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Future environmental and agricultural impacts of Brazil's Forest Code

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Abstract. The role of improving the enforcement of Brazil's Forest Code in reducing deforestation in the Amazon has been highlighted in many studies. However, in a context of strong political pressure for loosening environmental protections, the future impacts of a nationwide implementation of the Forest Code on both environment and agriculture remain poorly understood. Here, we present a spatially explicit assessment of Brazil's 2012 Forest Code through the year 2050; specifically, we use a partial equilibrium economic model that provides a globally consistent national modeling framework with detailed representation of the agricultural sector and spatially explicit land-use change. We test for the combined or isolated impacts of the different measures of the Forest Code, including deforestation control and obligatory forest restoration with or without environmental reserve quotas. Our results show that, if rigorously enforced, the Forest Code could prevent a net loss of 53.4 million hectares (Mha) of forest and native vegetation by 2050, 43.1 Mha (81%) of which are in the Amazon alone. The control of illegal deforestation promotes the largest environmental benefits, but the obligatory restoration of illegally deforested areas creates 12.9 Mha of new forested area. Environmental reserve quotas further protect 5.8 Mha of undisturbed natural vegetation. Compared to a scenario without the Forest Code, by 2050, cropland area is only reduced by 4% and the cattle herd by 8%. Our results show that compliance with the Forest Code requires an increase in cattle productivity of 56% over four decades, with a combination of a higher use of supplements and an adoption of semi-intensive pasture management. We estimate that the enforcement of the Forest Code could contribute up to 1.03 $PgCO_2e$ to the ambitious GHG emissions reduction target set by Brazil for 2030.

1. Introduction

Over recent decades, Brazil has become one of the top global producers and exporters of several agricultural commodities: it is the largest sugar and beef exporter, the second largest maize exporter and the third largest soybean exporter [1, 2]. This is possible because of the expansion of production area and gains in productivity. It is estimated that the average farm productivity increased by 2.55% per year between 1985 and 2006 [3]. Investment in infrastructure and the transformation of low-fertility soils into highly productive areas through the development of new technologies have also been key for the expansion of cultivated area in the Cerrado and Amazon biomes [3, 4]. As global demand for agricultural commodities, which is driven by population and income growth, is poised to increase in the coming decades [5, 6, 7], the amount of production that will result from additional land conversion in Brazil remains unclear [8].

The large-scale deforestation in the Brazilian Amazon in the mid-2000s, with a 27,772 km^2 deforestation peak in 2004 [9], is correlated to the expansion of pasture for cattle ranching and, to a lesser extent, soy [10, 11, 12, 13]. In 2005, land-use, land-use change and forestry (LULUCF) activities accounted for approximately 80% of Brazil's greenhouse gas (GHG) gross emissions [14, 15] with the deforestation in the Amazon representing the lion's share of the Brazil's LULUCF emissions. The situation has changed since 2005, with an 83% reduction in deforestation in the Brazilian Amazon between 2004 and 2012 to reach 4,656 km^2 [9]. This sharp reduction resulted from the combination of improved satellite monitoring systems, the creation of new protected areas [16], the interventions in critical food supply chains [17], and the enhanced enforcement of the Forest Code (FC) through imposing fines, restricting access to rural credits [18], confiscating cattle and machinery, and even implementing prison sentences for lawbreakers [19, 20, 21, 12, 22].

In the Paris Agreement, Brazil committed to reduce its GHG emissions by 37% below 2005 levels by 2025 and to reach a 43% reduction by 2030 [23]. Brazil's Nationally Determined Contributions (NDC) mentions the enforcement of the Forest Code as a key mitigation measure. However, the fact that 2016 encompassed the highest deforestation level in four years, with a 29% increase compared to 2015 and a 75% increase compared to 2012 [9], raised some new concerns about the enforcement of the Forest Code. Among its main provisions, the Forest Code identifies the minimum percentage of forest to be preserved, which is called the Legal Reserve (LR) and varies across the six biomes (Fig. S1), on each property; the LR ranges from 80% in the Amazon biome to 20% in the Atlantic Forest, and it designates environmentally sensitive areas, such as riversides and hilltops, as Areas of Permanent Preservation (APP). These measures correspond to vast areas since it is estimated that private properties cover 67% of the Brazilian territory [24] and contain more than 50% of Brazil's native vegetation [25]. However, enforcement has been a major issue; in 2005, in the Amazon region of Mato Grosso state, 82% of the farms surveyed were not in compliance with the Forest Code [26].

The 2012 revision of the Forest Code included the obligation that illegally deforested areas be restored at the landowners' expense, but it provided amnesty for small farms (from 20 ha

in southern Brazil to 440 ha in the Amazon). The provision of an environmental reserve quota system (Portuguese acronym: CRA), which is a 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 [27]. However, five years after the last revision, the Forest Code remains contested by both the agribusiness lobby, which still considers it a barrier to economic development, and the environmentalists, which consider the current code to be a step backward vis-à-vis the previous legislation [25].

We quantify the future impacts of Brazil's Forest Code, the country's main environmental law to reduce deforestation, on both the agricultural sector and the environment through the year 2050. The rigorously enforced Brazil's Forest Code scenario includes the full control of illegal deforestation, the amnesty of legal reserve debts from small farms, the environmental reserve quota mechanism, and the mandatory restoration of legal reserve debts. We use the recursive dynamic, global, bottom-up partial equilibrium model GLOBIOM [28, 29, 30]. GLOBIOM-Brazil includes a series of refinements that reflect Brazil's specificities [31]. The model computes consumption and trade for each of the 30 regions of the world; it also computes production and land use at the 50 km x 50 km grid level for the most important crops and animal products in Brazil. In this framework, deforestation depends on the feedback between future agricultural demand and biophysical and regulatory constraints on land. This is the main difference from other studies, where deforestation was first estimated separately, often on the basis of historical trends, and then spatially allocated using land characteristics [32, 10, 33, 34, 35]. Other approaches where deforestation is computed based on the expansion of agriculture have usually focused on only one commodity and did not take into account market feedback [36, 37].

Moreover, this study disentangles the impacts of two key measures of the Forest Code: the control of illegal deforestation and the restoration of illegally converted areas. To this end, we investigate the impact of an uneven enforcement of the Forest Code through alternative scenarios in which the control of illegal deforestation is either enforced only in the Atlantic Forest biome, or in the Atlantic Forest and the Amazon biomes, or fully enforced in the whole country. These scenarios highlight the role of the control of illegal deforestation and the potential leakage into other biomes. We also evaluate the effect of an imperfect enforcement of the Forest Code in the Amazon and the Cerrado biomes by generating scenarios that take into account the historical compliance with this environmental law. In April 2017, approximately 83% of the private properties were registered [38] in the GIS-based Environmental Cadastre (Portuguese acronym: CAR). To test for the restoration obligation of previously illegally converted areas, we use a map of the native vegetation debts, which was produced based on the CAR information [39]. Since the environmental reserve quota mechanism is still under discussion, we also run an alternative scenario with the full restoration obligation, i.e. without possible compensation from environmental surpluses elsewhere. The trade-offs between environmental conservation and agricultural production across different scenarios are highlighted.

2. Methods

The GLOBIOM-Brazil model adapts IIASA's Global Biosphere Management Model (GLOBIOM) to the Brazilian context. It is a global partial equilibrium model that simulates the competition for land among the main sectors of the land-use economy (i.e., forestry, agriculture and bioenergy) that are subjected to resource, technology and policy restrictions. GLOBIOM-Brazil is recursively run for 10-year time steps, starting at the baseline year of 2000 and continuing to the year 2050. The model simulates the competition for land at the pixel level by maximizing the sum of consumer and producer surpluses. The geographically explicit representation of the model is a uniform grid of 0.5° by 0.5° amounting to 3,001 pixels in Brazil, and it has a spatial resolution of approximately 50 km x 50 km at the equator.

The model considers international trade and exogenous drivers, such as gross domestic product (GDP) growth, population growth, and dietary trends. Population and GDP changes follow the assumptions from the 'middle-of-the-road' Shared Socioeconomic Pathway (SSP2) [40]. Production is endogenously adjusted to meet the demand for all 30 economic regions, which include Brazil. The equilibrium quantities and prices are obtained for each region and product as the result of the optimization procedure. The model optimizes over six land-use classes (see Fig. S2 and Table S1). The final demand, processing quantities, prices, and trade are computed at the regional level.

The model simulates 18 crop products, 5 forestry products and 7 livestock products. Crop productivities are defined by the biophysical model EPIC [41] for each crop and management system (i.e., subsistence, low-input rainfed, high-input rainfed, and high-input irrigated). The model also endogenously adjusts the productivity by changing the management system from low to high input. Livestock production systems cover five different species (bovines, sheep, goats, pigs and poultry). Ruminants are raised according to eight livestock production systems, ranging from grazing-humid to mixed-arid [42]. Intensification or extensification of livestock production and feed substitution is performed by making changes among the production systems. Particularly in Brazil, a semi-intensive cattle ranching production system is also allowed [30]. The RUMINANT model is used to estimate bovine and small ruminant productivity and feed requirements [43, 42]. Feeds consist of grass, crop residues, grain concentrates, and other feed stuff.

The projections presented in this study are based on a consistent 2000 land-cover and land-use map of Brazil. This map combines information from official statistics on crop and livestock production, from maps of protected areas, and from different satellite images for the base year 2000 (see Fig. S3). We use a detailed and up-to-date representation of the national transport infrastructure (see Fig. S4) with a discrimination of transportation costs per product type (i.e., solid, liquid and grain) and destination (e.g., nearest state capital, internal consumption, nearest seaport, or external markets).

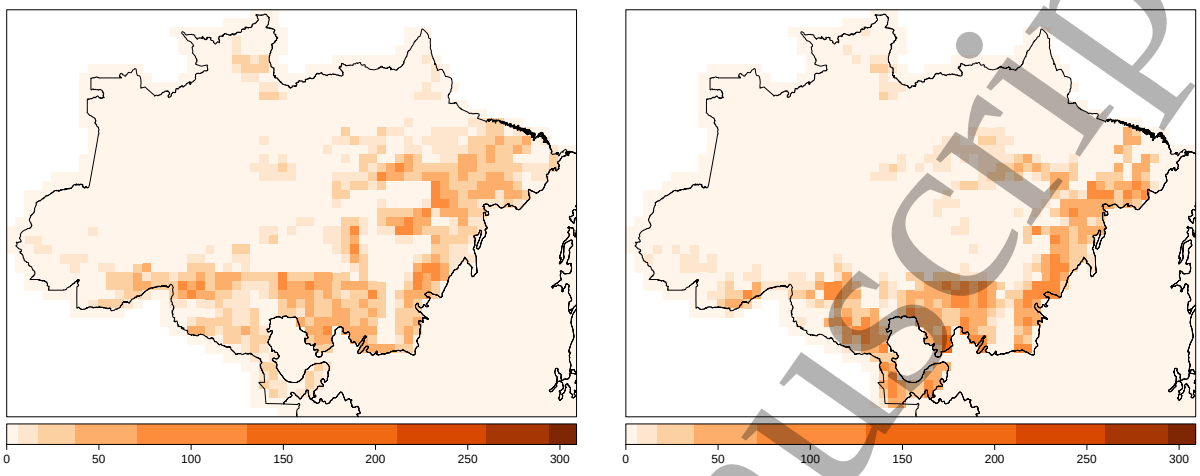
Due to the lack of information on property boundaries, we calculate the LR surpluses for each pixel (roughly 50 km x 50 km) as the amount of native vegetation that exceeds the legal reserve. The LR is calculated by multiplying the amount of land in a pixel by the percentage of the LR

requirement in that pixel (see Fig. S5 and S6). 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. Passive forest restoration is assumed, and it is also assumed there are 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, downscaled to 50 km x 50 km pixels (see Fig. S7), are based on CAR data downloaded in December 2016 [39]. The total environmental debts amount to 18.7 million hectares (Mha) in Brazil, 10.8 Mha of LR debts and 7.9 Mha of APP debts. Consolidated environmental debts are calculated by considering the amnesty of small farms [39].

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. Another source of uncertainty is related to the debt offset mechanism. First, we assume that environmental debts will be compensated by the quota system only in cells with deficits overlapping soybean and sugarcane production; this assumption is due to the profitability of these crops [44] and the agroecological restrictions of sugarcane production. Second, we assume that cells with larger deficits are compensated first, and cells 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.

Emissions from the land-use change and forestry (LUCF) sector are calculated from the endogenous land-use changes projected by the model and the different biomass maps. The carbon content from forests and native vegetation is taken from the Brazil's Third Emissions Inventory [45]. The carbon content in the biomass of short-rotation plantations comes from Havlik et al. [28]. The biomass map of Ruesch and Gibbs [46] is used for pasture and non-productive land. The release of carbon as CO_2 from the terrestrial biosphere to the atmosphere occurs in one simulation period (i.e., a 10-year time step) of deforestation and other land-use changes. By contrast, CO_2 removal from the atmosphere by forest regrowth varies from a few years to several decades. We defined different carbon uptake rates from forest regrowth according to each biome (see SI).

We compared the model results for the first period of simulation, i.e., 2000-2010, with Brazil's official statistics as a baseline for model validation (see Figs. S8-S13). Accumulated deforestation from PRODES/INPE [9] between 2001 and 2010 in the Amazon biome amounts to 16.53 Mha; in comparison, our model projects 16.45 Mha for the same period and region (see Fig. 1).



(a) PRODES/INPE (b) GLOBIOM-Brazil

Figure 1. Spatial distribution of accumulated deforestation in the Amazon biome from 2001 to 2010, as (a) determined by PRODES/INPE and (b) projected by GLOBIOM-Brazil. Color bar values are expressed in thousands of hectares per cell.

Differences were concentrated around the Xingu area and along road BR-163 in the state of Pará and are probably due to need of further improvements in the local transportation network. More importantly, the model captures the trends in deforestation and agricultural expansion in Brazil between 2000 and 2010 without using historical deforestation as input data, which enhances confidence in the future land-use changes projected by the model. For more details, see SI.

3. Forest Code Scenarios

The Forest Code (FC) scenario is a command-and-control scenario that attempts to capture the future impacts of all key provisions of a rigorously enforced Brazil's Forest Code. It includes the full control of illegal deforestation after 2010, the amnesty of LR debts for small farms (SFA) before 2010, the environmental reserve quota mechanism after 2020, and the mandatory restoration of LR 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.

Seven additional scenarios were designed to investigate a gradient of environmental protection around the Forest Code. The counterfactual analysis is a scenario without control of illegal

deforestation in all biomes (except for the Atlantic Forest) and without any requirement for forest restoration. The No Forest Code (NoFC) scenario allows both legal and illegal deforestation at all times, which is driven by the demand for agricultural commodities, and does not include any policy restrictions. 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 (IDC) is extended from the Atlantic Forest to the Amazon biome (IDCAmazon). Then, we expand the illegal deforestation control to the entire country (IDCBrazil). Three additional scenarios were built upon the NoFC to test different levels of compliance with the Forest Code regarding the IDC. In these scenarios the illegal deforestation control is imperfect or partial, and covers the Amazon and the Cerrado biomes. A probability of enforcement of the IDC is calculated per grid cell (see Fig. S14) and it is used as an index to restrict or not the illegal deforestation (IDCImperfect1). The probably of enforcement is increased by 25% (IDCImperfect2) and also by 50% (IDCImperfect3), and kept constant during the period 2010-2050. See SI for more information. Finally, we investigate the role of obligatory forest restoration with illegal deforestation control but without any compensation mechanism from the environmental reserve quota system (FCnoCRA). Table 1 shows an overview of the different scenarios.

Table 1. Overview of the main provisions of the Forest Code included in each scenario.

Scenarios	Illegal Deforestation Control				Native Vegetation Restoration	Environ. Reserve Quotas (CRA)
	Atlantic Forest	Amazon	Cerrado	Rest of Brazil		
NoFC	full	no	no	no	no	no
IDCAmazon	full	full	no	no	no	no
IDCBrazil	full	full	full	full	no	no
IDCImperfect1,2,3	full	partial	partial	no	no	no
FC	full	full	full	full	yes	yes
FCnoCRA	full	full	full	full	yes	no

4. Results

4.1. Agricultural gains and environmental losses of rigorously implementing the Forest Code

Figures 2-4 summarize results from the FC and NoFC scenarios in terms of crop area, pasture area, cattle herd and native vegetation stocks at national level.

As shown in Fig. 2a, the native vegetation area in the FC scenario almost stabilizes at approximately 422.5 Mha after 2030, with an accumulated net decrease of 12.1 Mha between 2010 and 2050 (25 Mha lost due to legal conversion of LR surpluses and 12.9 Mha gained due to forest restoration of LR and APP debts). In comparison, under the NoFC scenario, the native vegetation

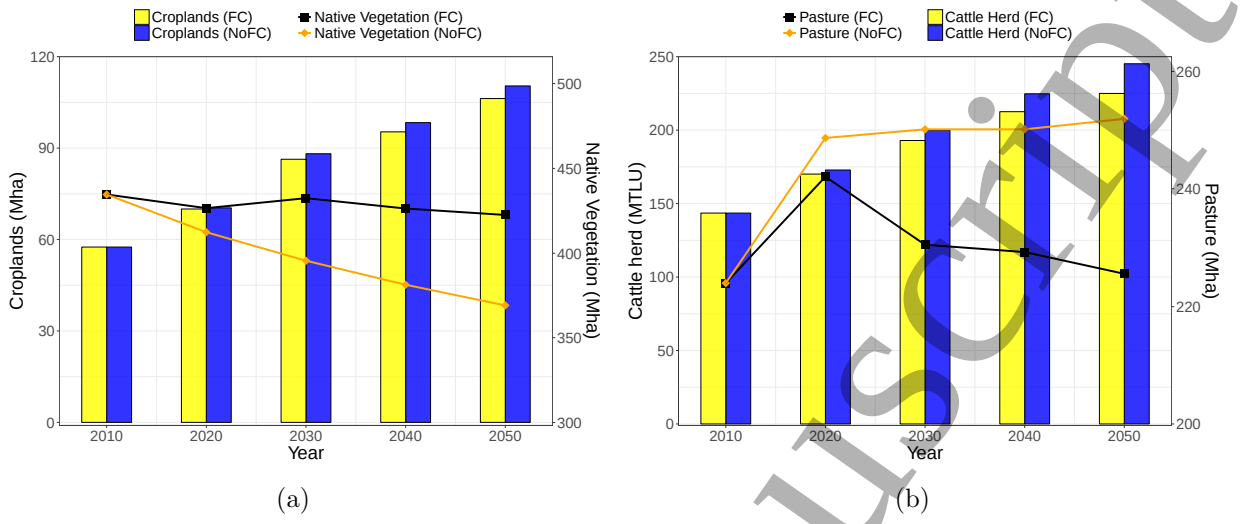
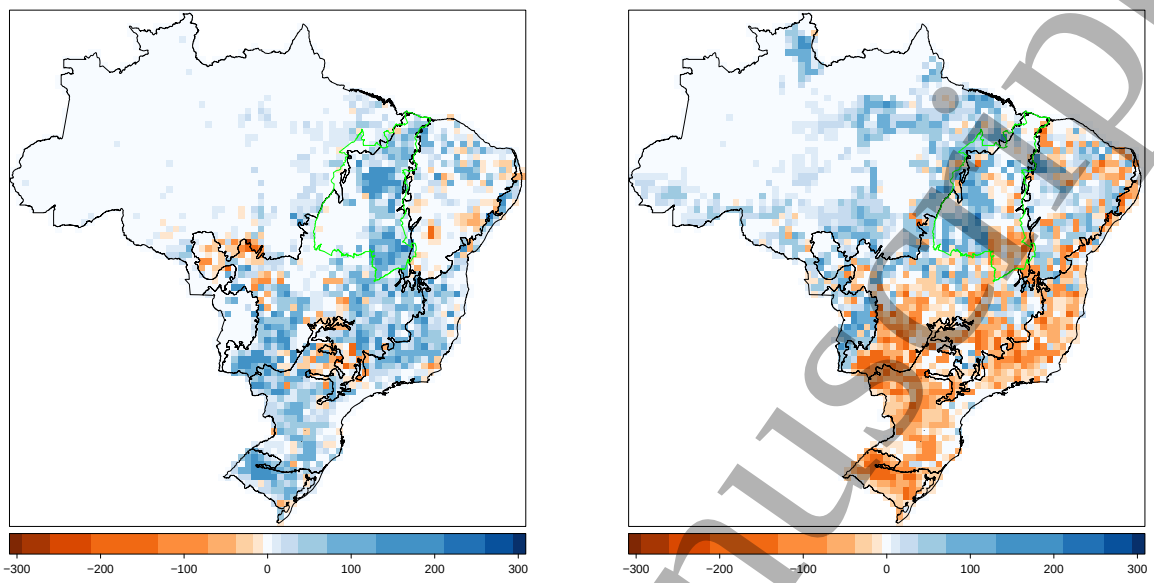


Figure 2. Production versus protection. (a) Cropland expansion (bar charts) and native vegetation area evolution (line charts) as projected by the Forest Code (FC) and No Forest Code (NoFC) scenarios. (b) Cattle heads (bar charts) and pasture area evolution (line charts) as projected by the FC and NoFC scenarios. Abbreviation: FC = Forest Code fully implemented; NoFC = no implementation of the Forest Code. 1 Mha = 10^4 km^2; 1 MTLU = 10^4 TLU; 1 TLU = 0.7 cattle heads.

area decreases to 369.1 Mha, which differs from the FC scenario by 53.4 Mha (43.1 Mha or 81% in the Amazon). Under the NoFC scenario, the accumulated deforestation in all of Brazil is 2.6 times higher than the accumulated deforestation projected by the FC scenario during the same period (i.e., 2011-2050). Under the FC scenario, the total cropland in Brazil increases by 85% between 2010 and 2050, from 57.5 to 106.3 Mha. In 2050, the crop area projected by the FC scenario is only 4% smaller than the one projected by the NoFC scenario. According to the FC scenario, between 2010 and 2050, the cattle herd increases by more than 81.4 million tropical livestock unit (MTLU; 1 TLU = 0.7 cattle head), though the total pasture area decreases by 16.5 Mha after 2020 (Fig. 2b). This result corresponds to a 56% growth in Brazil's cattle productivity, from 0.64 to 1 heads/ha (Fig. S14). Compared to the NoFC scenario, the projected pasture area under the FC scenario decreases by 26.4 Mha by 2050, while the cattle herd is only 8% smaller (or -20.2 MTLU).

Between 2010 and 2050, cattle ranching intensifies under the FC scenario, with an increase in the cattle herd (+57%) and a stabilization of the pasture areas (+0.7%). In the same period, cropland expands (+85%). In Brazil, cropland expands by 48.7 Mha (Fig. 3a), 25.8 in the Cerrado (53%) and 13.7 Mha the Atlantic Forest (28%). Within the Cerrado, 42% of this expansion will occur in the Matopiba region (a region in the states of Maranhão, Tocantins, Piauí and Bahia, located along the border between the Cerrado and the Caatinga biomes) and is led by soybeans and maize. The decrease in pasture area is also concentrated in the Cerrado and the Atlantic Forest biomes (Fig. 3b), showing that cattle ranching intensification spares land for cropland expansion and decreases the pressure of native vegetation conversion. Compared to the NoFC scenario, the



(a) Cropland loss/gain (b) Pasture loss/gain

Figure 3. Spatial distribution of cumulative loss (orange) or gain (blue) of (a) cropland and (b) pasture in Brazil as projected by the Forest Code (FC) scenario. Matopiba is highlighted in green. Color bar values are expressed in thousands of hectares per cell.

FC scenario projects that 68% less forest and native vegetation will be converted to pasture and that 39% less forest will be impacted by cropland expansion. On the other hand, the FC scenario doubles the use of non-productive areas between 2010 and 2050 (Fig. S16).

From 2010 to 2050, the Amazon biome has the highest relative growth of cattle heads per ha among the other biomes (70%), followed by the Atlantic Forest (43%) and the Cerrado (37%) biomes (Fig. S13). This cattle ranching intensification under the FC scenario is possible due to the combination of an 8% increase in the cattle herd growing in mixed grass and crop-based feed systems, which produce more meat per cattle head. Also, in 2050 43% of the cattle herd is maintained in semi-intensive managed pastures, which supports more cattle heads per hectare (Fig. S17). In spite of the overall decrease in pasture area in Brazil, between 2010 and 2050, pastures still expand in the Amazon by 55% over the LR surpluses (legal deforestation). The FC scenario projects that the cattle herd will increase by 164% in this biome, from 41 to 108 MTLU, during the same period. By 2050, 48% of Brazilian cattle will be kept in the Amazon. Since the expansion of cattle ranching is historically linked to deforestation in this biome, enforcing compliance with the environmental laws is critical to avoid a new surge in forest clearing [47].

In summary, by 2050, the agricultural gains obtained by not enforcing the Forest Code (NoFC) in Brazil include an increase of 4% in crop area and an increase of 8% in the cattle herd. On the environmental side, the lack of enforcement of the Forest Code between 2010 and 2050 results in an accumulated deforestation of 65.5 Mha without any forest restoration. Figure 4a shows this

loss is mainly located in the Amazon (47 Mha) and the Cerrado biomes (14 Mha). The NoFC scenario displays an average deforestation rate of 16.4 Mha per decade, with no stabilization of the total native vegetation area in Brazil in the future.

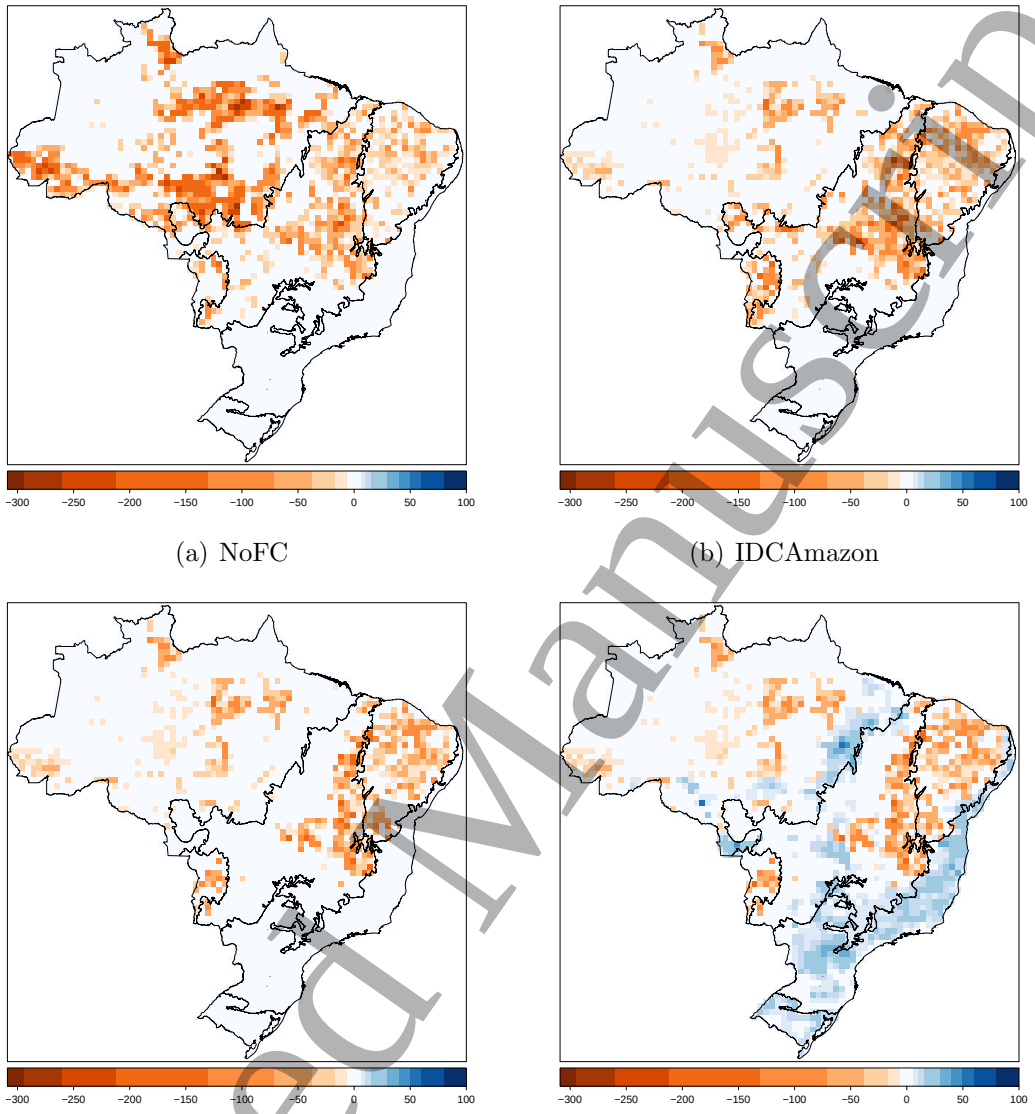
4.2. Evaluating alternative scenarios for the Forest Code

Different Forest Code requirements were investigated by alternative scenarios by incrementally increasing the level of enforcement of key provisions, such as the illegal deforestation control and the obligatory forest restoration. Between 2010 and 2050, the ban on illegal deforestation in the Amazon alone reduces the accumulated deforestation in this biome by 85%, from 46.7 Mha in the NoFC scenario to 7.1 Mha in the IDCAmazon scenario (Figs. 4a and b). This result highlights the importance of the panoply of law enforcement measures implemented by public and private stakeholders in the Amazon region, even before the revised Forest Code was approved. However, when we switch from the NoFC scenario to the IDCAmazon scenario, deforestation increases by 3.1 Mha in the Cerrado biome and 3.8 Mha in the Caatinga biome during the period 2010-2050. These results point to the risk of deforestation leakage into less protected biomes (in terms of LR requirements), such as the Cerrado and the Caatinga, when the law is enforced only in the Amazon [48, 6, 25].

Extending the illegal deforestation control to the entirety of Brazil's territory (IDCBrazil) results in a further accumulated deforestation reduction of 29%, from 34.1 Mha to 24.3 Mha, between 2010 and 2050. This extension is particularly important to avoid leakage effects into the Cerrado biome (Fig. 4c). When the ban on illegal deforestation across Brazil is complemented with the additional provisions of the Forest Code (i.e., the FC scenario), deforestation levels remain approximately the same, but 12.9 Mha of forest are restored (Fig. 4d). It is important to mention that the loss of dry forests in the Caatinga biome accounts for 8.1 Mha between 2010 and 2050 under the FC scenario; of this loss, 64% is due to pasture expansion, and 36% is due to cropland expansion. Due to water availability constraints (the rainy season is short and irregular, and the region is prone to frequent droughts), agricultural expansion in the Caatinga is limited to its historical trends in our simulations.

Although the Forest Code reduces the native vegetation losses in Brazil, it does not prevent 25 Mha of deforestation between 2010 and 2050. This legal conversion is located mostly in areas with large forest surpluses in the Amazon, the Caatinga and the east of Cerrado, where the last undisturbed remnants of this biome are located (Fig. 4d). Approximately 65% of this deforestation allowed by the law is due to pasture expansion, especially in the Amazon biome (Fig. 5a), and 35% is due to cropland expansion, especially in the Cerrado biome within the Matopiba region (Fig. 5b). The adoption of zero supply chain agreements by the private sector, similar to the soy and the cattle moratoria in both the Amazon and the Cerrado biomes, would prevent this legal deforestation.

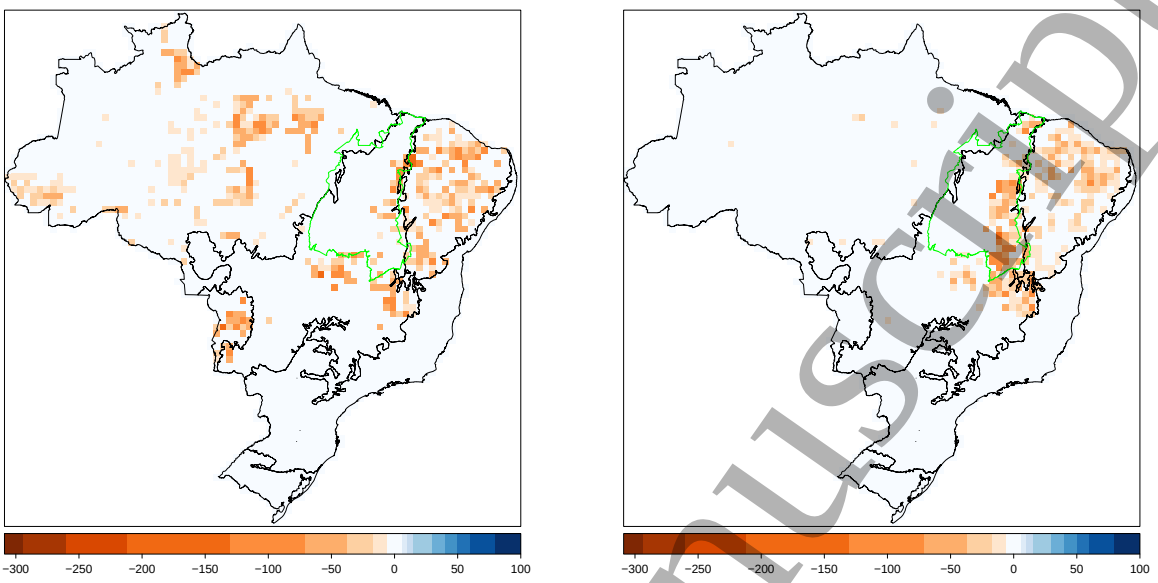
Under the FC scenario, the CRA compensates for approximately 5.8 Mha (Fig. S18) of the



(a) NoFC (b) IDCAmazon

(c) IDCBrazil (d) FC

Figure 4. Spatial distribution of cumulative loss (orange) or gain (blue) of native vegetation for the scenarios (a) NoFC, (b) IDCAmazon, (c) IDCBrazil and (d) FC between 2010 and 2050. Color bar values are expressed in thousands of hectares per cell. Scenario abbreviations: NoFC = no implementation of the Forest Code; IDCAmazon = illegal deforestation control in the Amazon and the Atlantic Forest biomes with no forest restoration; IDCBrazil = illegal deforestation control everywhere in Brazil with no forest restoration; FC = Forest Code fully implemented, i.e. with illegal deforestation control, forest restoration and compensation by the CRA.



(a) Deforestation due to pasture expansion (b) Deforestation due to cropland expansion

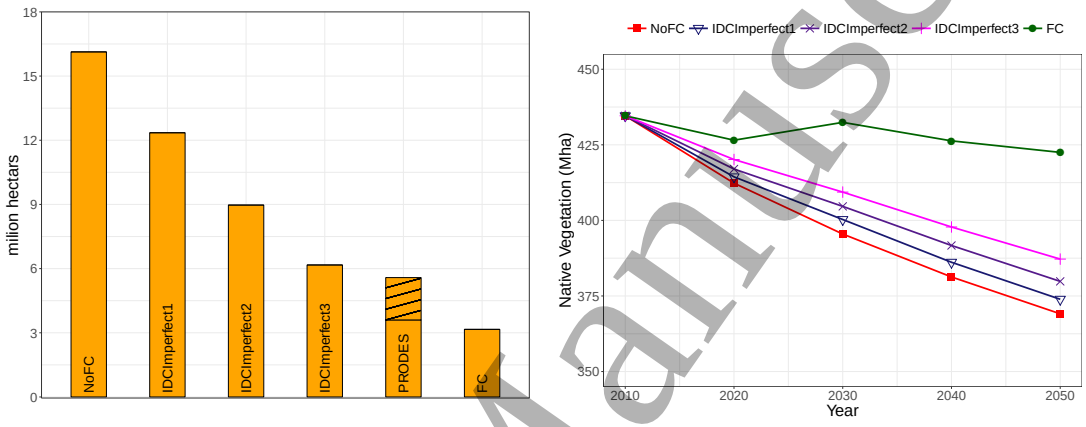
Figure 5. Spatial distribution of accumulated deforestation due to (a) pasture expansion, and (b) cropland expansion as projected by the FC scenario. Matopiba region is highlighted in green. Color bar values are expressed in thousands of hectares per cell.

LR debts, which decreases the area of forest restoration from 18.7 to 12.9 Mha. Our FCnoCRA scenario, where there is no compensation of any environmental debt, restores 18.7 Mha of LR debts (see Fig. S19). However, the FCnoCRA projects an increase of 1.4 Mha of deforestation by 2050 when compared to the FC scenario. This occurs because the quotas protect native vegetation from the legal conversion allowed by the law while keeping the already illegally converted areas in production. This emphasizes that environmental reserve quotas, if well implemented, can play important roles in the conservation of pristine native vegetation remnants. For the agricultural output, because the quotas generally transfer production from one site to another, the impact of the CRA in crop areas and on cattle herds is small and mostly related to productivity gradients within the biomes. The additional 5.8 Mha of forest restoration in the FCnoCRA scenario makes the net forest area of this scenario the highest among all the others, even with the increase in deforestation.

4.3. Evaluating different levels of compliance with the Forest Code

Different levels of compliance with the Forest Code were tested by implementing an imperfect or partial enforcement of the illegal deforestation control (IDCImperfect1, IDCImperfect2 and IDCImperfect3 scenarios). In these scenarios, the maximum amount of illegal deforestation depends on the probability of enforcement: the lower the probability of enforcement, the higher

the maximum amount of illegal deforestation (see SI for more details). Figure 6a shows the accumulated deforestation in the Amazon biome between 2011 and 2020 as projected by the FC, the NoFC and the IDCImperfect scenarios, and as observed by the PRODES/INPE until 2017 added by a constant annual deforestation rate of 0.66 Mha for the years 2018, 2019 and 2020 (hatched part). The value of 0.66 Mha is the annual rate of deforestation estimated by PRODES/INPE in the year 2017. Figure 6b shows the evolution of native vegetation in Brazil across different scenarios for the period 2010-2050.



(a) Amazon (2011-2020) (b) Brazil (2010-2050)

Figure 6. (a) Accumulated deforestation in the Amazon biome between 2011 and 2020; and (b) Native vegetation area evolution in Brazil as projected by the NoFC, FC, IDCImperct1, IDCImperfect2 and IDCImperfect3 scenarios.

The accumulated deforestation in the Amazon biome between 2011 and 2020 for the IDCImperfect scenarios are comprehended between the NoFC and FC (see Fig. 6a). The IDCImperfect3 is the scenario that better represents the historical compliance with the Forest Code, projecting 6.2 Mha of accumulated deforestation between 2011 and 2020. For comparison, linearly extrapolating PRODES/INPE results until 2020 gives 5.6 Mha of accumulated deforestation.

During the period 2011-2050, the IDCImperfect1 scenario reduces 4.8 Mha of accumulated deforestation in Brazil when compared to the NoFC scenario whereas the IDCImperfect2 reduces 10.7 Mha, and the ICDImperfect3 18.1 Mha. The evolution of the native vegetation as shown in Fig. 6b follows the NoFC behavior with no stabilization of the forest stocks. As already observed in the IDCAmazon scenario, any additional control of illegal deforestation in the Amazon causes an increase in the native vegetation loss, or leakage, in the Cerrado biome. Compared to the NoFC scenario, the model projects a leakage in the Cerrado through the period 2011-2050 of 0.43 Mha for the IDCImperfect1, 1.47 Mha for the IDCImperfect2 and 2.19 Mha for the IDCImperfect3 scenario. See Fig. S20 for the spatial distribution of the accumulated deforestation patters of these additional scenarios.

From the production side, increasing the level of illegal deforestation control as in the IDCImperfect scenarios has a positive impact in the process of cattle ranching intensification already observed in the FC scenario. In other words, as shown in Fig. S21, an increasingly enforced Forest Code leads to a reduction in pasture area by 2050 with a very little impact in the number of heads of the Brazilian bovine herd. Compared to the FC scenario, by 2050, cropland area is only reduced by less than 1.5% in the IDCImperfect scenarios.

4.4. LUCF emissions across different scenarios

Figure 7 illustrates Brazil's net emissions (positive and negative) from the LUCF sector between 2010 and 2050 across different 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, the native vegetation restoration. Under the FC scenario, the net emissions decline from 1.19 $PgCO_2e/yr$ in 2010 to 0.16 $PgCO_2e/yr$ in 2030 to 0.06 $PgCO_2e/yr$ in 2050 (see Table S2). When compared to the FC scenario, the FCnoCRA scenario projects a similar but slightly lower net emissions estimate due to the larger amount of native vegetation restoration (i.e., 5.8 Mha more than the FC scenario), which compensates for the increase in deforestation (1.4 Mha).

The IDCImperfect scenarios project a decrease in the LUCF emissions until 2030 followed by a constant emission up to 2050 as can be seen in Fig. 7. This is expected because the IDCImperfect scenarios project a constant average native vegetation loss per decade. Under the IDCImperfect3, the scenario that better represents the historical deforestation in the Amazon biome between 2011 and 2020, the net emissions reduce from 1.19 $PgCO_2e/yr$ in 2010 to 0.51 $PgCO_2e/yr$ in 2030 to 0.50 $PgCO_2e/yr$ in 2050.

Compared to 2010, the reduction in the LUCF emissions by 2030 amounts to 1.03 $PgCO_2e/yr$ under the FC scenario and 0.32 $PgCO_2e/yr$ for the NoFC scenario. Considering the proposed goal of reducing Brazil's GHG emissions from 2.1 $PgCO_2e/yr$ in 2005 to 1.2 $PgCO_2e/yr$ in 2030 (an absolute reduction of 0.9 $PgCO_2e/yr$), we observe that the emissions reduction coming from the LUCF sector and caused by the full enforcement of the Forest Code is key for the country to achieve its NDC commitments. However, if the other sectors increase their emissions compared to the 2005 levels, full enforcement of the Forest Code will not be enough.

5. Discussion and conclusions

Historically, the expansion of cropland and pasture in Brazil has occurred at the expense of pristine native vegetation and the environmental services they provide, including carbon storage and biodiversity conservation. Given the increasing global demand for agricultural products and the competitiveness of Brazilian agricultural production compared to other regions of the world,

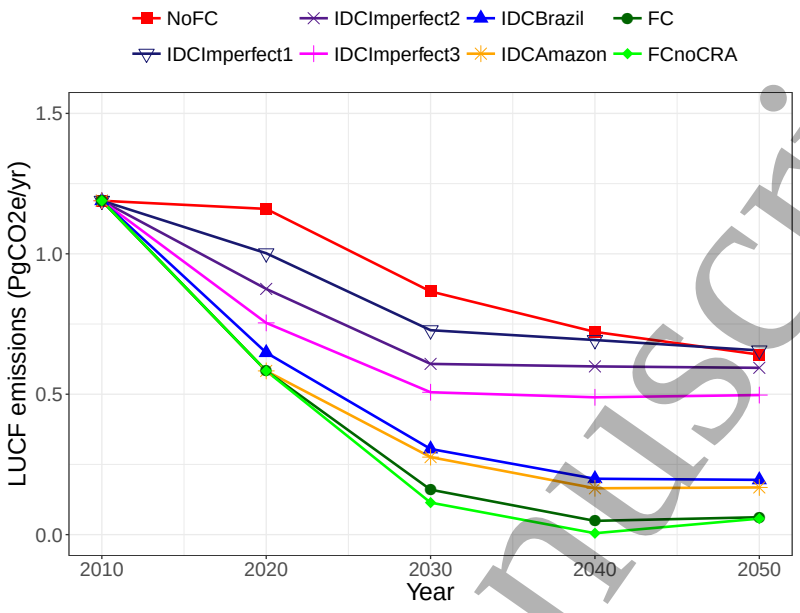


Figure 7. Net emissions per year from the land-use change and forestry (LUCF) sector in Brazil up to 2050 and across different scenarios. Scenario abbreviations: NoFC = no illegal deforestation control except in the Atlantic Forest biome and no forest restoration, i.e., no enforcement of the Forest Code; IDCImperfect1 = partial illegal deforestation control in the Amazon and the Cerrado biomes, full control in the Atlantic Forest biome and no control in the rest of Brazil, and no forest restoration; IDCImperfect2 = partial illegal deforestation control increased by 25% in the Amazon and the Cerrado biomes, full control in the Atlantic Forest biome and no control in the rest of Brazil, and no forest restoration; IDCImperfect3 = partial illegal deforestation control increased by 50% in the Amazon and the Cerrado biomes, full control in the Atlantic Forest biome and no control in the rest of Brazil, and no forest restoration; IDCAmazon = illegal deforestation control in the Amazon and the Atlantic Forest biomes with no forest restoration; IDCBrazil = illegal deforestation control everywhere in Brazil with no forest restoration; FC = Forest Code fully implemented, i.e., illegal deforestation control, forest restoration and CRA; FCnoCRA = FC scenario without the environmental reserve quotas.

our results show that the agricultural sector will continue to grow in Brazil in upcoming decades. We show that Brazil's revised 2012 Forest Code is a key tool for helping to reconcile the conflicting goals of environmental conservation and agricultural production growth. If the Forest Code is not fully implemented and rigorously enforced, which would ensure that the LRs and APPs are preserved and that the native vegetation areas that have been illegally deforested are restored or compensated, deforestation will rapidly increase, especially in the Amazon, with meager economic gains. An imperfect enforcement of the illegal deforestation control based on historical Forest Code compliance levels, as in the IDCImperfect1 scenario, prevents only 4.8 Mha of native vegetation loss in Brazil when compared to the NoFC scenario. Increasing the probability of enforcement in the Amazon and the Cerrado biomes (IDCImperfect3 scenario), the avoided native vegetation loss jumps to 18.1 Mha, which points to the importance of increasing the budget of the IBAMA

(Brazilian Institute of the Environment and Renewable Natural Resources) to expand command-and-control actions in these regions. If illegal deforestation is controlled only in the Amazon biome, our results show leakage to the other biomes i.e., a 3 Mha increase in native vegetation conversion in the Cerrado biome and a 3.8 Mha increase in conversion in the Caatinga biome between 2010-2050. Finally, full enforcement of the Forest Code could lead to 12.9 Mha of restored area.

In the Amazon, due to its huge size, complex land tenure structure and continuous expansion of cattle ranching, the projected decrease in deforestation remains vulnerable. A comparison between the NoFC and the FC scenarios shows that, between 2010 to 2050, cumulative deforestation in the Amazon could increase by almost 40 Mha if the fight against illegal deforestation is not stopped. The recent spike in the Amazon's deforestation rate demonstrates that pressure remains high despite the private sector's zero deforestation agreements, which are similar to the soy moratorium, and even with the current governmental presence, illegal deforestation occurs. The removal or reduction of that enforcement effort would likely result in greater forest losses. In terms of emissions, the average deforestation rate per decade of 6.3 Mha in the Amazon in the future without forest restoration, as projected by the IDCImperfect3, will project a reduction in the LUCF emissions by 2030 of 0.68 $PgCO_2e/yr$ compared to 2010, 66% of the projected emissions reduction (1.03 $PgCO_2e/yr$) for the FC scenario. These results highlight the importance of a rigorously enforced Forest Code for Brazil to achieve its international goals of emissions reduction.

As part of the NDC submitted for the COP Paris 2015, Brazil pledged to restore 12 Mha of forests by 2020, which is comparable with the 12.9 Mha of restored area in our simulations. Our study does not address how to achieve this restoration. We assume passive restoration in our simulations, but in reality, restoration might need some investments to work. A recent publication suggests that in Minas Gerais state, only 36% of the deficits could be restored using passive restoration and that the restoration of the highly degraded areas would more than double the restoration costs [49]. The cost of restoration and the lack of technical know-how might be a real challenge for poor farmers. In the Atlantic Forest biome, since 2000, many environmental NGOs have been willing to compensate part or all of the restoration costs; however, their lack of enforcement did not give farmers clear incentives to comply with the law [50].

Primary forests have a higher biodiversity value and carbon stocks than areas of regrowth, as it can take up to 300 years for biodiversity to be restored when a forest regenerates [51]. Therefore, the implementation of quotas has important implications on biodiversity, especially in the Cerrado, which is a biodiversity hotspot. Depending on how the CRA market is going to work (which has yet to be decided by a complementary law to be voted on by the Parliament), it could either protect and conserve environmentally important areas, rewarding law-abiding landowners, or simply legalize illegally deforested areas in exchange for low-conservation value areas [52]. The title price must be profitable for both creditors and debtors to avoid leakages and speculation. Moreover, farmers need to be informed about the existence and the functioning of this mechanism [53]. It is important that the quota market is quickly regulated because important areas in terms of conservation purposes may disappear if this measure takes too long to be implemented.

In the past, in many parts of Brazil, there has been a widespread sentiment among rural producers that the old Forest Code was unrealistically restrictive, providing insufficiently convincing reasons to comply with it [27]. Here, we show that, although Brazil's 2012 Forest Code is not perfect, there are both economic and environmental benefits for producers and other stakeholders to support it. On the economic side, the enforcement of the Forest Code accelerates agricultural intensification, and the small reduction in overall production might be compensated by higher market prices. The near completion of the rural Environmental Cadastre (CAR) is crucial but is not sufficient to guarantee the enforcement of the Forest Code. In addition, there must be political will and resources in the federal government to cross-check the information of the CAR, to carefully monitor the implementation of the law, and to rigorously enforce its application across the entire country. If Brazil succeeds in this endeavor, there will be multiple benefits for its citizens, and it will establish a useful model for other developing countries facing similar challenges.

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6. References

[1] Allen E and Valdes C 2016 Brazil's corn industry and the effect on the seasonal pattern of U.S. corn exports Tech. rep. USDA

[2] Meade B, Puricelli E, McBride W, Valdes C, Hoffman L, Foreman L and Dohlman E 2016 Corn and soybean production costs and export competitiveness in Argentina, Brazil, and the United States Tech. rep. USDA

[3] Rada N and Valdes C 2012 Policy, technology, and efficiency of Brazilian agriculture Tech. rep. USDA

[4] Pereira P, Martha-Jr G, Santana C and Alves E 2012 The development of Brazilian agriculture: future technological challenges and opportunities Agriculture and Food Security **1** 1–12

[5] Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: The 2012 revision Tech. rep. Food Agriculture Organization Rome

[6] Lapola D, Martinelli L, Peres C, Ometto J, Ferreira M, Nobre C, Aguiar A, Bustamante M, Cardoso M, Costa M, Joly C, Leite C, Moutinho P, Sampaio G, Strassburg B and Vieira I 2013 Pervasive transition of the Brazilian land-use system Nat Clim Change **4** 27–35

[7] Lambin E, Gibbs H, Ferreira L, Grau R, Mayaux P, Meyfroidt P, Morton D, Rudel T, Gasparri I and Munger J 2013 Estimating the world's potentially available cropland using a bottom-up approach Glob Environ Change **23**(5) 892–901

[8] Martini D, Moreira M, Cruz L, Formaggio A and Dalla-Nora E 2015 Potential land availability for agricultural expansion in the Brazilian Amazon Land Use Policy **49** 35–42

[9] PRODES PRODES - Amazon deforestation database `http://www.obt.inpe.br/prodes` accessed: 12 Aug 2016

[10] Soares-Filho B, Nepstad D, Curran L, Cerqueira G, Garcia R, Ramos C, Voll E, McDonald A, Lefebvre P and Schlesinger P 2006 Modelling conservation in the Amazon basin Nature **440** 520–523
[11] Macedo M, DeFries R, Morton D, Stickler C, Galford G and Shimabukuro Y 2012 Decoupling of deforestation and soy production in the southern Amazon during the late 2000s Proc Natl Acad Sci **109**(4) 1341–1346
[12] Nepstad D, McGrath D, Stickler C, Alencar A, Azevedo A, Swette B, Bezerra T, DiGiano M, Shimada J, Motta R, Armijo E, Castello L, Brando P, Hansen M, McGrath-Horn M, O C and Hess L 2014 Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains Science **344**(188) 1118–1123
[13] Gibbs H, Rausch L, Munger J, Schelly I, Morton D, Noojipady P, Soares-Filho B, Barreto P, L M and Walker N 2015 Brazil's soy moratorium Science **347**(6220) 377–378
[14] Boucher D, Elias P, Faires J and Smith S 2014 Deforestation success stories: Tropical nations where forest protection and reforestation policies have worked Tech. rep. Union of Concerned Scientists
[15] MCTI 2014 Estimativas anuais de emissões de gases de efeito estufa no Brasil Tech. rep. Brazilian Ministry of Science and Technology, Brasília
[16] Walker R, Moore N, Arima E, Perz S, Simmons C, Caldas M, Vergara D and Bohrer C 2009 Protecting the Amazon with protected areas Proc. Natl. Acad. Sci. USA **106**(26) 10582–10586
[17] Gibbs H, Munger J, L'Roe J, Barreto P, Pereira R, Christie M, Amaral T and Walker N 2015 Did ranchers and slaughterhouses respond to zero-deforestation agreements in the Brazilian Amazon? Conservation Letters
[18] Assunção J, Gandour C, Rocha R and R R 2013 Does credit affect deforestation? Evidence from a rural credit policy in the Brazilian Amazon Tech. rep. Climate Policy Initiative
[19] MMA 2013 Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (ppcdam): 3a fase (2012-2015) Tech. rep. Brazilian Ministry of Environment, Brasília
[20] MMA 2013 Brazil's submission of a forest reference emission level for deforestation in the Amazonia biome for results-based payment for REDD+ under the UNFCCC Tech. rep. Brazilian Ministry of Environment, Brasília
[21] 2015 Tree cheers: the world must follow Brazil's lead and do more to protect and restore forests Nature Publishing Group
[22] Börner J, Wunder S, Wertz-Kanounnikoff S, Hyman G and Nascimento N 2014 Forest law enforcement in the Brazilian Amazon: Costs and income effects Glob Environ Change **29** 294–305
[23] Brazil Intended Nationally Determined Contribution: towards achieving the objective of the United Nations Framework Convention on Climate Change Tech. rep. Federal Government of Brazil
[24] MDA 2011 Estatísticas do meio rural 2010-2011 Tech. rep. Brazilian Ministry of Agrarian Development, Brasília
[25] Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H and Alencar A 2014 Cracking Brazil's Forest Code Science **344**(6182) 363–364
[26] Stickler C, Nepstad D, Azevedo A and McGrath D 2013 Defending public interests in private lands: compliance, costs and potential environmental consequences of the Brazilian Forest Code in Mato Grosso Phil. Trans. Royal Society **368** 20120160
[27] May P, Bernasconi P, Wunder S and Lubowski R 2015 Environmental reserve quotas in Brazil's new forest legislation: an ex ante appraisal Tech. rep. CIFOR Occasional Paper Bogor, Indonesia
[28] Havlik P, Schneider U, Schmid E, Bottcher H, Fritz S, Skalsky R, Aoki K, De Cara S, Kindermann G, Kraxner F, Leduc S, McCallum I, Mosnier A, Sauer T and Obersteiner M 2011 Global land-use implications of first and second generation biofuel targets Energy Policy **39**(10) 5690–5702
[29] Havlik P, Valin H, Mosnier A, Obersteiner M et al. 2014 Climate change mitigation through livestock system transitions Proc. Natl. Acad. Sci. USA **111**(10) 3709–14
[30] Cohn A, Mosnier A, Havlik P, Valin H et al. 2014 Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation Proc. Natl. Acad. Sci. USA **111**(20) 7236–7241
[31] Camara G, Soterroni A, Ramos F, Carvalho A, Andrade P, Souza R, Mosnier A, Mant R, Buurman M, Pena M, Havlík P, Pirker J, Kraxner F, Obersteiner O, Kapos V, Affonso A, Espíndola G and Bocqueho G 2012

Modelling land use change in Brazil: 2000–2050 Tech. rep. INPE/São José dos Campos, IPEA/Brasília, IIASA/Laxenburg, UNEP-WCMC/Cambridge

[32] Laurance W, Cochrane M, Bergen S, Fearnside P, Delamônica P, Barber C, D'Angelo S and Fernandes T 2001 The future of the Brazilian Amazon Science **291**(5503) 438–439

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

[34] Aguiar A, Ometto J, Nobre C, Lapola D, Almeida C, Vieira I, Soares J, Alvala R, Saatchi S, Valeriano D et al. 2012 Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon Glob. Chang. Biol. **18**(11) 3346–3366

[35] Sparovek G, Berndes G, Barretto A and Klug I 2012 The revision of the Brazilian Forest Act: increased deforestation or a historic step towards balancing agricultural development and nature conservation Environ Sci Policy **16** 65–72

[36] Garret R, Lambin E and Naylor R 2013 Land institutions and supply chain configurations as determinants of soybean planted area and yields in brazil Land Use Policy **31** 385–396

[37] Strassburg B, Latawiec A, Barioni L, Nobre C, Silva J VP Valentim, Vianna M and Assad E 2014 When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil Glob Environ Chang **28** 84–97

[38] MMA 2017 Cadastro ambiental rural: Boletim informativo Tech. rep. Ministério do Meio Ambiente, Brasil

[39] Guidotti V, Freitas F, Sparovek G, Pinto L, Hamamura C, Carvalho T and Cerignoni F 2017 Números detalhados do novo código florestal e suas implicações para os pras Tech. rep. IMAFLORA

[40] O'Neill B, Kriegler E, Riahi K, Ebi K and Hallegatte S 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways Climate Change **122**(3) 387–400

[41] Williams J 1995 The EPIC model. Computer models of watershed hydrology Tech. rep. Water Resources Publications Highlands Ranch, CO

[42] Herrero M, Havlik P, Valin H, Notenbaert A, Rufino M, Thornton P et al. 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems Proc. Natl. Acad. Sci. USA **110**(52) 20888–93

[43] Herrero M, Thornton P, Kruska R and Reid R 2008 Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030 Agric Ecosyst Environ **126**(1) 122–137

[44] Soares-Filho B, Rajão R, Merry F, Rodrigues H, Davis J, Lima L, Macedo M, Coe M, Carneiro A and Santiago L 2016 Brazil's market for trading forest certificates PlosOne **11(4)** 1–17

[45] MCTI 2017 Estimativas anuais de emissões de gases de efeito estufa no brasil Tech. rep. Brazilian Ministry of Science and Technology, Brasília

[46] Ruesch A and Gibbs H 2008 New IPCC tier-1 global biomass carbon map for the year 2000

[47] Arima E, Barreto P, Araujo E and Soares-Filho B 2014 Public policies can reduce tropical deforestation: Lessons and challenges from brazil Land Use Policy **41** 465–473

[48] Sparovek G, Berndes G, Klug I and Barretto A 2010 Brazilian agriculture and environmental legislation: status and future challenges Environ Sci Technol **44**(16) 6046—-53

[49] Nunes F, Soares-Filho B, Rajão R and Merry F 2017 Enabling large-scale forest restoration in minas gerais state Environ. Res. Lett. **12** 044022

[50] Pinto S, Melo F, Tabarelli M, Padovesi A, Mesquita C, Scaramuzza C, Castro P, Carrascosa H, Calmon M, Rodrigues R, Cesar R and Brancalion P 2014 Governing and delivering a biome-wide restoration initiative: the case of Atlantic Forest Restoration Pact in Brazil Forests **5** 2212–2229

[51] Liebsch D, Marques M and Goldenberg R 2008 How long does the Atlantic Rain Forest take to recover after a disturbance? changes in species composition and ecological features during secondary succession Biol. Conserv. **141** 1717–1725

[52] Rajão R and Soares-Filho B 2015 Policies undermine brazil's ghg goals Science **350**(6260) 519–a

[53] Rasmussen L, Jung S, Brites A, Watkins C and Agrawal A 2017 Understanding smallholders' intended

deforestation behavior in the Brazilian Cerrado following environmental registry Environ. Res. Lett. **12** 094001