution of the probability of enforcement as predicted by the IBAMA's optimal enforcement strategy calculated for the Amazon and the Cerrado biomes, excluding the protected areas, and upscaled to a grid cell of 50 km by 50 km. Areas with historycally high deforestation rates have a higher probability of being inspected.

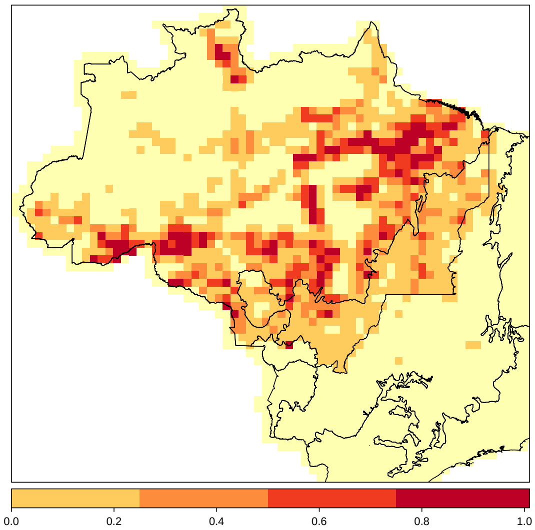


Figure 35: Spatial distribution of the probability of enforcement as predicted by the IBAMA's optimal enforcement strategy for the Amazon and the Cerrado biomes.

Soy moratorium implementation

The SoyM is implemented as a ban of direct conversion from 'Unmanaged forests' into 'Soy land' in the Amazon biome from 2006 to 2050. Since the land use class 'Unmanaged forests' represents forests and native vegetation in Brazil, this transition tracks deforestation and loss of native vegetation due to soybean expansion. Naturally, the control of the direct conversion into soybeans is only possible because the new land use class 'Soy land' has been created. We included a safeguard in the model to guarantee that only areas already cleared before the agreement can be converted into soybean. We calculated the total area of 'Pastures' and 'Croplands' in the Amazon in 2005. This amount defines the maximum area possible for the soybean expansion free from deforestation and native vegetation loss. In this study, we are considering full compliance with the SoyM in the Amazon biome from 2006 onwards.

Emissions estimates

Carbon content in the equilibrium state of land-cover classes is used to estimate GHG emissions from land-use changes. Positive and negative emissions are determined by the difference between the carbon content of the original class and that of the new class. Positive emissions are generated by deforestation or native vegetation loss and other land-use changes (e.g., transitions from 'Pasture' to 'Cropland', from 'Nonproductive' land to either 'Cropland' or 'Pasture'). Afforestation from 'Planted forests' and passive restoration by 'Forest regrowth' cause negative emissions by removing CO_2 from the atmosphere. In this study, positive emissions from deforestation, or native vegetation loss, and negative emissions from forest regrowth are estimated based on the carbon content from the Brazil's third emissions inventory (see Fig. 36), used in official communications to the UNFCCC in 2016. The carbon stocks of this map were estimated per vegetation type in each Brazilian biome (national coverage) taking into account values of living above- and belowground biomass; different land use data for the period 1994 to 2010 from projects such as RADAMBRASIL and PROBIO, as well as from the literature; different allometric equations to estimate biomass; and different biomass to carbon conversion factors [MCTI, 2015].

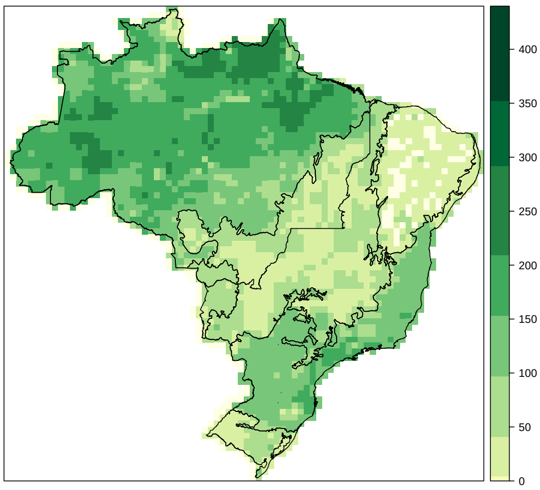


Figure 36: Spatial distribution of the total above- and belowground (TBC) biomass from the Brazil's Third Emissions Inventory [MCTI, 2015]. Values are expressed in thousands of C per hectare per pixel.

The release of carbon from the terrestrial biosphere to the atmosphere as CO_2 occurs in one simulation period (5-year time step) for deforestation and other land-use changes (i.e., other LUCs). In contrast, CO_2 removal from the atmosphere by forest regrowth takes several decades. The model accounts for carbon uptake from forest regrowth according to each biome. In the Amazon and the Atlantic Forest biomes, forest regeneration takes 25 years to recover 70% of the original biomass following the growth curve defined in Ramankutty et al. [2007].. In the Cerrado, Caatinga, and Pantanal biomes, we assume that it takes 20 years to recover their full biomass content, i.e., 70% in the first decade and 30% in the second decade. As the Pampa has grassland-based vegetation, we assume that its regeneration takes 3 years thus it is completed in one time step (i.e., five years). These regrowth periods in the Cerrado, Caatinga, Pantanal, and Pampa biomes were estimated by the ratio between the global carbon estimates for woody savannahs and grasslands provided by [Liu et al., 2015] and the average mean annual increment per biome estimated by the G4M model [Kindermann et al., 2008].

When non-productive land is converted to agricultural use or to short-rotation plantation, we assume that all biomass is released into the atmosphere. Litter, dead wood, and soil organic carbon are not considered. This is the approach that Brazil has adopted to compute the forest reference emission level (FREL) submitted to the UNFCCC [MMA, 2013a].

Climate change and biophysical shocks

In its Fifth Assessment Report (AR5), the Intergovernmental Panel for Climate Change (IPCC) defined four emission scenarios, call Representative Concentration Pathways (RCP), representing the global greenhouse gas (GHG) emissions, land use change, and consequent climate tendencies for the 21st century [Stocker et al., 2013]. In the optimistic scenario, also known as mitigation scenario, the emission trajectory results in a stable radiative forcing of 2.6W/m^2 in 2100, after a peak of 3.1W/m^2 in 2050 [van Vuuren et al., 2011]. In this scenario, the mean global temperature rise would be about 1°C (±0.4°C) by the end of the century [Collins et al., 2013]. This is the only scenario where temperature projections would be within the goals established in the Paris Agreement. In the pessimistic scenario, the increase in the radiative forcing would reach 8.5W/m^2 by 2100 in an ascending trajectory, resulting in an average global temperature increase of 3.7°C (±0.7°C; Collins et al. [2013]). Current emissions already surpassed the RCP8.5 trajectory [Peters et al., 2012].

GHG emissions and land use change defined by the RCPs are used to force Global Climate Models (GCMs), resulting in historical (forced by observed changes in radiation and land use since the industrial revolution until 2005) and future projections of climate variables such as temperature, precipitation, and moisture. These information can be used by Global Gridded Crop Models (GGCMs) to assess the biophysical impacts of climate change in crops and grass productivity as well as the regions where these crops will be more or less affected by the climate change. Finally, these biophysical shocks provide the necessary input to assess the impacts of climate changes in land use competition and other economic variables. These impacts are modeled through Global Economic Models such as GLOBIOM-Brazil. These steps are summarized in Figure 37.

In this study, we utilize the biophysical shocks from two GGCMs: EPIC [Williams, 1995, Izaurralde et al., 2006] and LPJmL (Lund-Potsdam-Jena managed Land) [Bondeau et al., 2007, Fader et al., 2010, Waha et al., 2012, Schaphoff et al., 2013]. Initially developed to quantify the effects of erosion on soil productivity, EPIC was continuously extended becoming a complex agroecosystem model [Williams, 1995]. It estimated various crop variables, such as yield, crop competition, and nutrient and carbon cycle, considering a range of crop management options [Balkovič et al., 2014]. LPJmL is a process-based ecosystem model developed to simulate vegetation composition and distribution and the complete hydrological and carbon cycles [Rosenzweig

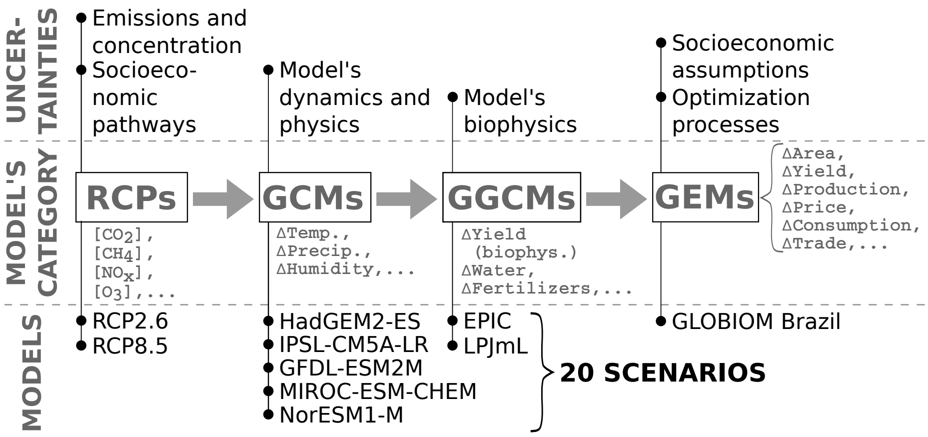


Figure 37: Impact modeling chain from RCP scenarios and GCM through crop and economic impact models (GGCMs and GEMs, respectively), resulting in 20 scenarios. Variables below each Model's Category (in gray) represent the output variable from that category utilized in the next link of the chain. Abbreviations: ΔTemp. and ΔPrecip.: variations in temperature and precipitation; biophysis.: biophysical impacts in yield, or changes in potential productivity.

et al., 2014, Weindl et al., 2015]. Crops and grasses simulations explicitly account for the C3 and C4 photosynthesis pathways [Weindl et al., 2015]. However it does not represent nutrient dynamics, such as nitrogen [Müller and Robertson, 2014].

The changes in biophysical productivity from both GGMCs were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Fast-Track platform (Rosenzweig et al. [2014], Elliott et al. [2015]; available at `https://esg.pik-potsdam.de/projects/isimip/`). ISIMIP provides spatially interpolated and bias-corrected projections of future climate change from five GCMs (HadGEM2-ES, IPSL-CM5A-LR, GFDL-ESM-2M, MIROC-ESM-CHEM, and NorESM1-M) in four Representative Concentration Pathways (RCP; Hempel et al. [2013]). These GCMs are selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. [2012]) archive and represent the range of global mean precipitation and temperature changes [Warszawski et al., 2014]. We make use of GGCMs results forced by all 5 GCMs available in ISIMIP, considering the highest and the lowest emission scenarios, RCP8.5 and RCP2.6, respectively. For both GGCMs, the levels of CO_2 vary according to the emission scenario and thus the results include effects of CO_2 fertilization.

Figure 37 also identifies the main uncertainties related to each link of this impact modeling chain. Future emissions in each RCP scenario are based on coherent socioeconomic pathways and on historical concentration of GHG and other air pollutants, with uncertainties rising from the translation of emissions profiles into concentrations and radiative forcing [van Vuuren et al., 2011]. These emissions, along with time-evolving land use changes, are inputs for GCMs under CMIP5 and consequently ISIMIP platforms. In addition to the uncertainties from RCP scenarios, each GCM responds differently to external forcing due to differences in their dynamic core (set of equation and parameterization), resulting in a large uncertainties [Kirtman et al., 2013]. Similarly, GGCMs simulations also incorporate uncertainties from the previous links of the modeling chain together with those related to the model's assumptions and performance [Elliott et al., 2015].

Results

Comparison with official statistics

Here we show the comparison between official statistics and GLOBIOM-Brazil projections for the historical period (2005, 2010 and 2015) regarding the major Brazilian commodities and deforestation trends. These include the harvested area and production from PAM (Municipal Agricultural Survey) and PPM (Municipal Livestock Survey) of the IBGE, and the deforestation in the Amazon and the Cerrado biomes from PRODES/INPE.

Figure 38 shows the accumulated deforestation in the Amazon biome between 2001 and 2020 as projected by the various scenarios, as well as the observed deforestation by PRODES/INPE until 2018. Note that, for sake of comparison, a constant annual deforestation rate of 0.79 Mha for the years 2019 and 2020 was added to the 2018 deforestation (hatched part). The value of 0.79 Mha is the annual rate of deforestation estimated by PRODES/INPE in the year 2018. The IDCImpf is the scenario that better represents the historical deforestation.

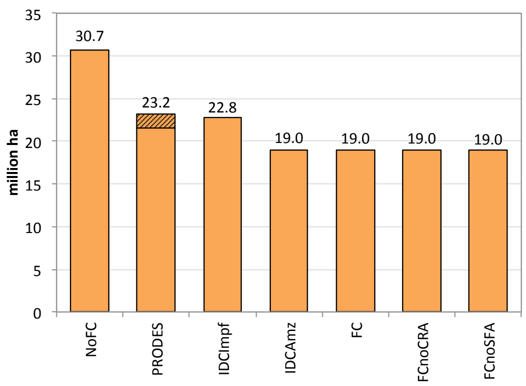
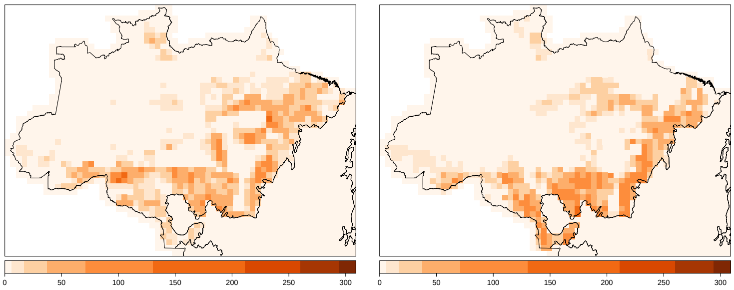


Figure 38: Accumulated deforestation in the Amazon biome between 2001 and 2020 as projected by the various scenarios and from PRODES/INPE.

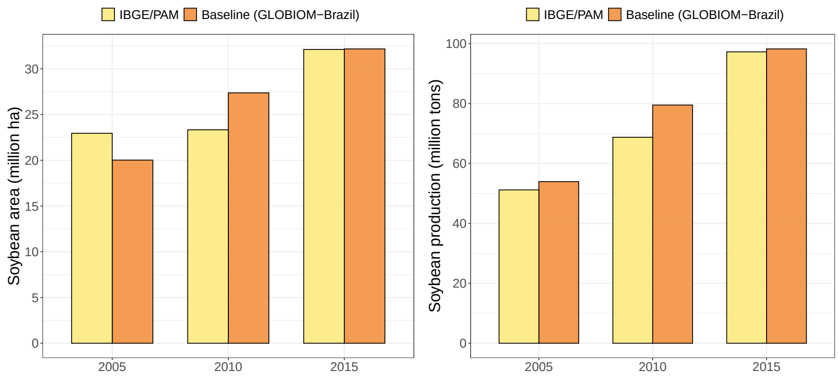
Figure 39 illustrates the spatial distribution of the accumulated deforestation from PRODES/INPE and as projected by the IDCImpf scenario, between 2001 and 2015. Differences concentrate around the indigenous Xingu Park and along the road BR-163 in the state of Pará and are probably related to the local transportation infrastructure network considered in our version of the model and which needs to be further improved. More importantly, the model captures the deforestation trends in the Amazon without using historical deforestation as an input data. Land-use changes projected by the model attend the internal and external demand of commodities such as soybeans and beef.



(a) PRODES (b) IDCImpf scenario

Figure 39: Spatial distribution of accumulated deforestation in the Amazon biome from 2001-2015 (a) as determined by PRODES/INPE and (b) as projected by IDCImpf scenario of GLOBIOM-Brazil. Color bar values are expressed in thousand of hectares per cell.

Since the IDCImpf better captures the business as usual governance in terms of deforestation trends, we selected this scenario for the comparison with official statistics regarding the agricultural outputs. Figure 40 shows the soybean harvested area and production, respectively, in Brazil according to IBGE/PAM and the IDCImpf scenario for the years 2005, 2010 and 2015. The differences between IBGE/PAM and GLOBIOM-Brazil projections for soybean vary from 0.2% to 17.3%, and they are smaller than 1.0% by the year 2015.

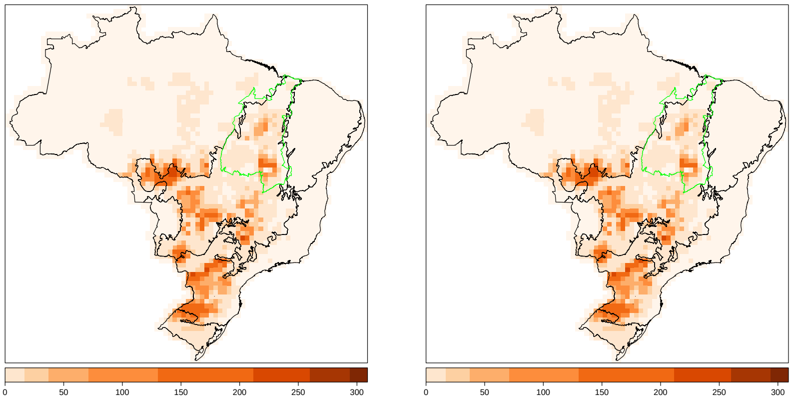


(a) Soybean area (b) Soybean production

Figure 40: Brazil's soybean (a) area and (b) production for the years 2005, 2010 and 2015 according to IBGE/PAM and as projected by the IDCImpf scenario of GLOBIOM-Brazil.

Figure 41 shows the spatial distribution of the 2015 soybean area in Brazil from the IBGE/PAM data upscaled to 50 km by 50 km pixels, and as projected by the model according to the IDCImpf scenario. The model captures the major soybean areas in the Amazon and the Cerrado biomes, including the Matopiba region (highlighted in green).

Figure 42 compares the cattle herd in million tropical livestock unit (TLU) between IBGE/PPM and the IDCImpf scenario in Brazil for the years 2005, 2010 and 2015. The difference between IBGE/PPM and GLOBIOM-Brazil at national level in 2015 is smaller than 3.0%. The TLU is a common unit to describe livestock numbers across species; 1 TLU is equal to 0.7 cattle head.



(a) IBGE/PAM (b) IDCImpf scenario (GLOBIOM-Brazil)

Figure 41: Spatial distribution of the 2015 soybean area in Brazil from (a) IBGE/PAM and the (b) IDCImpf scenario. The Matopiba border is indicated in green. Color bar values are expressed in thousands hectares per pixel.

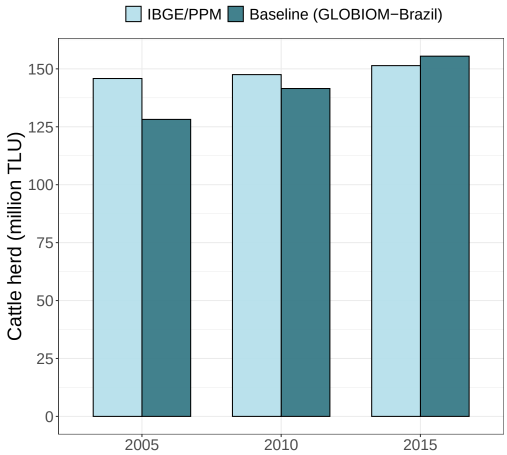


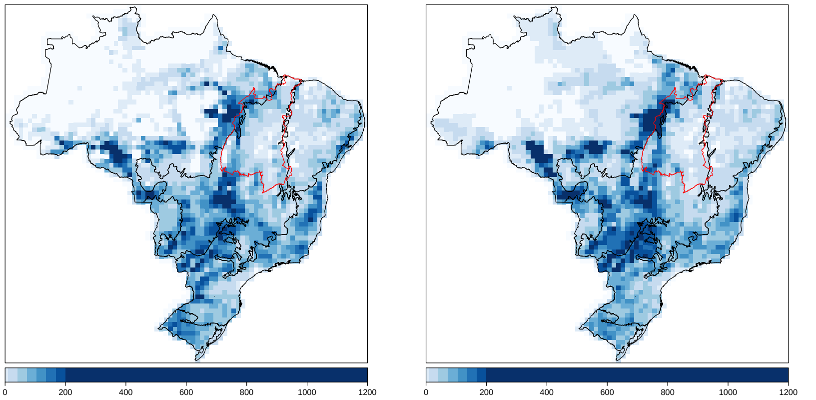
Figure 42: Brazil's cattle herd in million TLU for the years 2005, 2010 and 2015 according to IBGE/PPM and as projected by the IDCImpf scenario of GLOBIOM-Brazil.

Figure 43 illustrates the spatial distribution of the cattle herd in 2015 in Brazil according to IBGE/PPM data upscaled to 50 km by 50 km pixels, and as projected by the IDCImf scenario. The model captures the main cattle ranching locations in the Amazon, Cerrado and Atlantic Forest biomes.

Overall, the model captures the trends in forest loss and expansion of the major commodity-driven deforestation (soybeans and cattle herd) at national level with differences smaller than 10% when validated against official statistics.

Impacts on land-use and production

The scenarios designed for this study have a gradient of governance and restoration targets (see Fig. 31) that comprehends the past and possible futures in Brazil regarding the land use and emissions. In a nutshell, the FC is the most restrictive scenario in terms of illegal deforestation control. The IDCAmz focus on the command-and-control actions and does not allow illegal deforestation in the Amazon. The IDCImpf is the current business as usual scenario in terms of deforestation trends in the Amazon and the Cerrado biomes. The counterfactual scenario, NoFC, represents a very weak

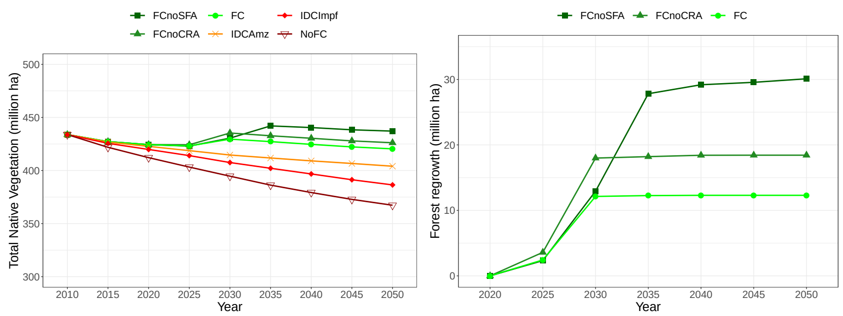


(a) IBGE/PPM (b) IDCImpf scenario (GLOBIOM-Brazil)

Figure 43: Spatial distribution of the 2015 cattle herd in Brazil from (a) IBGE/PPM and (b) as projected by the IDCImpf scenario. Color bar values are expressed in thousands hectares per cell.

governance and allows the evaluation of the FC vis-à-vis an unsustainable future where there is no compliance with the FC. The FCnoSFA has the greater restoration target among the 'FC scenarios' (i.e. FC, FCnoCRA and FCnoSFA). The combination of a large restoration area with the full control of illegal deforestation makes the FCnoSFA the greener among all scenarios.

Figures 44 to 48 summarize results from all scenarios in terms of crop area, crop production, pasture area, cattle herd, nonproductive land and native vegetation stocks at national level.



(a) Total native vegetation (b) Restoration

Figure 44: Evolution of the (a) native vegetation and (b) restoration area as projected by the various scenarios.

Figure 44a shows a near stabilization of the native vegetation area in Brazil around 425 Mha after 2025 for the scenarios FC, FCnoCRA and FCnoSFA. These scenarios have different forest restoration targets that follow the PLANAVEG's curve (Fig. 44b). Table 8 summarizes the accumulated losses and gains as projected by the various scenarios from 2015 to 2050. The FCnoSFA is the only scenario where the net accumulated native vegetation increases by 9.9 Mha (20.2 Mha lost due to legal conversion of LR surpluses and 30.1 Mha gained due to restoration of environmental debts). Under the NoFC scenario, the accumulated deforestation in Brazil is almost 3 times higher than the accumulated deforestation projected by the FC scenario through the same period.

The 54.6 Mha of legal and illegal deforestation projected by the NoFC scenario between 2015 and 2050 is likely to be mainly located in the Amazon (69%) followed by the Cerrado biome (19%), as can be seen in Fig. 45a. An

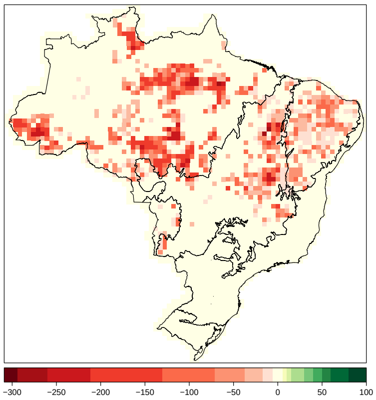
Scenarios	Accumulated loss	Accumulated gain	Net loss (-) or gain (+)
FCnoSFA	-20.2	+30.1	+9.9
FCnoCRA	-19.5	+18.7	-0.8
FC	-19.1	+12.3	-6.8
IDCAmz	-27.7	0	-27.7
IDCImpf	-39.2	0	-39.2
NoFC	-54.6	0	-54.6

Table 8: Accumulated native vegetation losses and gains in Mha, between 2015 and 2050, as projected by the various scenarios.

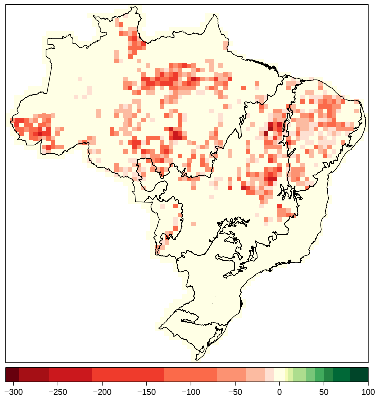
imperfect or partial control of illegal deforestation, as the one implemented in the IDCImpf scenario, projects 39.2 Mha of deforestation with a similar dynamic as the NoFC scenario during the same period: 59% located in the Amazon and 25% in the Cerrado biome (see Fig. 45b). When the illegal deforestation control is fully enforced in the Amazon (IDCAmz), the accumulated deforestation sharply decreases in this biome to only 5.1 Mha in 35 year (see Fig. 45c). However, there is a leakage effect to the Cerrado with a deforestation increase of 3.25 Mha in this biome through the same period. The patterns and aggregated numbers of deforestation projected by the FC, the FCnoCRA and the FCnoSFA scenarios are similar: approximately 27% located in the Amazon, 40% in the Cerrado, and 30% in the Caatinga biome. The major difference among these scenarios is the amount and the spatial distribution of native vegetation restoration.

The approximately 12 Mha of forest restoration projected by the FC scenario is likely to occur mainly in the Atlantic Forest (40%) followed by the Amazon (23%) and the Cerrado (23%) biomes (Figure 45d). Clearly, the CRA mechanism appears to be an important Forest Code disposition for the landowners from the Cerrado. When this disposition is not active, the restoration area in this biome increases from 2.8 to 6 Mha, when compared to the FC scenario (Fig. 45e). The absence of small farms debts amnesty (FCnoSFA) increases the amount of restoration mainly in the Atlantic Forest, from 4.9 to 12 Mha, and the Amazon biomes, from 2.9 to 8.6 Mha, when compared to the FC (see Fig. 45f). Visibly, the small farms amnesty come across as a Forest Code disposition particularly tailored for the farmers in the Atlantic Forest biome to keep their lands on the productive side.

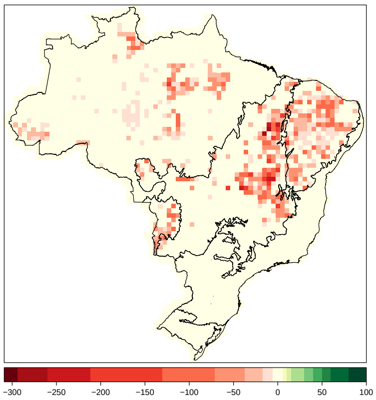
As shown in Fig. 46a, croplands in Brazil are expected to increase, between 2015 and 2050, regardless the scenario. The FCnoSFA and NoFC scenarios project, respectively, the smaller and the greater cropland area expansion. In 2050, the crop area projected by the FCnoSFA is only 5% smaller than the one projected by the NoFC scenario, which shows a small difference between these two opposite scenarios. In terms of crop production, the differences between FCnoSFA and NoFC scenarios are smaller than 1.5% for all crops.



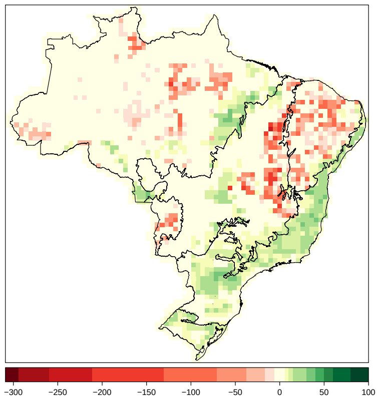
(a) NoFC



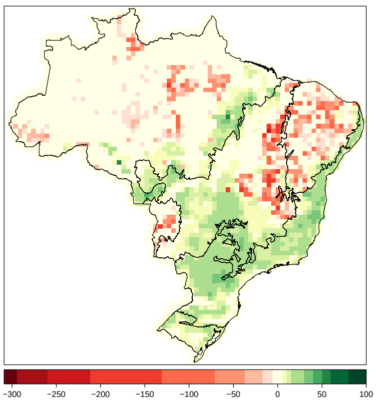
(b) IDCImpf



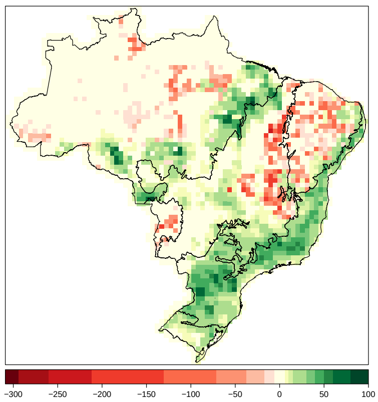
(c) IDCAmz



(d) FC



(e) FCnoCRA

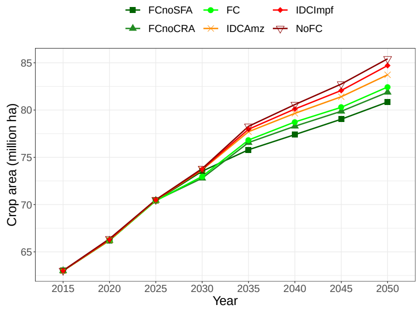


(f) FCnoSFA

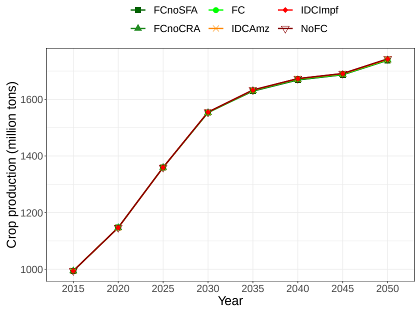
Figure 45: Spatial distribution of cumulative loss (red) or gain (green) of native vegetation for the various scenarios between 2015 and 2050. Color bar values are expressed in thousands of hectares per cell.

An endogenous productivity increase is observed in the scenarios with the major restrictions on land such as the FC, FCnoCRA and FCnoSFA. In 2050, soybean and sugarcane productivities are, respectively, 4.5% and 8.4% higher in the FCnoSFA when compared to the NoFC scenario.

Figure 47 shows the pasture area, cattle herd evolution, and cattle productivity between 2015 and 2050 for all scenarios. At national level, the pasture area increases in the NoFC and the IDCImpf scenarios. After 2025, the area increase is almost constant for the IDCAmz, while in the FC, FCnoCRA, and



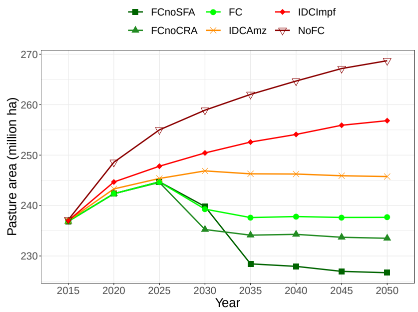
(a) Crop area



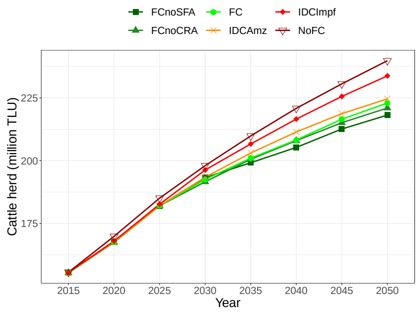
(b) Crop production

Figure 46: Evolution of the (a) cropland area and (b) crop production, between 2015 and 2050, as projected by the various scenarios.

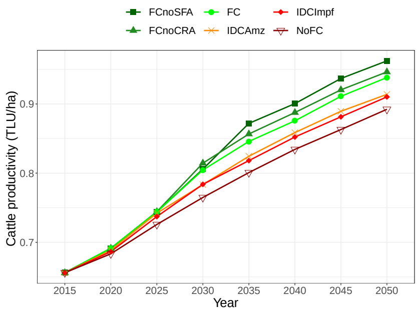
FCnoSFA scenarios it decreases. Note that the stronger the governance the smaller the pasture area by 2050. The difference in grasslands between the FCnoSFA and NoFC scenarios by this year is 42 Mha. Although the pasture area decreases after 2025 for the FC, FCnoSFA, and FCnoCRA, the cattle herd is projected to increase regardless the scenario (see Fig. 47b).



(a) Pasture area



(b) Cattle herd



(c) Cattle productivity

Figure 47: Evolution of the (a) pasture area (b) cattle herd and (c) cattle productivity, between 2015 and 2050, as projected by the various scenarios.

This result correspond to a 47% growth in Brazil's cattle productivity, between 2015 and 2050, as projected by the FCnoSFA scenario, from 0.9 to 1.4 heads per ha. On the other hand, the NoFC scenario projects only a 36% growth in cattle productivity at national level during the same period. Even though the cattle productivity is projected to increase, there are production losses in the cattle sector. The cattle herd is 10% (7%) smaller for the FCnoSFA (FC) scenario when compared to the NoFC by 2050. Regarding the use of nonproductive lands, when the governance is weak, as in the NoFC scenario, the conversion of those areas are smaller when compared to scenarios with stronger governance as the FC scenario (see Fig. 48).

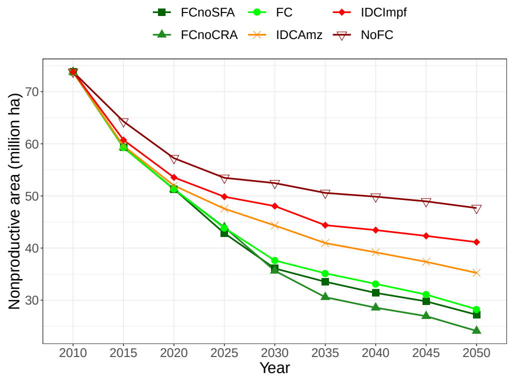


Figure 48: Evolution of nonproductive land in Brazil between 2015 and 2050 among the various scenarios.

In summary, by 2050, the agricultural gains obtained by not enforcing the Forest Code in Brazil include an increase of 3% in crop area and 7% in the cattle herd (comparison between the NoFC and the FC scenarios). The controversial disposition that exempts the payment of environmental debts by small farmers slightly increases the agricultural gains of not enforcing the Forest Code by 5% regarding the crop areas and by 10% regarding the cattle herd (comparison between the NoFC and the FCnoSFA scenarios). On the environmental side, the lack of enforcement of the Forest Code between 2015 and 2050 results in an accumulated deforestation of 54.6 Mha. The scale of native vegetation loss would be equivalent to the areas of Germany, Austria, Switzerland, and Netherlands together.

The accumulated native vegetation conversion projected by the IDCImpf scenario between 2015 and 2050 is 39.2 Mha without any forest restoration. Although this scenario is the closest to the deforestation trends observed during the historical period, it is as much unsustainable as the NoFC scenario in the long term. This highlights the fact that a lax law enforcement is as worse as no enforcement at all.

Restoration costs

We estimated the restoration costs of environmental debts (APP and LR) as projected by the FC (12.3 Mha), FCnoCRA (18.7 Mha), and FCnoSFA (30.2 Mha) scenarios over the six Brazilian biomes. The costs take into account various restoration methods ranging from natural regeneration to active planting as proposed in PLANAVEG [MMA, 2014b] and summarized in Table 9.

Figure 49 shows the total restoration costs across the various governance scenarios combined with the PLANAVEG restoration scenarios A, B and C.

As expected, the total restoration costs are proportional to the amount of projected forest regrowth and ranges from 41.8 billion BRL (FC combined with C) to 151,1 billion BRL (FCnoSFA combined with A). Regardless the amount of forest regrowth, the restoration scenario C has the overall lower costs because it presumes a higher percentage of natural regeneration (60%)

Method	Description	Total cost (BRL/ha)	Restoration scenarios A	B	C
I	Total planting of the area (1,666 individuals/ha) with fencing	10,000	30%	20%	10%
II	High enrichment and high density planting (800 ind./ha)	5,000	15%	15%	15%
III	Low enrichment and low density planting (400 ind./ha)	3,400	15%	15%	15%
IV	Natural regeneration with isolation of the area by fencing	2,400	20%	25%	30%
V	Natural regeneration with abandonment of pasture (no fencing)	1,400	20%	25%	30%

Table 9: Restoration plans from PLANAVEG [MMA, 2014b].

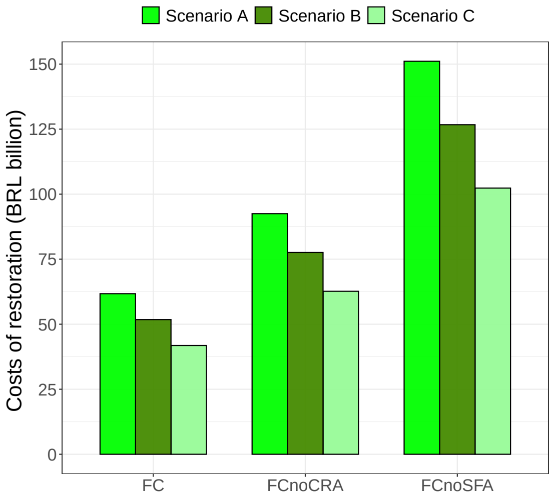


Figure 49: Costs of restoration for the scenarios FC, FCnoCRA and FC-noSFA considering distintic restoration plans from PLANAVEG.

than active planting (40%) when compared to scenarios B (respectively, 50% and 50%) and A (respectively, 40% and 60%). We considered the same restoration costs per hectare in APP and LR. The estimated average cost of restoration per ha is 5,020 BRL according to scenario A; 4,219 BRL for the scenario B; and 3,400 BLR for the scenario C.

LUCF emissions

Figure 50 illustrates Brazil's net emissions (positive and negative) estimates from the LUCF sector, between 2010 and 2050, as projected by the various scenarios. Positive emissions come from deforestation and other land-use transitions. Negative emissions come from afforestation of short-rotation plantations and passive forest regrowth. The decrease in the net emissions primarily results from the control over deforestation and, additionally, native vegetation restoration.

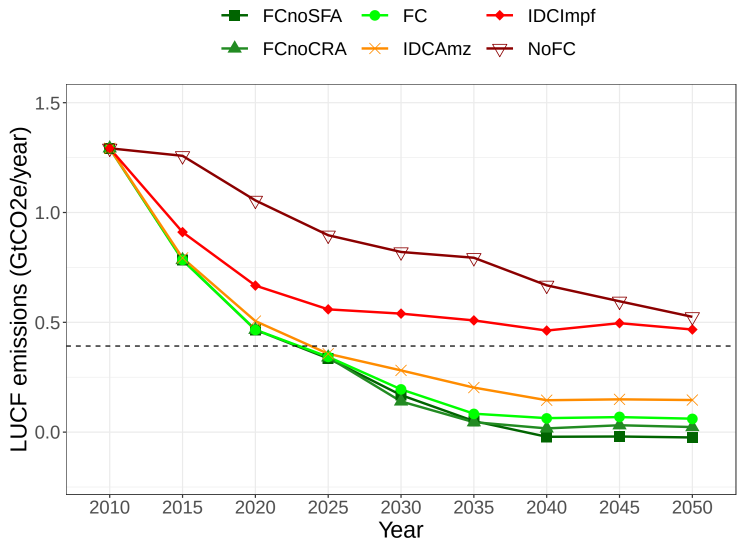


Figure 50: Net emissions per year from the LUCF sector in Brazil as projected by the various scenarios.

The IDCImpf scenario projects a decrease in the LUCF emissions until 2035 followed by an almost constant emission up to 2050. Note that, by 2050, the emissions estimates from both IDCImpf and NoFC scenarios are very close. Since the carbon stocks are higher in the Amazon compared to the rest of the country, the full illegal deforestation control in this biome has an important contribution to Brazil's emissions reduction. Under the FC scenario, the net emissions decline from 1.292 $GtCO_2eq$ in 2010 to 0.195 $GtCO_2eq$ in 2030 and 0.061 $GtCO_2eq$ in 2050. The FCnoCRA and FCnoSFA project a similar but lower net emission estimates due to the larger amount of native vegetation restoration (see Table 10). Although the restoration area in the FCnoSFA scenario is 17.8 Mha larger than in FC by 2050, the difference in emissions estimates is not proportionally as large. While the release of carbon from the terrestrial biosphere to the atmosphere as CO_2 occurs in only one simulation period, the CO_2 removal from the atmosphere by forest regrowth takes several decades. In addition, the restoration follows the PLANAVEG's curve where less than 3 Mha of native vegetation are expected to be restored in the first ten years, regardless the scenario. The restoration area as projected by the FCnoSFA scenario is close to 30 Mha only after 2035.

Scenarios	2010	2020	2030	2040	2050
FCnoSFA	1.292	0.466	0.169	-0.021	-0.024
FCnoCRA	1.292	0.466	0.140	0.017	0.023
FC	1.292	0.466	0.195	0.064	0.061
IDCAmz	1.292	0.506	0.281	0.145	0.146
IDCImpf	1.292	0.667	0.540	0.462	0.467
NoFC	1.292	1.055	0.820	0.668	0.525

Table 10: Emissions from the LUCF sector in $GtCO_2eq/yr$ in Brazil as projected by the various scenarios.

In its NDC, Brazil has committed to reduce the country's GHG emissions by 43% by 2030, which corresponds to an absolute reduction of 0.9 $GtCO_2eq$, from 2.1 $GtCO_2eq/yr$ in 2005 to 1.2 $GtCO_2eq/yr$ [Brazil, 2015]. Compared to 2010, the scenarios that reach a reduction greater than 0.9 $GtCO_2eq$ by 2030 are: IDCAmz, FC, FCnoCRA and FCnoSFA (see the curves that cross the dotted line in Fig. 50). We observe that the emissions reduction from the LUCF sector, resulting from a rigorous enforcement of the Forest Code, is key for the country to achieve its NDC commitments. This is also specially true when considering the full illegal deforestation control in the Amazon. The FC is a key policy for the country to achieve a near zero emissions from the LUCF sector as well. Since this law allows the deforestation of LR surpluses at all times, a way to achieve zero emission from LUCF sector in Brazil is through a restoration area larger than 12 Mha. The FCnoSFA scenario projects zero emissions (or a small carbon sink) regarding the LUCF sector as early as 2040. Another way to achieve zero emissions from the LUCF sector is through a policy-mix where the rigorous enforcement of the Forest Code is combined with zero-deforestation agreements for the major commodity-driven deforestation such as a cattle agreement in the Amazon and a soy moratorium expansion to the Cerrado biome.

Figure 51 shows the net emissions estimates from the LUCF sector in the Amazon biome, between 2010 and 2050, as projected by the various scenarios. The differences in net emission by 2050 among the scenarios IDCAmz, FC, FCnoCRA, and FCnoSFA are small. The FCnoSFA is the only scenario where the emissions estimates from the LUCF sector reach a value slightly lower than zero (-0.006 $GtCO_2eq$) in the Amazon by 2050. The full control of illegal deforestation in this biome has a greater contribution to the emissions reduction than the carbon uptake from forest restoration. Regardless the scenario, more than 90% of the positive emissions in the Amazon is due to the forest conversion for cattle ranching. Thus, a zero-deforestation agreement for the cattle sector combined with the rigorous enforcement of Forest Code is important for the Amazon to achieve zero emissions from deforestation. To transform the Amazon forest into a carbon sink, forest restoration should also be in place combined with a mix of public and private policies focused on halting deforestation.

These emissions estimates from the various scenarios point to the importance of stopping deforestation in the Amazon for Brazil to achieve its pledges on emissions reductions and contribute to the global effort to mitigate climate change. Nevertheless, if the other sectors – such as energy, industry, and transport – increase their emissions compared to 2005 levels, the full illegal deforestation control, as projected by the FC scenario or the large scale restoration as projected by the FCnoSFA, will not be enough.

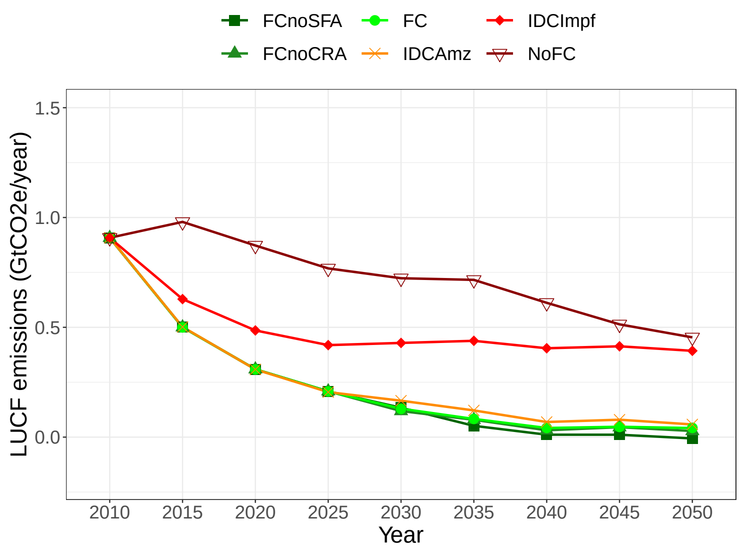


Figure 51: Net emissions per year from the LUCF sector in the Amazon biome as projected by the various scenarios.

Land use and production impacts of climate change

Here we analyse how climate change could potentially affect land use competition and, consequently, production of the main Brazilian commodities. To this end, we analyzed GLOBIOM-Brazil results for 20 scenarios, resulting from the combination of two emission pathways (RCPs), five climate models (GCMs), and two biophysical models (GGCMs). Results are aggregated per GGCM and RCP.

Soybean

In 2018, Brazil produced 116.2 Mton of soybean [PAM/IBGE, 2019], equivalent to 31% of all soybean produced in the world. This places the country as the second largest soybean producer, only behind USA, and the largest soybean exporter [EMBRAPA, 2018]. Soybean production in Brazil is located mostly in the Cerrado biome, mainly in Mato Grosso state, responsible for 27.3% of the national production, and South Brazil (Parana and Rio Grande do Sul states, responsible for 16.3% and 14.5% of the national production, respectively). Future economic projections suggest a northward displacement of the soybean production toward Matopiba region, expanding mostly over pasture areas [MAPA, 2018].

Regardless the positive impacts of climate change on soybean potential productivity, land use competition and market dynamics projected by GLOBIOM-Brazil result in a reduction of Brazilian soybean area and production throughout 2050, compared to the noCC scenario (Fig 52a and b). Until 2015, the difference between noCC (black line and filled circles) and median scenario for each GGCM (orange and green lines for EPIC and LPJmL, respectively) and RCP (solid lines with upward triangles for RCP2.6 and dashed line with downward triangle for RCP8.5) projections for both area and production are small, with all values close to the Brazilian official statistics (blue line and filled squares). Considering the next decade, GLOBIOM Brazil projections for noCC and climate change median scenarios are below the official average projection of agriculture expansion (red horizontal line in 2028) provided by the Agriculture Ministry (MAPA, MAPA [2018]). From 2020 on, the median soybean area and production projected by GLOBIOM-Brazil is smaller than for noCC scenario. This reduction is consistent among all 10 scenarios for LPJmL, as shown by the green shaded envelope in Figure 52a-b). These scenarios are more pessimistic, with median LPJmL production below the lower limit of MAPA projections for 2028. EPIC scenarios for both area and production are less pessimistic and within MAPA projections for 2028, but with a larger spread among them which increases uncertainties (orange envelope in Fig 52a-b; see also the first two boxes in Fig 54a and c, and Table 11).

Even though the results from the two GGCMs are not directly comparable, they indicate two pathways for soybean in Brazil. The reduction in area is similar for both GGCMs (Fig 52a), and is followed closely by a reduction in production in LPJmL median scenarios (Fig 52b). Thus, the yield in the median scenarios of LPJmL are similar to the yield in the noCC scenario (Fig 52c). On the other hand, the reduction in production in EPIC median scenarios (Fig 52b) is offset by an increase in yield (Fig 52c). These results suggest that Brazilian soybean production can still grow despite the adverse effects of climate change, as long as the necessary technological development is achieved. However, it is important to emphasize that yields projected by GLOBIOM-Brazil are not restricted by any physical parameter and thus may become unrealistic. Even though GLOBIOM Brazil projected yields for 2028 is within MAPA projections (see red vertical line in Fig 52c), the necessary technological development in terms of increase of potential productivity may not be physically achievable. A deeper analysis of these limitations would involve the analysis of no adaptation scenarios, planned as future steps.

As observed for the EPIC shifters, the GLOBIOM-Brazil projections for soybean production and area are also spatially variable, resulting in displacement of soybean area and production from tropical to subtropical regions (Fig 53c and e and Fig 54a and c). Cerrado and particularly Matopiba, currently considered as the main production region and the expansion frontier, respectively (Fig 53a and b), will not thrive under climate change scenarios. In Matopiba, the median decrease in soybean area and production in RCP8.5 in 2050 will be -74.3% and -63.7%, respectively (Fig 54a and c, and Table 11). Part of this production will be displaced southward, resulting in an increase in soybean area and production in the southern portion of the Atlantic Forest biome and Pampa (Fig 53c and e and 54a and c). All these results are robust among EPIC scenarios (changes in lower and upper quartiles have the same signal) and for each GCM and RCP individually (see triangles in Fig 54a and c).

Projections based on LPJmL scenarios also indicate a reduction in soybean area and production in Cerrado (Fig 53d and f). In fact, LPJmL projections are more pessimistic with reduction in soybean area and production on all main soybean production areas, except in the Atlantic Forest biome (Fig 53d

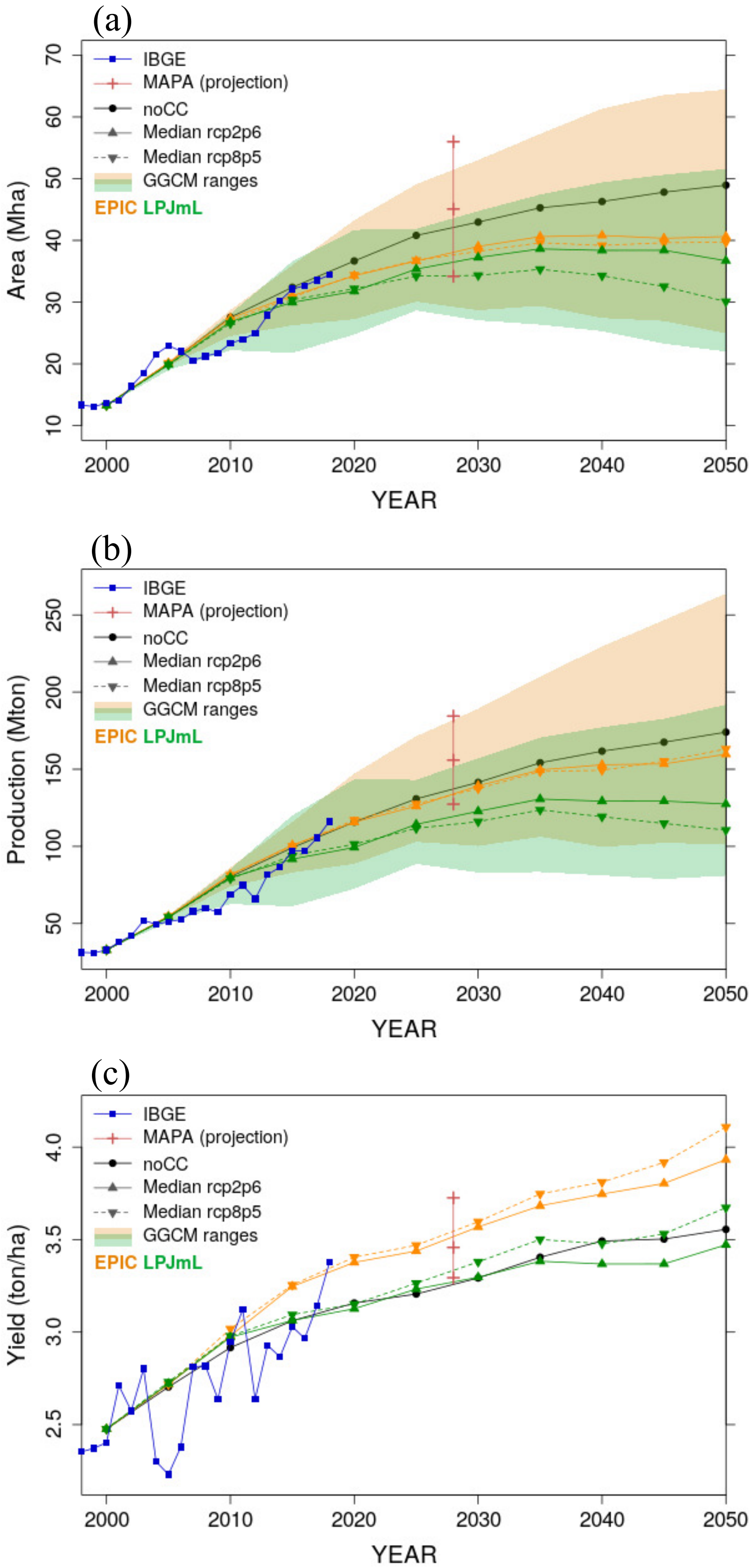


Figure 52: Projection of soybean (a) area (in Mha), (b) production (in Mton), and (c) yield (in ton/ha) aggregated over Brazil for noCC (black solid line with filled circle), EPIC (orange), and LPJmL (green) scenarios. Solid (dashed) lines and upward (downward) triangles: median values for RCP2.6 (RCP8.5) emission scenarios in each GGCM; Blue line and filled squares: IBGE annual soybean statistics PAM/IBGE [2019]. Red vertical line and crosses: MAPA average projections for soybean in 2028 and its lower and upper limits (source: MAPA [2018]). Orange (green) shaded area in (a) and (b): envelope of scenarios for EPIC (LPJmL), defined by aggregated value of the minimum and maximum scenarios for each year.

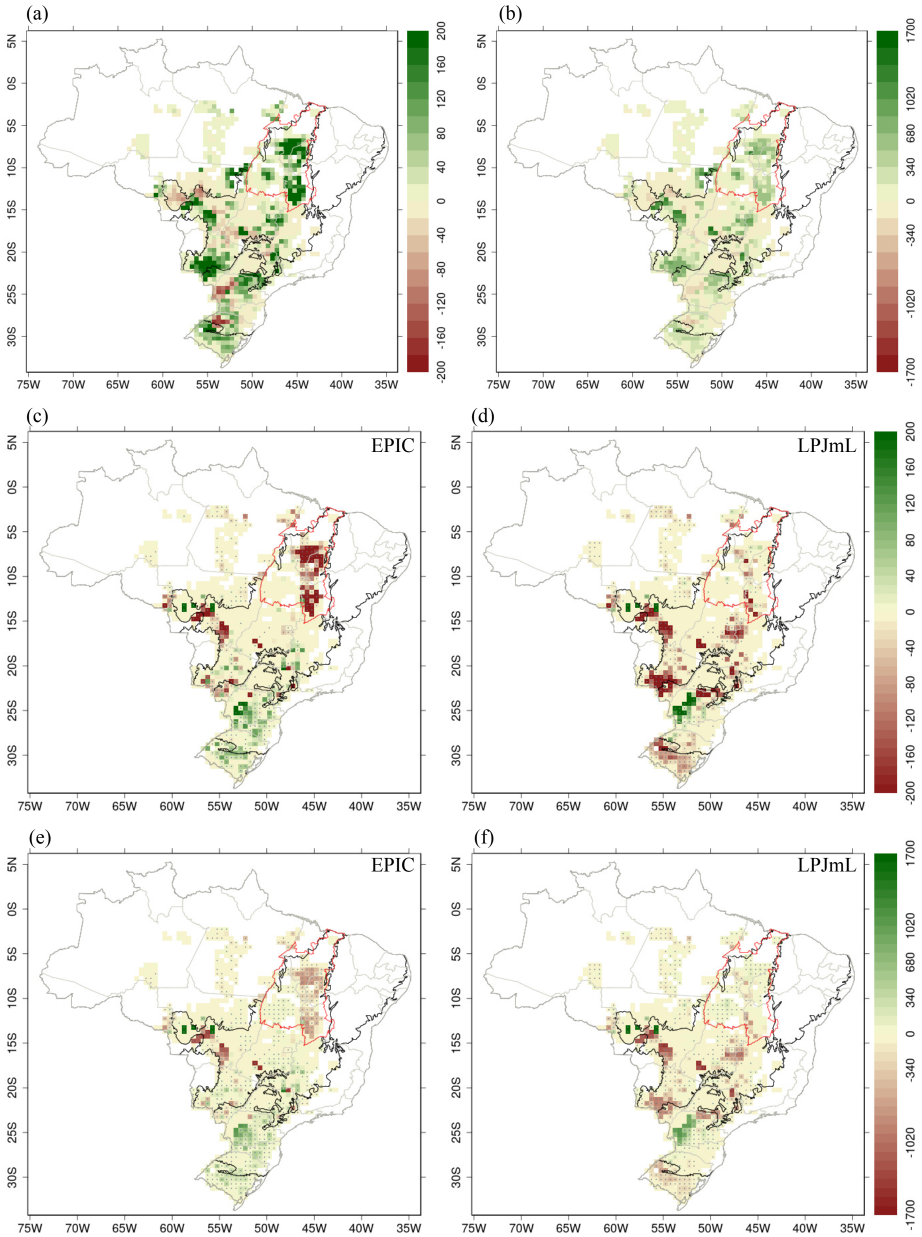


Figure 53: (a)-(b): Evolution of soybean (a) area (in kha) and (b) production (in kton) from 2000 to 2050 in noCC scenario, with increase (decrease) represented in green (red) shades. (c)-(f): Median changes in soybean (c)-(d) area (in kha) and (e)-(f) production (in kton) for (c) and (e) EPIC and (d) and (f) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Pixels where the difference between the median and the noCC scenarios are positive (negative) are shaded green (red); Stippled pixels indicate areas where the lower and upper quartiles have same signal.

and f). Interesting to notice that, for projections based on LPJmL scenarios, soybean production in Matopiba is not affected by climate change. Furthermore, substantial decrease in area and production also occur in Pampa, with median decrease of -78.8% in area and -83.2% in production for the RCP8.5 scenario (Fig 54b and d and Table 11).

Hence, projections of the economic impact of climate change indicate a reduction in soybean area over Cerrado, particularly on Matopiba. Despite the large spread among scenarios, this result is consistent among all but one of the 20 individual scenarios analyzed (triangles in Fig 54a and b). The robustness of the production reduction is smaller and depends on the changes in yield. The agreement among all 10 scenarios based on EPIC projections suggest that investments in technology expressed as a yield increase could reduce the impacts on soybean production on these regions (Fig 54b). Part

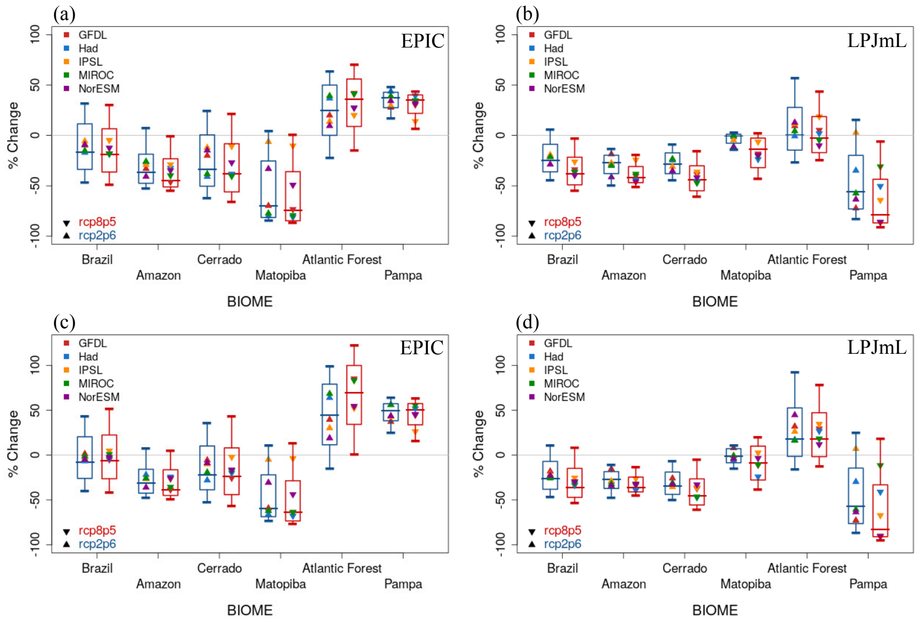


Figure 54: Percentage changes (compared to noCC in 2050) in soybean (a)-(b) area and (c)-(d) production aggregated over Brazil, main biomes, and Matopiba, for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in Table 11. Upper (lower) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left).

of the soybean production from Cerrado is displaced southward toward the southern portion of the Atlantic Forest biome, with all 20 scenarios indicating an increase in production (Fig 54c and d) and 17 of the 20 scenarios indicating an increase in area (Fig 54a and b) in this region. The largest discrepancies among the GGCM scenarios occur in Pampa, where all 10 scenarios based on EPIC projections suggest an increase in soybean area and production while 9 of the 10 scenarios based on LPJmL projections suggest the opposite result.

Corn

Corn is the second most important crop in Brazil, currently occupying 16.6 Mha and producing 89.2 Mton, 74.6% of which in the states of Mato Grosso, Mato Grosso do Sul, Goiás, Minas Gerais e Paraná [MAPA, 2018]. More than 70% of corn area and production in Brazil occur as a second crop in succession to soybean. GLOBIOM Brazil is adapted to account for this specificity and the noCC scenario is able to satisfactorily reproduce the location of double cropping areas and their production. However the inclusion of climate change impacts on this second crop is still limited due to the lack of biophysical productivity data.

GLOBIOM-Brazil projections of corn area from 2000 to 2015 (Fig 55a), for both noCC (black line and filled circles) and median climate change scenarios (orange and green full and dashed lines and triangles), are similar to the official Brazilian statistics (blue line and filled squares), even though GLOBIOM-Brazil underestimates production (Fig 55b) and, consequently, yield (Fig 55c). For the next decade, GLOBIOM Brazil projections in noCC and median scenarios are optimistic, located within the upper half of the MAPA official projections for corn in 2028 (red vertical line in Fig 55a and b). From 2025 on, corn area and production in the median scenarios are projected to be smaller than in noCC scenario, with larger agreement among LPJmL scenarios. The impacts of climate change on corn production for

Table 11: Median (lower and upper quartile) change in soybean area and production in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil, main biomes, and Matopiba.

REGION	RCP2.6		RCP8.5	
	Area (%)	Production (%)	Area (%)	Production (%)
EPIC				
Brazil	-17.0 (-33.7; 11.5)	-8.2 (-25.9; 20.5)	-18.9 (-36.6; 6.7)	-6.3 (-26.3; 22.5)
Amazon	-36.7 (-47.4; -18.5)	-31.4 (-42.4; -15.7)	-45.1 (-51.0; -23.1)	-38.9 (-44.9; -16.3)
Cerrado	-34.2 (-50.3; 0.6)	-22.5 (-38.6; 10.2)	-38.8 (-56.; -8.2)	-24.0 (-44.0; 8.1)
Matopiba	-70.2 (-81.4; -25.3)	-59.6 (-68.6–21.9)	-74.3 (-84.6; -35.9)	-63.7 (-73.3; -28.5)
Atlantic Forest	24.8 (0.1; 50.0)	44.4 (11.5; 79.1)	35.4 (8.9; 56.0)	69.5 (34.3; 99.9)
Pampa	37.4 (27.5; 42.9)	49.4 (38.3; 57.4)	34.9 (21.9; 40.2)	50.1 (33.8; 57.5)
LPJmL				
Brazil	-25.0 (-36.1; -8.8)	-26.8 (-38.1; -7.0)	-38.5 (-48.9; -21.6)	-36.5 (-47.0; -14.7)
Amazon	-27.2 (-37.8; -19.6)	-27.3 (-37.1; -18.4)	-41.9 (-46.8; -30.9)	-36.1 (-41.0; -24.5)
Cerrado	-28.7 (-37.9; -17.2)	-34.8 (-43.7; -18.9)	-44.1 (-54.8; -30.1)	-45.5 (-55.6; -26.5)
Matopiba	-0.7 (-7.7; 1.2)	-1.3 (-8.5; 7.2)	-14.3 (-31.9; -2.6)	-9.2 (-27.7; 10.0)
Atlantic Forest	0.1 (-14.5; 27.9)	17.5 (-1.4; 52.6)	-3.2 (-17.0; 18.7)	17.2 (-1.6; 47.3)
Pampa	-56.3 (-73.0; -19.8)	-57.3 (-76.3; -14.4)	-78.8 (-86.7; -43.5)	-83.2 (-90.8; -33.1)

scenarios using LPJmL are not as pronounced as in area, resulting in a small increase in yield. For EPIC scenarios, reduction in area and production are similar to each other, resulting in no change in yield. Projections using LPJmL median scenarios become more pessimistic than EPIC's after 2035. Notice that to achieve the projected production, even in the noCC scenario, it would be necessary a substantial increase in corn productivity, whose current Brazilian average is about 5.6ton/ha CONAB [2019]. This would demand heavy investments in technology.

In the noCC scenario, Brazilian corn production has been migrating from South Brazil to Cerrado biome, with this tendency projected to persist until 2050 (Fig 56a and b). However, climate change impacts will affect the land use competition, resulting in a reduction of area and production (Fig 55a and b). In Brazil, the median percentage of corn area and production reduction in 2050 are -14.6% (-37.5%) and -12.9% (-29.4%), respectively, for EPIC (LPJmL) in RCP8.5 emission scenario. These results are robust among all 20 individual

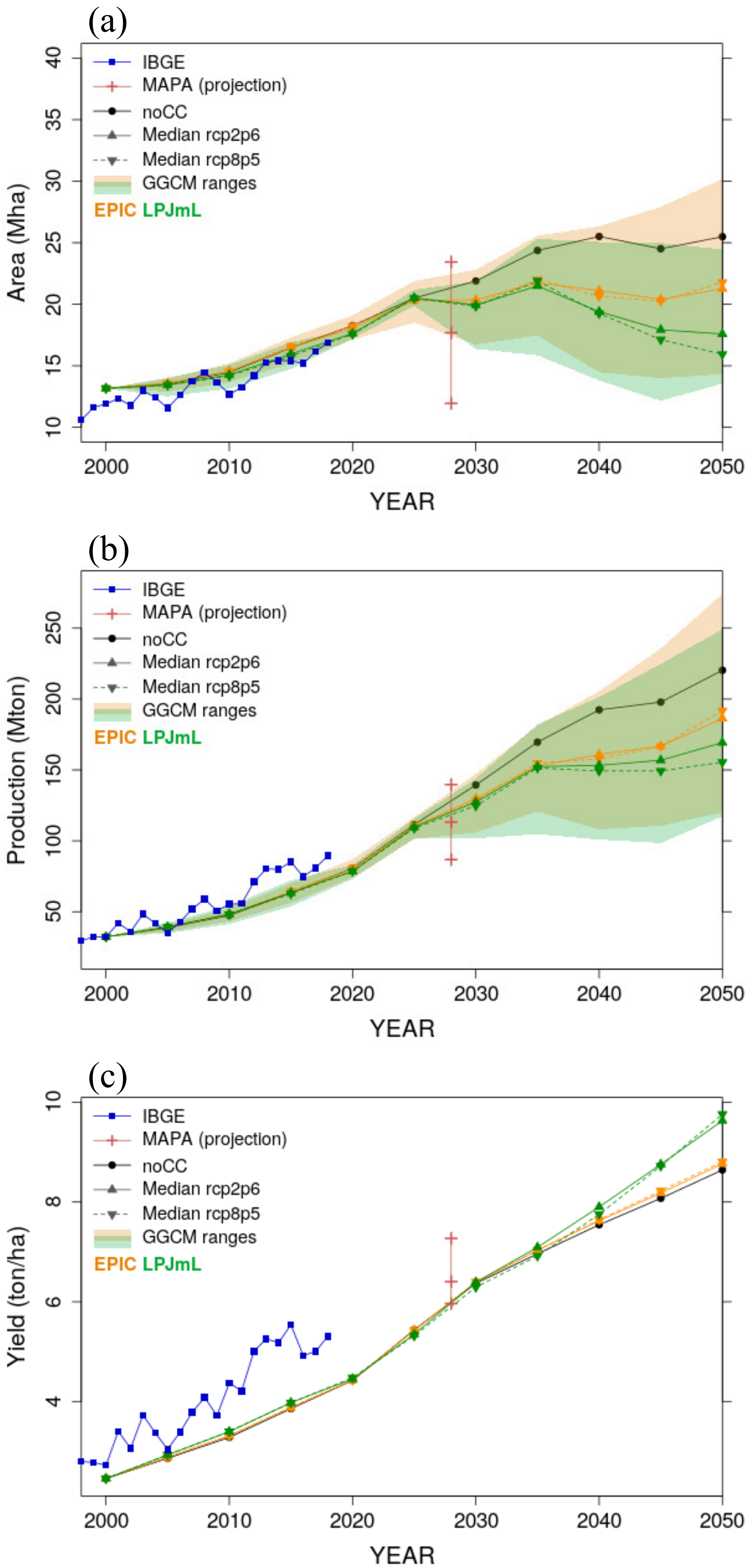


Figure 55: As in Figure 52 for Corn.

scenarios (Fig 57), with agreement in the signal of the lower and upper quartiles in LPJmL scenarios for both RCPs (Table 12). The largest reduction occur in Amazon, with -37.9% area and -39.8% production in EPIC scenarios, and Cerrado, with a reduction of -60.2% in corn area and -62.6% in production in LPJmL scenarios, both considering RCP8.5 emissions. Taking each of the 20 scenarios individually, MIROC-CHEM-ESM has the most pessimistic projections in Cerrado, with -61.5% reduction in area and -62.6% reduction in production (LPJmL in RCP8.5 emission scenario, green downward triangle in Fig 57b and d); NorESM2-M has the most pessimistic projections in Amazon, with -41.8% reduction in area and -43.0% reduction in prodcution (LPJmL in RCP2.6 emission scenario, purple downward triangle in Fig 57b and d). The spatial pattern of the changes in corn area and production suggest a displacement of the production from tropical biomes to the subtropics (Fig 56c and e). The spatial pattern of the changes in corn area and production suggest a displacement of the production from tropical biomes to the subtropics (Fig 56c-e and Fig 57). Differently than for soybean, corn production in Matopiba will not be affected by climate change.

Part of the corn production (and area) is displaced southward to the southern portion of the Atlantic Forest biome (Fig 56c to f), with a median increase of 21.0% (74.6%) in area (production) in the LPJmL forced by RCP8.5 emission scenario (Table 12). Individually 18 (19) of the 20 scenarios indicate an increase in area (production) in this biome (Fig 57). However, the agreement among LPJmL scenario is larger than among EPIC scenarios. The most optimistic scenario suggest an increase of 50.9% in area (LPJmL scenario forced with IPSL-CM5A-LR and RCP8.5 scenario) and 108.6% production (LPJmL froced with HadGEM2-ES and RCP8.5 scenario).

Hence, all scenarios analyzed suggest a decrease on corn area and production in Amazon and Cerrado. In 19 of the 20 scenarios considered, part of this production is displaced toward South Brazil, in the Atlantic Forest biome. This result is robust when considering LPJmL scenarios. However, these results have to be carefully considered due to the lack of shifters for the double cropping system. As mention before, more than 70% of the corn produced in Brazil is as a second crop after soybean. In the noCC scenario (as well as in all climate change scenarios considered here), virtually all corn is produced in a double cropping system by 2050. Corn in this system is planted between January and February and harvested no later than August, which corresponds to the dry season in most parts of Brazil. The impacts of climate change in this season are different from those observed during the wet season. Consequently, the potential productivity of the corn planted during this season will also be different from the productivity of the corn planted during the wet season (as a first crop). However, GGCMs from ISIMIP platform do not consider this management system. Here, we considered that the effects of climate change on the productivity of corn planted as a second crop will be the same as the corn in first crop. Thus, it is possible that the tendencies described here are unrealistic.

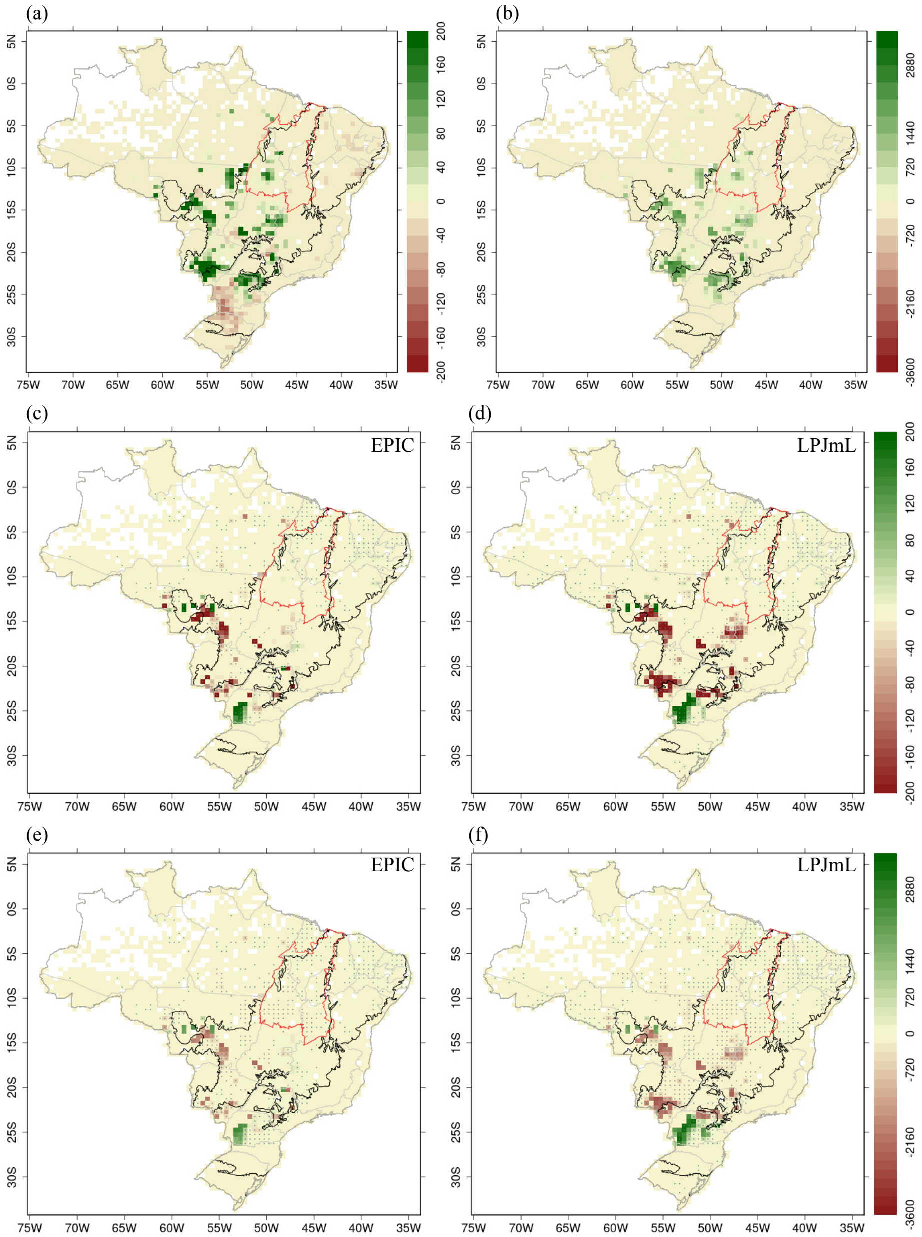


Figure 56: As in Figure 53 for Corn.

Grassland and Livestock

According to the preliminary results of the 2017 Brazilian census of agriculture IBGE [2017], the country has 158.6 Mha of pastureland, either natural or with some type of management. However, this value can be underestimated since it only considers private properties, not accounting for natural land areas explored for grazing. These preliminary results also quantified the Brazilian bovine herd in 171.9 million heads. This number is well below the 214.9 million heads informed by IBGE national annual inventory [PPM/IBGE, 2019], which is also the number considered by FAO. Brazil has the second largest bovine heard in the world, behind India USDA [2019]. More than one third of this herd is raised in Centre West region of Brazil, with 29.7 million heads in Mato Grosso and 21.5 million heads in Mato Grosso do Sul.

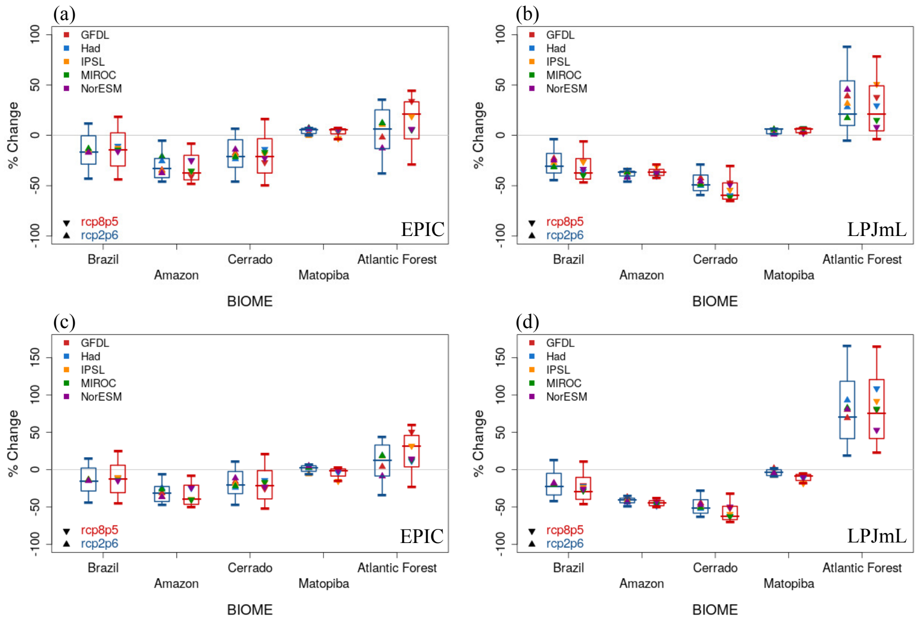


Figure 57: As in Figure 54 for Corn. Values in 12.

REGION	RCP2.6 Area (%)	RCP2.6 Production (%)	RCP8.5 Area (%)	RCP8.5 Production (%)
EPIC				
Brazil	-16.6 (-28.6; -0.4)	-15.4 (-28.4; 2.2)	-14.6 (-30.4; 2.5)	-12.9 (-30.7; 6.0)
Amazon	-32.9 (-42.0; -23.0)	-32.0 (-42.6; -22.4)	-37.9 (-44.2; -19.8)	-39.8 (-46.3; -20.7)
Cerrado	-21.3 (-31.7; -4.3)	-20.9 (-32.0; -2.4)	-21.6 (-37.4; -3.3)	-21.5 (-39.0; -1.2)
Matopiba	5.6 (1.8; 6.9)	2.3 (-2.2; 5.3)	5.3 (1.5; 6.5)	-1.9 (-8.5; 1.1)
Atlantic Forest	5.8 (-13.2; 25.3)	11.9 (-8.4; 33.1)	20.7 (-3.5; 33.3)	31.0 (3.9; 45.9)
LPJmL				
Brazil	-31.0 (-37.4; -17.9)	-23.2 (-33.8; -4.8)	-37.5 (-43.4; -23.0)	-29.4 (-39.7; -10.2)
Amazon	-36.9 (-40.3; -35.6)	-41.1 (-44.2; -38.0)	-37.3 (-39.8; -33.8)	-45.1 (-48.1; 41.5)
Cerrado	-49.3 (-54.9; -39.4)	-51.8 (-58.1; -40.0)	-60.2 (-63.3; -47.2)	-62.6 (-66.7; -48.9)
Matopiba	5.7 (1.6; 6.1)	-4.1 (-7.8; 0.0)	6.0 (2.6; 7.1)	-8.8 (-14.4; -6.2)
Atlantic Forest	21.1 (9.8; 54.1)	70.1 (41.6; 118.3)	21.0 (4.5; 49.2)	74.6 (41.7; 120.7)

Table 12: As in Table 11 for Corn.

Climate change scenarios based on both GGCMs suggest a median decrease in grassland area by 2050 (Fig 58a). However, the spread among the 20 scenarios is very large (green and orange envelopes) and thus confidence in this result is very low. Historically, pasture area and livestock has been moving toward Amazon, with noCC projections suggesting that this biome would hold the largest bovine herd by 2050 (Fig]59a and b). With the inclusion of climate change impacts, there is a large abandonment of grassland area (conversion to natural land, not shown) along the border between Amazon and Cerrado biomes, with the pasture moving south and southeastward (Fig 59c and d). LPJmL scenarios indicate an expansion toward Pampa biome (Fig 59d) while in EPIC scenarios there is a decrease in grassland area over this region (Fig 59c). However, the agreement among scenarios is very small, even when considering each biome separately (Fig 60a and b).

The biophysical impacts of climate change considered here directly affect only grassland productivity. However, we also investigate the indirect effects on the livestock sector through losses in grassland productivity and, to a lesser extent, through losses in soybean and corn, used as livestock feed. The final impact on the herd size is not as pronounced due to an increase in cattle intensity (Fig 58b and c). The herds also move southeastward toward the border of Cerrado and Atlantic Forest biomes (Fig 59e and f). LPJmL scenarios suggest an increase in herd size in Pampa biome (Fig59f and Fig60d) whereas EPIC indicate a decrease (Fig59e and Fig60c). However, agreement among scenarios is small.

Discussion

The inclusion of climate change scenarios in the analysis of future land use competition in Brazil raised interesting aspect regarding the feasibility of the current projections for agriculture expansion. As reported by the Brazilian agriculture expansion plan [MAPA, 2018], soybean area should increase by 10 Mha in the next ten years, mostly in the Matopiba region, where it should reach 8.9 Mha by 2028. However, all scenarios considered in this study suggested a reduction of soybean production in Cerrado biome and a southward displacement of the crop, toward subtropical areas of Atlantic Forest (Fig 61a). In particular, 19 (18) of the 20 scenarios indicated a reduction in soybean area (production) in Matopiba. This represents a reduction from 13.2 Mha of soybean in noCC scenario in 2050 to a median area of 3.4 Mha (11.4 Mha) when considering EPIC (LPJmL) and RCP8.5 projections. Consequently, instead of producing 21.4% of Brazilian soybean in 2050, according to the noCC projections, Matopiba would be responsible for only 8.3% (median for the EPIC forced with RCP8.5 emission scenario) of the national production. Cerrado biome would still be responsible for about 50% of soybean production, below the 62% projected in the noCC scenario, mostly on the southern part of the biome, along the border with Atlantic Forest biome. On its turn, Atlantic Forest biome would account for at least 25% of the national production, most of it in the states of Paraná and Santa Catarina.

Part of the impact of climate change in soybean could be offset by increase in productivity, as suggested by scenarios based on EPIC potential productivity. Currently, soybean average productivity in Brazil is around 3 ton/ha

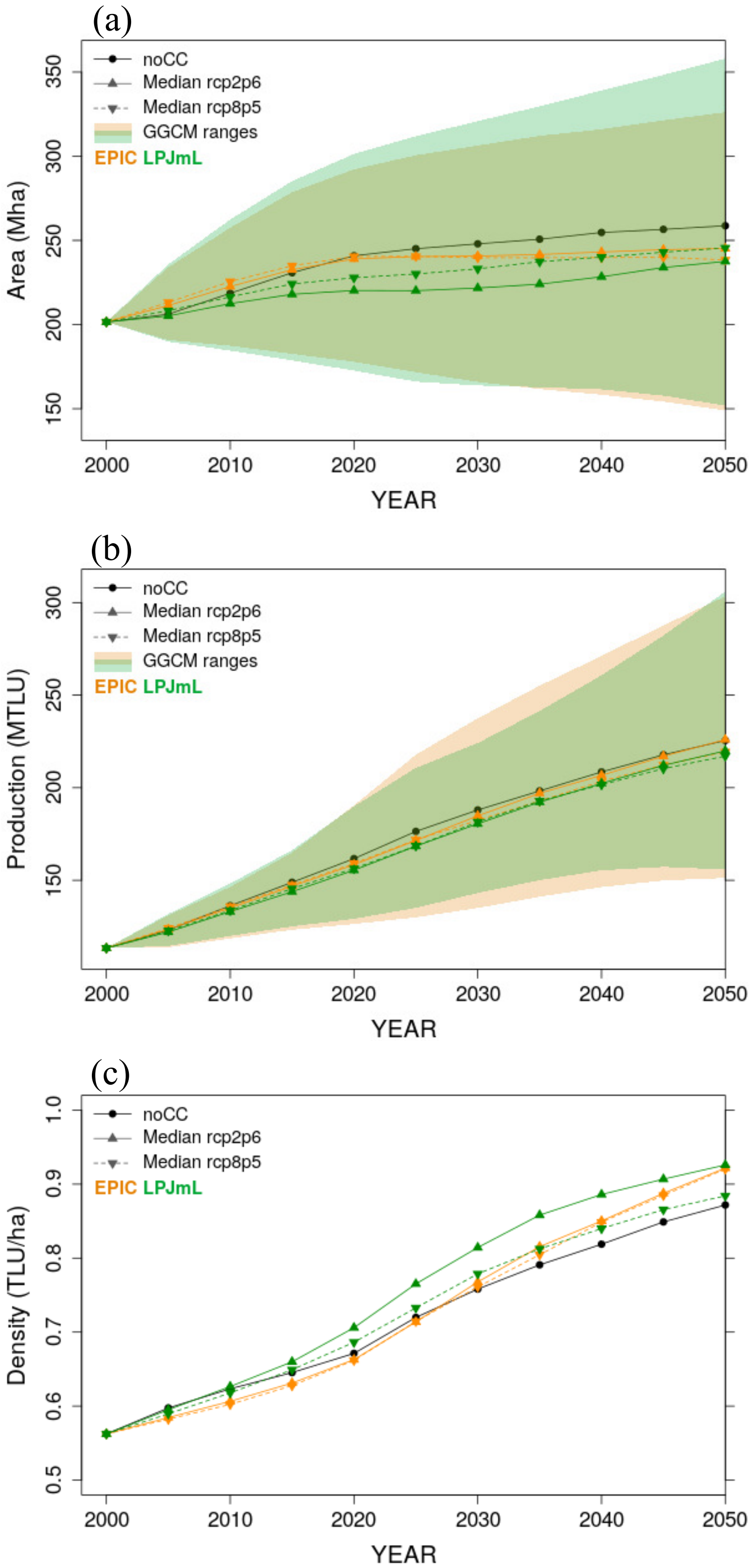


Figure 58: Projection of (a) grassland area (in Mha), (b) cattle production (in MTLU), and (c) cattle density (in TLU/ha), aggregated over Brazil for noCC (black solid line with filled circles) and for EPIC (orange) and LPJmL (green) scenarios. For GGCMs, solid (dashed) lines with upward (downward) triangles represent the median values for RCP2.6 (RCP8.5) emission scenarios. In (a) and (b) orange (green) shaded area represents the envelope of scenarios for EPIC (LPJmL), defined by aggregated value of the minimum and maximum scenarios for each year.

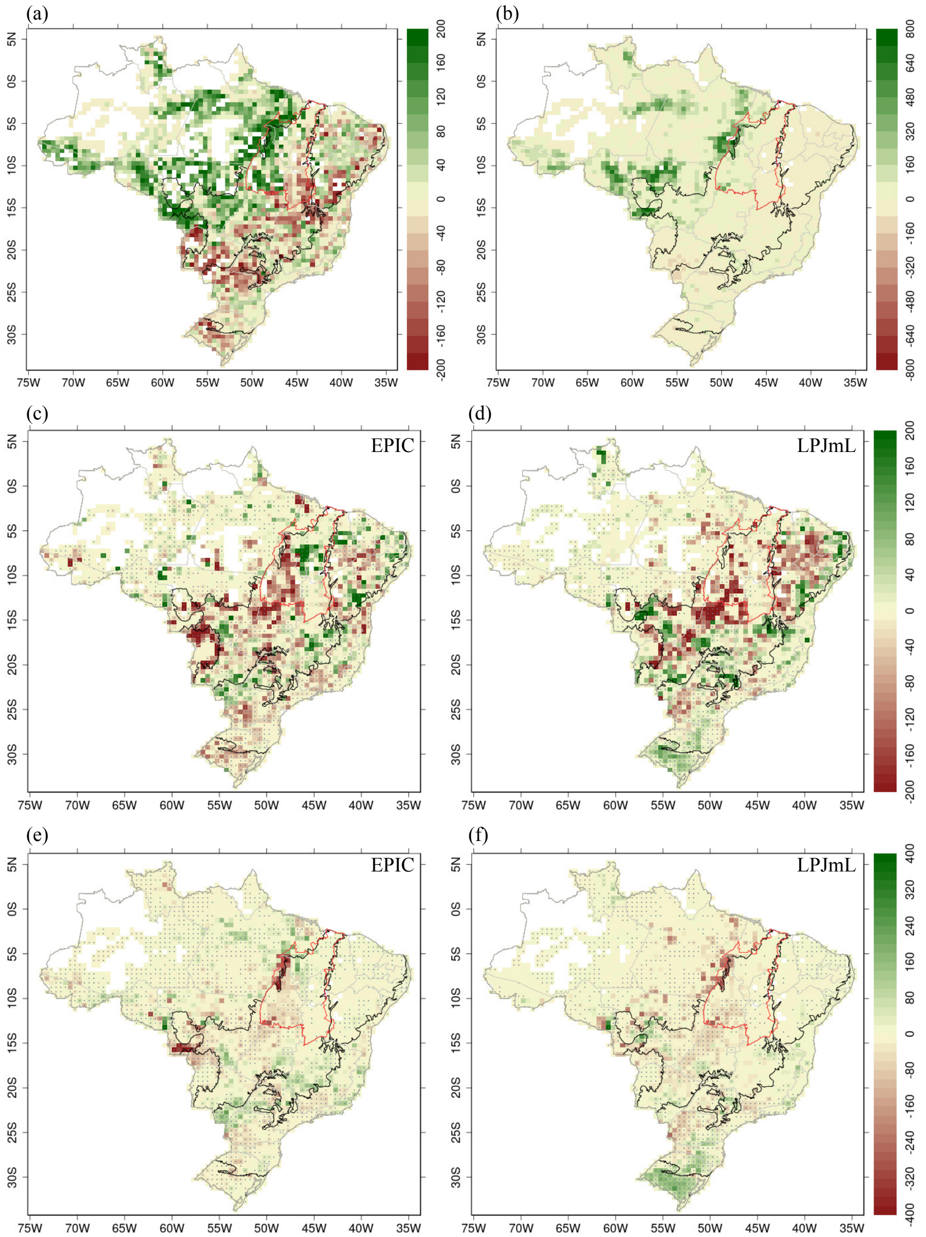


Figure 59: (a)-(b): Evolution from 2000 to 2050 for (a) grassland area (in kha; a) and (b) production (in kton) in the noCC scenario, with increase (decrease) represented in green (red) shades. (c)-(f): Median changes in (c)-(d) grassland area (in kha) and (e)-(f) cattle production (in kTLU) for (c) and (e) EPIC and (d) and (f) LPJmL GCCM in RCP8.5 scenario, expressed as the difference from noCC scenario in 2050. Green (red) shades indicate pixels where the median difference from the noCC scenario is positive (negative); stipples represent pixels where the lower and upper quartiles have same signal.

and projections indicate a tendency of stagnation [MAPA, 2018]. To attain the production projected for 2028, soybean productivity would have to be between 3.4 ton/ha and 3.9 ton/ha, which is considered as a challenge by the producers [MAPA, 2018]. GLOBIOM Brazil projections considering EPIC scenarios is within the productivity range projected by the Brazilian Ministry of Agriculture for 2028 [MAPA, 2018]. However, to reach the production projected by EPIC median scenarios in 2050, soybean productivity would have to be 4.1 ton/ha. Sentelhas et al. [2015] demonstrated that it is possible to have a productivity of 4.0 ton/ha in Cerrado, and as high as 4.5 ton/ha in South Brazil. This would demand investments in technology and management processes such as adaptation of the sowing calendar, utilization of drought resistant cultivars, implementation of irrigation, and investments in fertilization, soil improvement, and precision agriculture. GLOBIOM Brazil

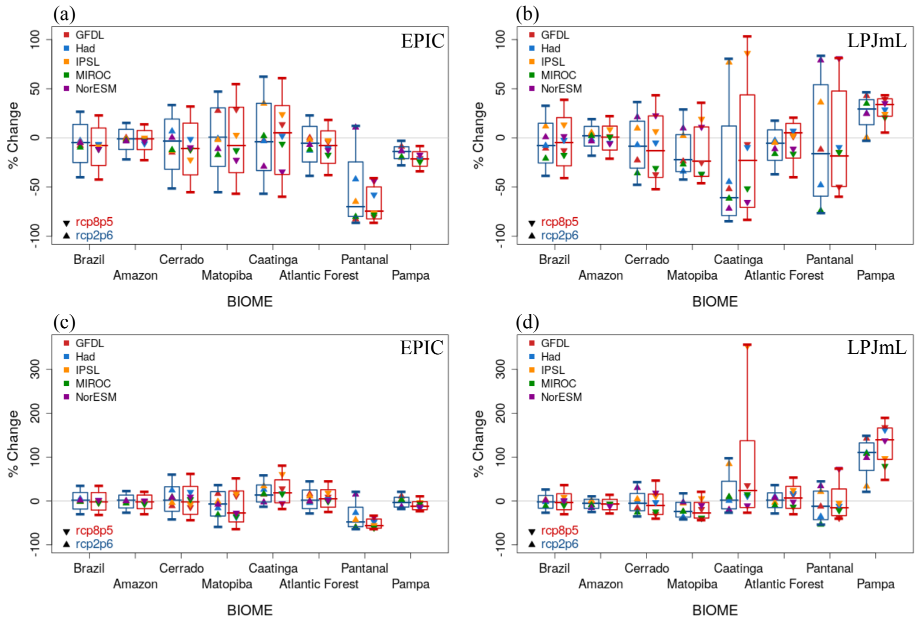


Figure 60: Percentage changes (compared to noCC in 2050) in (a)-(b) grassland area and (c)-(d) cattle production aggregated over Brazil, main biomes, and Matopiba, for (a) and (c) EPIC; and (b) and (d) LPJmL GGCMs. Boxplots: median (central bar), lower and upper quartiles (box), and minimum and maximum (whiskers). Values in 13. Upper (lower) triangles: area and production in RCP2.6 (RCP8.5) scenario for each GCM (color key in the upper left)..

projections discussed here partially account for technological improvements through changes in the management system (from low input to high input agriculture, for example). However, it does not limit the productivity increase, which could be unrealistic. Furthermore, it only considers limited implementation of irrigation systems and water competition. These issues will be addressed in the next steps of this activity.

As observed for soybean, national corn production is also projected to decrease under climate change scenarios, with the producing areas projected to migrate southward (Fig 61b). Cerrado biome would still produce more than 50% of Brazilian corn, mainly in Mato Grosso and Mato Grosso do Sul states, even though the participation of these regions in the total Brazilian production would decrease in all 20 scenarios considered here. Part of the production would shift toward the Atlantic Forest biome, which would be responsible for more the 25% of the national production. However, agreement among scenarios is smaller over this biome.

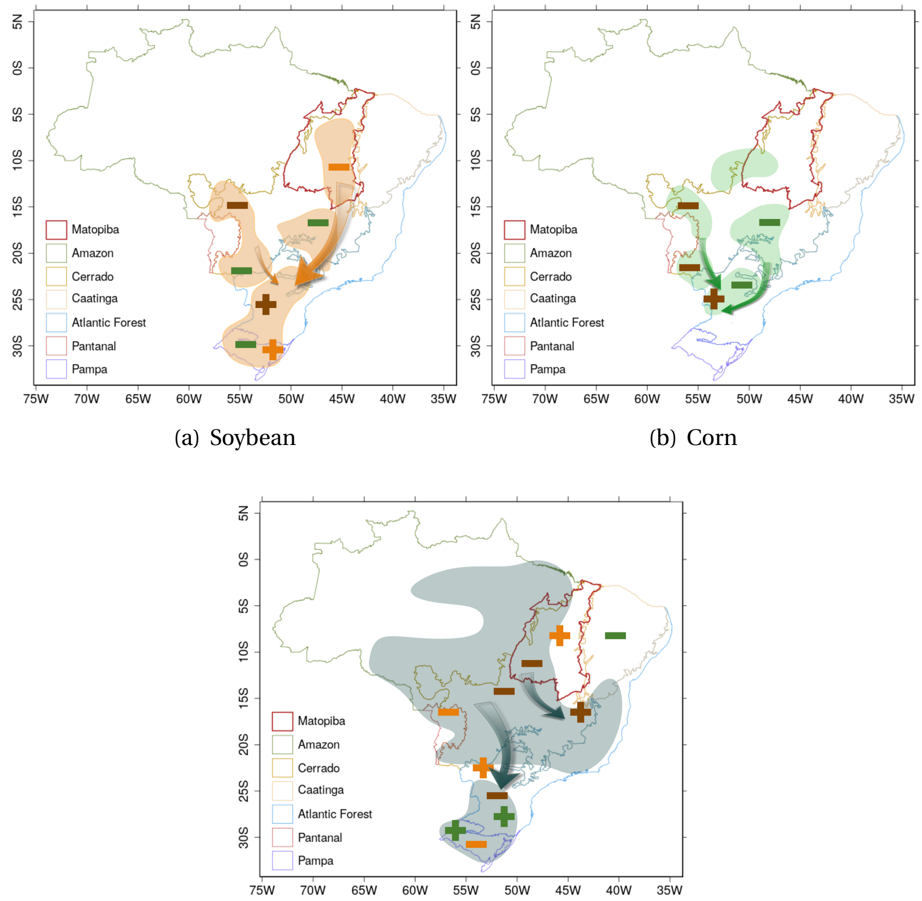
Despite reproducing the observed area of corn relatively well, GLOBIOM Brazil underestimates the corn production. This can be attributed, in part, to the representation of the double cropping production system implemented in Brazil. Historically, corn cultivated as a second crop was considered marginal mostly because of the climatic risk. Nowadays, the second crop is responsible for more than 70% of the Brazilian corn production, with a productivity similar or even higher than the one observed for the first crop. GLOBIOM Brazil captures well this migration of the corn production to the second crop, accurately reproducing the total production and spatial distribution. However, the productivity of the corn in the second crop for both noCC and climate change scenarios is estimated based on soybean and corn productivity in HI management system. The next step in improving GLOBIOM

REGION	RCP2.6 Area (%)	RCP2.6 Production (%)	RCP8.5 Area (%)	RCP8.5 Production (%)
EPIC				
Brazil	-5.2 (-25.0 13.8)	0.2 (-18.4; 19.4)	-7.8 (-27.9; 10.1)	-2.7 (-20.7; 19.3)
Amazon	-0.9 (-11.8; 8.7)	1.0 (-15.9; 13.4)	-1.4 (-11.9; 7.6)	-2.9 (-17.6; 13.5)
Cerrado	-3.7 (-31.9; 19.2)	1.2 (-23.5; 32.6)	-10.7 (-37.6; 15.0)	-3.0 (-30.5; 33.2)
Matopiba	0.6 (-29.0; 30.5)	-8.3 (-34.3; 21.4)	-8.3 (-35.4; 31.3)	-27.4 (-47.7; 22.8)
Caatinga	-4.1 (-33.2; 35.2)	12.0 (-2.3; 36.5)	5.0 (-37.1; 32.9)	17.4 (-4.2; 48.1)
Atlantic Forest	-5.5 (-24.5; 11.7)	0.1 (-17.5; 25.1)	-7.8 (-25.9; 7.2)	4.3 (-14.1; 25.9)
Pantanal	-70.1 (-79.9; -24.4)	-48.3 (-58.6; -14.2)	-74.5 (-82.4; -49.8)	-57.2 (-61.9; -41.1)
Pampa	-14.4 (-21.0; -8.9)	-3.7 (-13.9; 8.4)	-22.0 (-28.8; -14.0)	-13.0 (-19.9; -1.4)
LPJmL				
Brazil	-8.2 (-25.5; 14.9)	-2.5 (-16.5; 12.7)	-5.1 (-38.4; 20.7)	-3.8 (-19.9; 16.4)
Amazon	2.2 (-8.3; 11.7)	-5.8 (-16.9; 4.0)	0.3 (-12.3; 12.0)	-8.4 (-19.9; 3.9)
Cerrado	-8.9 (-30.7; 17.0)	-6.0 (-22.2; 17.1)	-13.2 (-40.1; 22.4)	-11.3 (-30.8; 15.8)
Matopiba	-22.3 (-34.3; 3.3)	-23.9 (-36.6; -3.0)	-23.9 (-39.0; 11.2)	-28.4 (-39.0; -3.2)
Caatinga	-60.9 (-78.9; 12.1)	0.9 (-18.0; 45.0)	-23.6 (-70.7; 43.8)	22.2 (-14.9; 137.1)
Atlantic Forest	-5.7 (-22.9; 8.2)	1.4 (-15.0; 18.7)	4.7 (-20.5; 14.7)	5.7 (-16.8; 33.4)
Pantanal	-16.2 (-59.3; 54.1)	-12.9 (-42.5; 22.6)	-18.9 (-49.4; 47.7)	-16.0 (-33.4; 27.3)
Pampa	29.2 (13.4; 38.9)	109.6 (69.6; 132.4)	33.6 (22.1; 39.8)	138.7 (94.7; 166.4)

Table 13: Median (lower and upper quartile) change in grassland area and cattle production in 2050, expressed as a percentage of the noCC scenario. Values aggregated for Brazil, main biomes, and Matopiba.

Brazil representation of corn production will be based on the simulation of the soybean-corn double cropping system prevalent in Brazil, both for the current conditions and for future climate changes.

Finally, the impacts of climate change in grassland and livestock production is not as defined as for corn and soybean with the lack of agreement among scenarios reducing the confidence in the projections. Projections based on the noCC scenario indicated an increase in grassland and livestock



(a) Soybean (b) Corn

(c) Grassland

Figure 61: Scheme with main producing areas (shades) and changes in (a) soybean, (b) corn, and (c) grassland projected by EPIC and LPJmL considering RCP8.5 emission scenario. Shades: main producing areas of soybean (orange), corn (green), and grassland (gray) according to the noCC scenario. "✚" and "▬" represent regions where either EPIC (orange symbols), LPJmL (green symbols), or both GGCMs (brown symbols) indicated a median area increase or decrease, respectively. Large arrows indicate displacement of the main producing regions.

on the Amazon biome, on the region known as the deforestation arch. When introducing the climate change shifters affecting grassland productivity, the increase in production in this area is not as pronounced, with the median scenarios suggesting a south- and southeastward shift toward eastern Cerrado and South Brazil (Fig 61c). However, in addition to the lack of agreement among scenarios, these projections also do not account for impacts of climate change on livestock.

Land use implications of ethanol demand

Brazil is the world's largest sugarcane producer, growing more sugarcane than the next five largest producing countries combined in 2016 FAO [2018]. Sugarcane crops in Brazil are essentially used as feedstock in the production of sugar and ethanol. Although the production of sugar within Brazil is mostly driven by external markets, the ethanol produced in the country is particularly directed to fulfill the domestic demand for biofuels from the light-duty vehicles (LDV) passenger transport sector. This high domestic demand for ethanol results from the default fuel blend mandate – currently 27% of anhydrous ethanol, in volume – and the increasing numbers of flex-fuel LDV in the national fleet, which are vehicles able to use not only the default fuel blend, but also the 100% hydrous ethanol and any blend in between this range. Despite the already established ethanol market in Brazil, the government has announced on its NDC to expand biofuels consumption, in order to increase the share of sustainable biofuels in the energy mix up to 18% by 2030 [Brazil, 2015]. Such commitments have been reinforced in the Brazilian legal framework with the recently approved biofuels policy RenovaBio.

Here we estimate three different scenarios of ethanol demand in Brazil towards 2030. To this end, our methodology summarized in Fig. 62 takes into account three main steps: (1) projection of the LDV demand for transport towards 2030; (2) estimation of the future fuel consumption associated to the transportation demand; and (3) modeling of the land-use implications of the ethanol demand development.

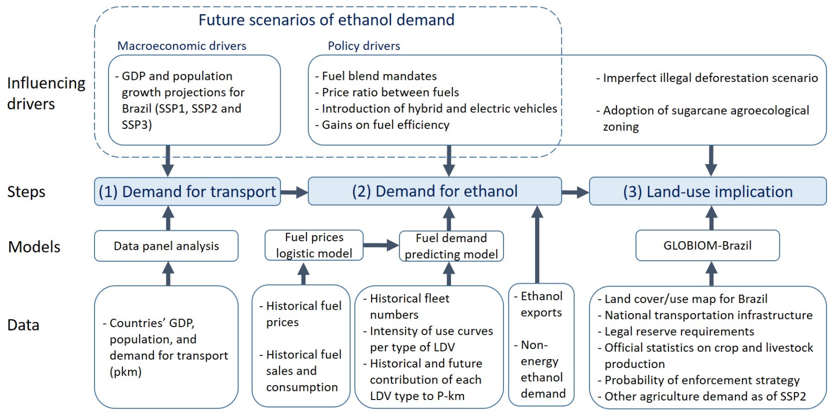


Figure 62: Three main steps of our methods, their models and input data. On top, both macroeconomic and policy drivers. The dashed lines highlights those considered to vary across future scenarios of ethanol demand.

The demand for transportation was projected by estimating future passenger-kilometer (pkm) for LDV in Brazil towards 2030. One pkm represents the transport of one passenger over one kilometer. We assessed the relationship between road passenger transport by passenger cars (expressed in pkm per capita), and GDP per capita through a panel analysis between 1970 and 2016 for a selection of countries with available data. GDP coefficient, intercept, and most country fixed effects were found significant, showing a virtually zero *p-value*. We used transport demand data from OECD statistics for all countries. Brazilian passenger transport demand for LDV in 2013 (5,259 pkm per capita) was added to derive the country fixed effect [COPPE/EPE, 2014]. Future fuel demand for every type of LDV in a given year was estimated based on the total passenger transport demand for LDV in pkm, the percentage of each type of LDV contributing on meeting the passenger transport demand, and a fuel consumption coefficient, expressed as toe/pkm. The percentage of each type of LDV contributing to the total transport demand is determined based on different dataset reporting historical vehicle numbers in the Brazilian fleet, which were used to compute the average driven distance per type of LDV, and then per passenger using an average LDV occupancy coefficient. Historical data on vehicle numbers is based on the National Emissions Inventory for Road Vehicles [MMA, 2014a].

Since there is no historical statistics on driven distance for each type of LDV in Brazil, the distribution of distance driven within the fleet in a given year was estimated by applying the 'intensity of use' curves per type of vehicle and age class developed by the São Paulo state environmental department [Bruni and Bales, 2013]. These values are used as a proxy for the whole country. Thus, the historical passenger transport values per type of LDV was estimated by combining the average driven distance per each type of LDV to the historical fleet numbers and to an average occupancy rate of 1.5 persons per LDV trip for passenger cars and one person per motorcycle, as adapted from IPCC [2014]. During the period between 2006 and 2011, flex-fuel vehicles increased their contribution from 11.1% towards 56.3%. Conversely, gasoline-only vehicles had their contribution reduced from 62.3% to 20.7% during the 11-year period. Time is considered an independent variable in our approach to model future contributions of each type of LDV in meeting the demand for passenger transport towards 2030 from 2006 to 2011. Because flex-fuel motorcycles started being produced only in 2009, we model the contribution of the two-wheelers in meeting the passenger transport demand towards 2030 based on their 5 year contributions. Diesel LDV, showing a relatively stable percentage over the last 11 years, are assumed to maintain the same contribution to demand from 2016 to 2030.

Exponential models were used for these projections because they present the best fit for the curves of LDV contributions to transport demand. These curves are used to model the LDV contributions towards 2030 with the contribution of diesel vehicles kept constant at their 2016 value. Flex-fuel cars, which contribute to the largest share of passenger transport demand, are assumed to take 100% of the passenger transport demand reduced by the contributions of ethanol-only cars, gasoline-only cars, diesel LDV, total motorcycles, hybrid and electric vehicles. Similarly, flex-fuel motorcycles are assumed to take 100% of the total motorcycles passenger transport demand reduced by the trend of gasoline-only motorcycles and electric motorcycles. For the fuel consumption coefficient per vehicle type we are using the values from COPPE/EPE [2014].

In the case of flex-fuel LDV, the market share in the consumption of hydrous ethanol and default blend is not fixed and depends on the relative prices of the two fuel types. To estimate the relationship between fuel prices and hydrous ethanol consumption preference in flex-fuel LDV, we perform an non-linear least-square regression along a logistic curve profile linking the proportion of hydrous ethanol consumption in the total fuel consumption from flex-fuel LDV and monthly observations – from January 2008 to December 2012 – of the relative prices between hydrous ethanol and the default fuel blend. Montly observations on average fuel prices come from the National Oil Agency (ANP) in Brazil [ANP, 2017a]. The fuel consumption specific for flex-fluel LDV is found by using data on actual hydrous ethanol and default blend monthly sales from fuel suppliers [ANP, 2017b] reduced, respectively, by the fuel consumption from ethanol-only cars and gasoline-only cars and motorcycles found in the National Vehicles Emissions Inventory [MMA, 2014a]. Because this inventory presents fuel consumption on annual basis, we transformed this data to monthly values by assuming that monthly fuel consumption fluctuations from ethanol-only cars and gasoline-only cars and motorcycles would follow the same monthly fluctuation pattern of total fuel sales from fuel suppliers in Brazil [ANP, 2017b].

In summary, to define the ethanol demand projections of this study we needed to consider different factors: (i) population and GDP growth, (ii) demand for light vehicles passenger transport, (iii) default fuel blend mandates, (iv) relative prices between ethanol and the default duel blend, (v) composition of the fleet, and (vi) improvements in fuel consumption efficiency. Since these factor are influenced by macroeconomic context and policy interventions, we developed three potential scenarios of ethanol demand in Brazil up to 2030 called 'Renewable Fuels Oriented' (RFO), 'Business As Usual' (BAU), and 'Fossil Fuels Oriented (FFO). These scenarios are mapped with the macroeconomic elements of the three SSPs: SSP1 (sustainability), SSP2 (middle of the road) and SSP3 (regional rivalry) as described in Riahi et al. [2017], respectively. GDP and population assumptions directly determine projections of passenger transport demand for each scenario based on the panel model. The other drivers of ethanol demand associated to the scenarios are presented in Table 14. Although most of the ethanol production in Brazil is allocated to the domestic transportation sector, a portion of it is traded in the international market and a smaller fraction is consumed for non-energy purposes. Because the non-energy ethanol demand has historically not represented substantial impact in domestic ethanol production, and since there is no evidence in the international biofuels policy indicating that ethanol exports from Brazil should increase in the short-to-medium term, we keep future ethanol exports, as well as the demand for non-energy ethanol, at their average level observed in the period 2008-2017 [MME/EPE, 2006, 2018].

	Scenario 1 Renewable Fuels Oriented (RFO)	Scenario 2 Business As Usual (BAU)	Scenario 3 Fossil Fuels Oriented (FFO)
Macroeconomic drivers and pkm demand	Based on SSP1	Based on SSP2	Based on SSP3
Default fuel blend mandate	35%	27%	20%
Average price ratio between ethanol and the fuel-blend	60%	67.8%	75%
Presence of hybrid and electric vehicles	12%	4%	1.33%
Net improvement on fuel consumption	1.53% p.a.	1% p.a.	0% p.a.

Table 14: Driver assumptions for future scenarios of ethanol demand in Brazil by 2030.

The passenger transport demand for LDV in Brazil towards 2030 according to the different scenarios of ethanol demand in Brazil are reported in Table 15. Considering that LDV passenger transport demand in Brazil was 5,259 pkm per capita in 2013, results show a considerable increase in passenger transport demand towards 2030 for all scenarios, from 1,422 billion pkm in FFO, to 1,650 pkm in RFO. The RFO scenario presents the highest demand for transport results among all scenarios, because it also shows the highest projection of GDP per capita according to the SSP1 scenario for Brazil. Figure 63 shows the percentage of each type of LDV contributing to the total passenger transport demand in each scenario.

	FFO/SSP3		BAU/SSP2		RFO/SSP1	
	pkm per capita	Total pkm (billions)[a]	pkm per capita	Total pkm (billions)[a]	pkm per capita	Total pkm (billions)[a]
2013	5,259	1,064	5,259	1,064	5,259	1,064
2020	5,476	1,192	5,683	1,219	5,773	1,226
2025	5,740	1,313	6,302	1,399	6,570	1,428
2030	5,964	1,422	6,966	1,588	7,467	1,650

[a] *Based on population projections from each SSP*

Table 15: Passenger transport demand projections for LDV in Brazil.

The contribution of flex-fuel cars to the Brazilian LDV passenger transport demand, which was 53.5% in 2015, will continue to increase, reaching 76.6% in the FFO scenario (Fig. 63a) and 74.3% in the BAU scenario (Fig. 63b) towards 2030. The RFO scenario shows a faster introduction of hybrid and electric vehicles reducing the flex-fuel cars' contribution to the passenger transport demand mix after achieving a peak of 69.5% in 2025 (Fig. 63c). On the other hand, contribution of gasoline-only cars – already in decline – would keep reducing their percentage for meeting passenger transport demand. Similarly, flex-fuel motorcycles and gasoline-only motorcycles share would decrease, although at a slower pace. Nonetheless, the contribution of total motorcycles in meeting LDV passenger transport demand is slightly decreasing from 17.9% in 2015 to 13.2% in 2030 across all scenarios.

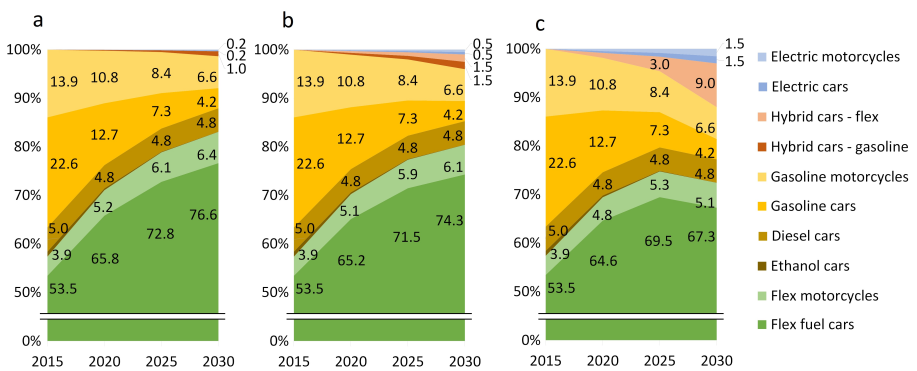


Figure 63: Contribution of each type of LDV in meeting passenger transport demand in the (a) Fossil fuels oriented scenario, (b) Business as usual scenario, and (c) Renewable fuels oriented scenario.

Transforming fleet and transport demand development into fuel consumption leads to an overall increase in fuel demand from LDV in Brazil. Ethanol demand would increase to 17.5 million tonnes of oil equivalent (Mtoe) in the FFO scenario, 24 Mtoe in the BAU, and 34.4 Mtoe in the RFO scenario in 2030

(Fig. 64). These projections are 46%, 100%, and 186% higher, respectively, than the consumption observed in 2010. In terms of ethanol volume (i.e. combined volume of anhydrous and hydrous ethanol), these numbers represent a future demand of 33.8 billion litres in the FFO scenario, 46.6 billion litres in the BAU, and 67 billion litres in the RFO scenario. When incorporating ethanol exports and non-energy ethanol demand, these numbers rise to 37.4, 50.2, and 70.7 billion litres, repectively, in 2030. In Fig. 64, future numbers of diesel and biodiesel demand consider a 15% biodiesel-diesel blend mandate, in terms of volume, regardless on the scenario.

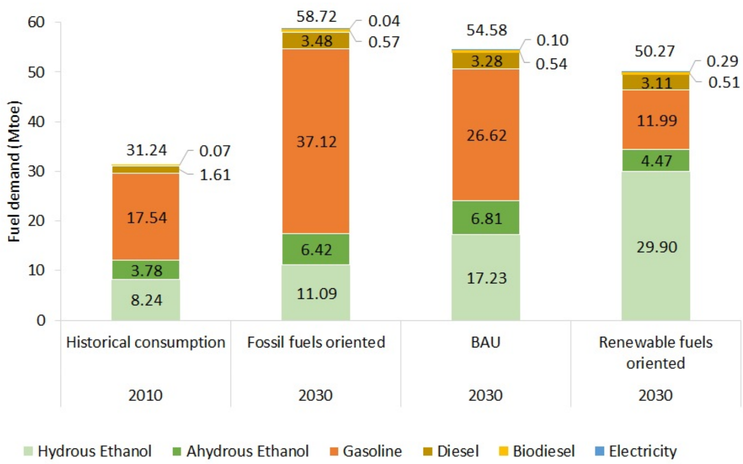


Figure 64: Future fuel demand across scenarios in comparison to consumption numbers in 2010, according to MMA (2013). Fuel demand is expressed in million tonnes of oil equivalent (Mtoe).

Land-use implications are assessed by projecting Brazil's land-use change and agricultural outputs through 2030, taking into account the future scenarios of ethanol demand. Here we are using the scenario IDCImpf of GLOBIOM-Brazil model for 10-yr time steps (see Table 7 and [Soterroni et al., 2018]). As expected, the future demand for ethanol in Brazil has a direct impact in the area of sugarcane. According to our projections, between 2010 and 2030, sugarcane production would increase by 295 Mton in the FFO scenario, 454 Mton in the BAU, and 705 Mton in the RFO scenario (Figure 65a). Similarly, sugarcane area would expand by 1.6 Mha in the FFO scenario, 3.1 Mha in the BAU, and 5.4 Mha in the RFO scenario during the period 2010-2030 (Figure 65b). The comparison between extreme scenarios of ethanol demand shows a difference in sugarcane area of 3.8 Mha by 2030. In 2026, the Brazil's sugarcane area is projected to be between 9.4 and 12.3 Mha according to the FFO and RFO scenarios, respectively. Projections from the Ministry of Agriculture, Livestock and Supply (MAPA) in Brazil [MAPA, 2017] estimate a sugarcane area ranging from 8.2 to 12.8 Mha for the same year. More importantly, regardless the scenario of ethanol demand, sugarcane expansion in Brazil would present no considerable effect in the area or production of other crops (Figure 65). In other words, there is no evidence of competition between sugarcane and other crops simulated by the model since their expansion remains the same in all simulated scenarios.

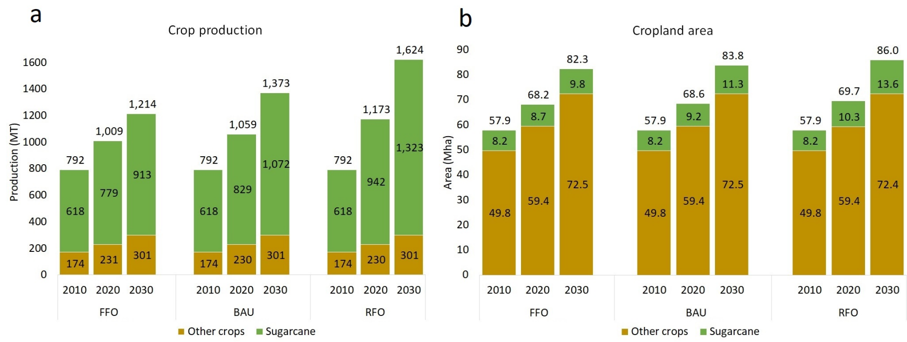


Figure 65: Cropland harvested area (a) and crop production (b) evolution between 2010 and 2030 based on GLOBIOM-Brazil projections.

Cattle herd would increase 55 million of tropical livestock units (TLU) between 2010 and 2030, with no considerable difference across scenarios. However, the expansion of pastureland area shows a different dynamic. Pastureland area would decrease or remain constant in all biomes after 2020. The RFO scenario projects a reduction of 2.7 Mha of pastures in comparison with the FFO projections. The greater the ethanol demand, the smaller is the projected pasture. This intensification would lead to a rise stocking rates by 25.8% in the FFO scenario, 26.4% in the BAU, and 27.2% in the RFO scenario between 2010 and 2030. This projected increase in stocking rates is on par with a recent empirical study [Dias et al., 2016] that, using remote sensing imagery combined with census and inventory data, shows that the stocking rate in Brazil has increased by 28% per decade (50% in the Amazon) between 1990 and 2010. Note that a small growth in stocking rate liberates enough pasture area to accommodate the expansion of ethanol consumption, and thus of sugarcane crop area, across scenarios. Detailed evolution of cattle herd numbers, pastureland area and stocking rates is presented in Table 16.

	FFO		BAU		RFO	
	2020-2010	2030-2010	2020-2010	2030-2010	2020-2010	2030-2010
Cattle herd (Mtlu)	27.3	55.2	27.2	55.2	27.0	55.3
Pasturelands (Mha)	21.7	22.7	21.5	21.5	20.9	20.0
Stocking rates (tlu/ha)	0.054	0.165	0.055	0.169	0.056	0.174

Table 16: Evolution of cattle herd numbers, pastureland area and stocking rates across scenarios between 2020-2010 and 2030-2010. Abbreviations: Mtlu = million tropical livestock units; Mha = million hectares; tlu/ha = tropical livestock units per hectare.

Overall, our results indicate that most of the sugarcane expansion between 2010 and 2030 occurs at the expenses of grassland, with a loss of 0.72 ha of pastures for each additional hectare of sugarcane. Many studies corroborate this result, showing that the vast majority of cropland (and sugarcane, in particular) expansion in Brazil during the last decades occurred on pastureland. For two recent studies using very different approaches, see van der Hilst et al. [2018], Zalles et al. [2019]; for a review, see Bordonal et al. [2018]. More importantly, we projected that sugarcane expansion would have limited direct and indirect impacts on total native vegetation area in Brazil. Across scenarios, from minimum (FFO) to maximum (RFO) ethanol demand, deforestation increases only 0.7% in Brazil by 2030, from 24.94 to 25.12 Mha. Deforestation change for the Cerrado and the Amazon biomes are, respectively, 1.5%

(from 8.44 to 8.57 Mha), and 0.2% (from 12.34 to 12.37 Mha). To put this into context, the expansion of sugarcane area by 2030, from 1.6 Mha in the FFO scenario to 5.4 Mha in the RFO, would result in a loss of 0.18 Mha of native vegetation – which represents 4.8% of this sugarcane expansion (see Table 17, particularly in the comparison between RFO and FFO scenarios). Therefore, these results suggest a weak correlation between sugarcane expansion and deforestation growth in Brazil, in particular in the Amazon.

Table 17: Evolution of cattle herd numbers, pastureland area and stocking rates across scenarios between 2020-2010 and 2030-2010. Abbreviations: Mha = million hectares.

	BAU-FFO (Mha)	BAU-FFO $\Delta(\%)$[1]	RFO-FFO (Mha)	RFO-FFO $\Delta(\%)$[1]
Sugarcane	1.44	100%	3.77	100%
Other crops	-0.01	-0.7%	-0.15	-4.1%
Planted forest[2]	-0.01	-0.7%	-0.02	-0.7%
Native vegetation	-0.10	-6.9%	-0.18	-4.8%
Nonproductive land[3]	-0.12	-8.4%	-0.71	-18.8%
Pasture	-1.20	-83.3%	-2.70	-71.7%

[1] *In relation to the sugarcane expansion.*

[2] *Or short rotation tree plantation.*

[3] *Or mosaics of natural vegetation and areas converted from agriculture but not currently under production.*

Quantitatively, each additional sugarcane hectare results in a loss of 0.05 ha of native vegetation (72% in the Cerrado and 17% in the Amazon). The additional loss of grass, shrubs, and secondary vegetation areas (i.e., areas which have suffered some degree of anthropization in the past but are currently not under production; see "non-productive land"), increases the potential loss of native vegetation to 0.24 ha per hectare of sugarcane. However, this last figure is probably overestimated since under the label "non-productive land", large areas of unproductive degraded pasture are also included. In any case, this result compares well with Ferreira Filho and Horridge [2014] and van der Hilst et al. [2018], who found, respectively, a potential loss of 0.14 and 0.26 ha of native vegetation per additional hectare of sugarcane.

Although we run GLOBIOM-Brazil with three different ethanol demand scenarios, land use competition in this study is modeled assuming a governance scenario that captures the historical deforestation trends in Brazil (see Table 7 and Soterroni et al. [2018]). In this sense, more optimistic or pessimistic governance scenarios could also impact the land use competition, depending on how the country complies with its land-use policy commitments, such as the control of illegal deforestation and the AEZ for sugarcane. These circumstances are particularly relevant in the current political context of transitioning governments and the uncertainties that it brings to the future of the commitments made by Brazil to the Paris Agreement.

Final Remarks

During most of the period covered by this report, the cause/effect mechanisms highlighted in the original proposal were still valid and its goals remained achievable by the measures already included in the project's work plan. However, in October 2018 a far right populist candidate, Jair Bolsonaro, was elected Brazil's new president in October 2018. During his campaign, this candidate has pledged to shut down Brazil's environmental ministry, relax environmental law enforcement and licensing, open indigenous reserves to mining, ban inter-national environmental NGOs such as Greenpeace and WWF from the country, and back out of the Paris climate accord. Although the Ministry of Environment was not abolished, the new minister is known to be aligned with the agribusiness interests and support the idea that companies should self-regulate the environmental licensing process for major infrastructure and development projects. In addition, the Brazilian Forestry Service was transferred to the Ministry of Agriculture, and the new Minister of Foreign Affairs is a climate change denier that has declared that global warming is a Marxist plot. As a direct consequence, Brazil is no longer going to host UN's COP-25 in 2019 because the new government withdrew the country's candidacy. Moreover, Brazil's NDC 2025 and 2030 targets, including the restoration of 12 million hectares of native vegetation, are no longer a priority, to say the least.

It is under this unfavorable political context that the RESTORE+ Brazilian team is preparing to operate until the end of the project in 2022. Although we do not expect that the most controversial anti-environment measures to be eventually enacted (the new government already backtracked on the Paris accord due to strong international pressures), we do expect delays or lenience in the enforcement/implementation of Brazil's major environmental laws and programs, like the Forest Code, the PLANAVEG and the RenovaBio.

Overall, the new political situation, strongly pro agribusiness, will probably result in more deforestation (and, thus, more carbon emissions), and less restoration. Within this context, studies on commodity-driven deforestation, such as soybeans and beef, and restoration agreements like the Bonn Challenge become ever more relevant because they mobilize the private sector in their implementation, and usually have a strong impact in the civil society. Also, in spite of the opposition of global warming deniers like the Foreign

Affairs minister, climate change impacts on agriculture will remain a key issue for policy makers and will have a high priority in a government largely supported by the powerful agribusiness lobby.

In any case, regardless the government in power in Brasilia, our task within RESTORE+ is to use science to continually inform policy makers and relevant stakeholders that in Brazil a compromise between agricultural production and environment protection can be achieved to the benefit of all, producers and environmentalists. Moreover, our goal will be met if we succeed to demonstrate that compliance with Brazil's environmental law and international commitments do not hinder the country's development and progress. All the contrary, it decisively contributes to the transformation of a low-yield, deforestation-driven production sector, characterized by the waste of large amounts of land, water, human and other resources, into a modern, high-yield agricultural sector, more amenable to resist the impact of climate change.

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