





Slow-down of deforestation following a Brazilian forest policy was less effective on private lands than in all conservation areas

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Private lands are important for conservation worldwide, but knowledge about their effectiveness is still insufficient. To help fill this important knowledge gap, we analyzed the impacts of a national policy for conservation on private lands in Brazil, a global biodiversity hotspot with high potential for nature-based climate solutions. Through the evaluation of over 4 million private rural properties from the Rural Environmental Cadastre, we found that the last policy review in 2012 mainly affected the Amazon Forest. The amnesty granted to 80% of landowners of small properties prevented the restoration of 14.6 million hectares of agricultural land with a carbon sequestration potential of 2.4 gigatonnes. We found that private lands exist within the limits of public conservation areas and that between 2003 and 2020 deforestation rates in these private lands were higher than those across all conservation areas. The Rural Environmental Cadastre can be an effective tool for managing forests within private lands, with potential to integrate governance approaches to control deforestation and mitigate climate change.

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The world continues to experience rapid environmental degradation¹. In this context, private lands are important for the conservation of biodiversity and carbon stocks worldwide^{2–6}. The role of private lands for conservation is an emerging topic of environmental governance, sometimes addressed by livelihood, voluntary stewardship and economic incentives, and more often by policy instruments—e.g., conservation easements³. Previous studies have noted that conservation actions encounter a major challenge when targeting private lands, and suggest that complementary efforts (e.g., programs of payment for ecosystem services) may increase landowners' engagement⁷. A limited number of studies have assessed conservation efforts in private lands in tropical regions using multiple approaches and across local to national scales. Such studies have evaluated the impacts of different land tenure regimes on deforestation⁸, have performed systems modeling to assess the effects of environmental policy changes⁹, assessed the effectiveness of sustainable supply chain agreements for forest conservation¹⁰, or analyzed non-governmental mechanisms (e.g., financial mechanisms) to engage landowners in conservation strategies¹¹. Yet, it is still unclear how effective private lands in global conservation efforts^{2,4,12–14}. In this study we create additional knowledge by providing a large-scale analysis of the impacts of a national conservation policy on private lands located in crucial biodiversity hotspots of Brazil. Our study advances on previous studies by integrating self-declared land ownership and conservation data from landowners, which improve the assessment of policy compliance and conservation beyond what can be learned from satellite remotely sensed data alone¹⁵.

Brazil is home to the largest tropical forest areas worldwide¹⁶, including key hotspots of biodiversity such as the Atlantic Forest¹⁷. At the same time, the country has demonstrated political will to govern natural vegetation areas within private properties since the 1930s¹⁸. This enterprise, although not entirely successful, has been modernized over time to meet the standards set by both, domestic and international players^{19,20}. The latest review of the Native Vegetation Protection Law in Brazil (hereafter “Forest Code”) in 2012 (Law 12651/2012), fostered a large participatory process by different groups of stakeholders, towards achieving a common agreement on the legal norms to be defined by the “New Forest Code” (NFC) of 2012^{20–23}. The NFC created an instrument named “Cadastro Ambiental Rural” (CAR—Rural Environmental Cadastre), to obtain environmental information about private rural properties to facilitate environmental monitoring (e.g., deforestation), improve land management, and to foster the NFC compliance of landowners^{18,24}. This constituted a first attempt to create a national record of all private rural properties in the country, with the potential of fostering sustainable development in the Brazilian rural sector. However, the NFC granted “amnesty” for millions of hectares impacted by prior illegal deforestation activities and there are still uncertainties influencing land use in Brazil²⁵.

Through CAR, the NFC obliges all private rural landowners to self-declare their property boundaries, along with the location of their production areas and designated areas of protected natural vegetation [i.e., areas for sustainable use where no land clearing is allowed, known as legal reserves (LR), and permanent preservation areas (PPA)^{26–28}]. Landowners provide this self-declared information by creating polygons in a geo-web tool²⁹. The large areal extent and number of private landowners in Brazil have resulted in a correspondingly large dataset; over 6 million polygons detailing private properties are included in the latest version of CAR. This self-declared dataset provides valuable information on land ownership, land use and conservation, beyond what could be obtained from satellite data alone^{30–32}. However, because landowners independently upload the files into the system by drawing polygons on satellite imagery using their own

knowledge, or importing coordinates obtained using Global Positioning System receivers, there is a high potential for mis-specification of property boundaries, resulting in spatial overlaps of property polygons²⁸.

Since 2012 when the NFC posited changes, Brazil has gone through different political and economic cycles, with agribusinesses playing an important role not only on the national economy but also on its policies^{22,33,34}, thus influencing land change dynamics³⁵. Furthermore, the period since 2012 has also been characterized by a strong pressure to enact additional changes to the NFC³⁶, mainly by representatives of the agribusiness sector (private and public actors), such as removing the requirement for legal reserves²³. Since Brazil is a signatory of international agreements for forest conservation and climate change mitigation^{37,38}—two dimensions that are managed at the national level but with global implications because Brazilian deforestation affects the global climate³⁷—it is crucial to evaluate the effectiveness of the 2012 NFC over its first decade of implementation.

In this study we address two main questions: (1) Has the implementation of the NFC (and the CAR) allowed Brazil to reach the national Forest Code's aim of reducing the loss (and even enhance the recovery) of natural vegetation on private rural lands? (2) What are the overall effects of the NFC implementation on carbon sequestration? Through the use of the self-declared data provided by landowners (property boundaries, LR, and PPA), this study goes beyond prior analyses of land-use and land-cover (LULC) changes and carbon stocks under the NFC^{25,26,28,36,39–41}. This study advances the understanding of conservation in private lands by: (i) estimating impacts (individual and combined effects) on carbon and natural vegetation cover according to different legal *Articles* brought by the NFC; (ii) quantitatively confronting results from previous studies to make evident uncertainties inherent to handling big data through modeling and analytical approaches⁴¹; (iii) showing how imprecisions in self-declared data may lead to large overlapping areas between private lands and protected areas (i.e., indigenous territories and conservation units); and (iv) providing a suite of quantitative validation methods to deal with such a large dataset as the CAR. This is particularly important and timely given the increasing pressure in Brazil to produce more soybeans and beef in private lands for both international and domestic markets^{42–44}. In this study we refer to any kind of natural vegetation (i.e., forest, savanna, and natural grasslands) loss as “deforestation.” We argue that the CAR under the NFC may help with the development of effective governance systems to manage natural vegetation and drive carbon-based solutions to cope with climate change.

Results

Private rural properties and natural vegetation cover dynamics.

Based on the CAR data, we found a total of 4,347,256 private rural properties within the Amazon, Atlantic Forest, and Cerrado biomes. Small rural properties represent 91% (3,965,448) while 9% (381,808) are considered medium/large properties [rural property size group is defined by the number of fiscal modules (FM) with small properties intended to represent “family farming” units (see complete definitions in “Methods”)]. A total of 176 Mha of natural vegetation cover (derived from the Map-Biomass v.6.0 dataset—<https://mapbiomas.org/>) was found to be located within rural private properties in 2020, with 87.3 Mha (50%), 22.9 Mha (13%), and 65.6 Mha (37%) located in the Amazon, Atlantic Forest, and Cerrado biomes, respectively. In the Amazon, natural vegetation cover within private rural properties composed 25% of the total natural vegetation cover in the biome (Fig. 1a). This proportion is higher in the Cerrado (63.6%) and the highest in the Atlantic Forest (68.7%) (Fig. 1b, c).

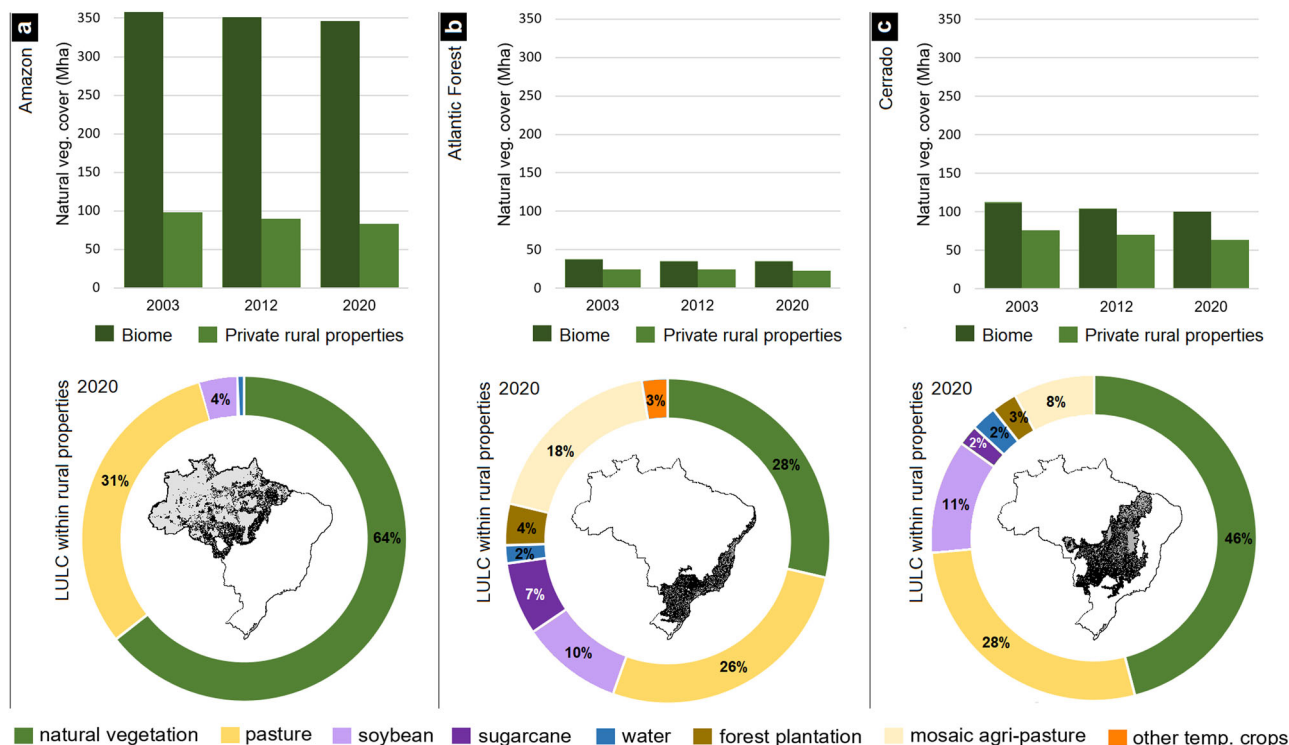


Fig. 1 Natural vegetation cover through time, and land use and land cover within private rural properties in 2020. **a** Amazon biome; **b** Atlantic Forest biome; **c** Cerrado biome. In the upper panels the bar charts indicate the total natural vegetation cover at the biome level (darker shade) and the relative area within rural private properties (lighter shade); In the lower panels the doughnut charts show the proportion of LULC found in rural private properties in the three biomes analyzed (colors are for land use/cover shown in the legend below the doughnuts).

With the exception of the Atlantic Forest in the 2003–2012 period, along the two time periods examined (2003–2012 and 2012–2020), natural vegetation cover declined at the biome level, with the largest percentage decreases observed in the Cerrado [5.1% (5.8 Mha) and 4.3% (4.6 Mha) in the two periods, respectively]. However, the Amazon biome exhibited the greatest total area of deforestation in both periods [9.2 Mha (2.5%) and 6.3 Mha (1.8%), respectively]. Although natural vegetation cover loss continued in the Amazon and Cerrado biomes (Fig. 1a, c), a reduction in the deforestation amount was observed in the 2012–2020 period. In contrast, in the latter period, the Atlantic Forest exhibited the lowest deforestation rate (0.5%–0.19 Mha, Fig. 1b). Within private properties, the average rates of deforestation were higher than observed at biome level. For instance, the Amazon’s private lands exhibited deforestation rates of 7.1% (6.9 Mha) and 3.9% (3.6 Mha) in the 2003–2012 and 2012–2020 periods, indicating that 72% of the biome’s deforestation in 2003–2012 was within private properties, declining to 53% in 2012–2020. The Cerrado’s private lands exhibited a total deforestation of 6.6% (4.9 Mha) and 5.4% (3.7 Mha) in the first and second periods, respectively, corresponding to 84% in 2003–2012 of total deforestation at biome level, and 99% in 2012–2020. A similar trend was observed in the Atlantic Forest, with 70% and 99%, respectively, which indicates that natural vegetation in private lands, in all three biomes, is under greater pressure compared to public lands (including conservation units and indigenous territories). The decline in deforestation rates between 2003–2012 and 2012–2020 was significant in private rural properties in the Amazon biome (*Wilcoxon test*, $p < 0.01$, $n = 703,817$) but not in the Cerrado (*Wilcoxon test*, $p = 1$, $n = 1,039,715$).

With respect to land use, pasture represents the largest class in private rural properties, while soybean constitutes the main crop

(Fig. 1a–c). In the Cerrado, 87% of the total soybean production comes from medium/large properties, along with 93% of citrus, 83% of rice, and 93% of forest plantations (Supplementary Table 1). For the Atlantic Forest biome, the areal distribution of pasture and soybean production is more balanced among property sizes. Sugarcane, citrus, and forest plantations are mainly produced on medium/large properties (78%, 88%, 74%, respectively), while the areas under rice and coffee are highly concentrated on small farms [78% and 64%, respectively (Supplementary Table 1)]. In the Amazon, pasture exhibits a more balanced distribution (45% and 55% for small and medium/large rural properties, respectively), while 80% of soybean, the most important crop, is planted in medium/large rural properties (Supplementary Table 1). A total of 52 Mha was found to be located in overlapping (i.e., superimposed boundaries of different private rural properties) areas among rural properties (see more details in Supplementary Notes 1 and Supplementary Fig. 1).

Given the large dataset analyzed in this study, we developed two additional analyses for validation purposes and applied them to the Amazon biome (see Methods). First, a stratified random sample of 188,304 (26% of the total) private properties (178,666 small, 9,638 medium/large) was selected to verify the degree of overlapping among rural properties. The full dataset on the Amazon indicated 17% overlap while our validation sample found 16%. Second, we used a random sample comprising 10% of the small and of the medium/large properties, respectively, to evaluate deforestation trends. While in the full Amazon dataset we observed 7.1% and 3.9% deforestation in the periods 2003–2012 and 2012–2020, respectively, in the samples comprising 10% of the properties we found 7.2% and 4.1%, respectively. In addition, from the MapBiomas data, the natural vegetation cover for 2020 at the biome level (considering the same classes used in our study—see “Methods”) was 347 Mha in the Amazon,

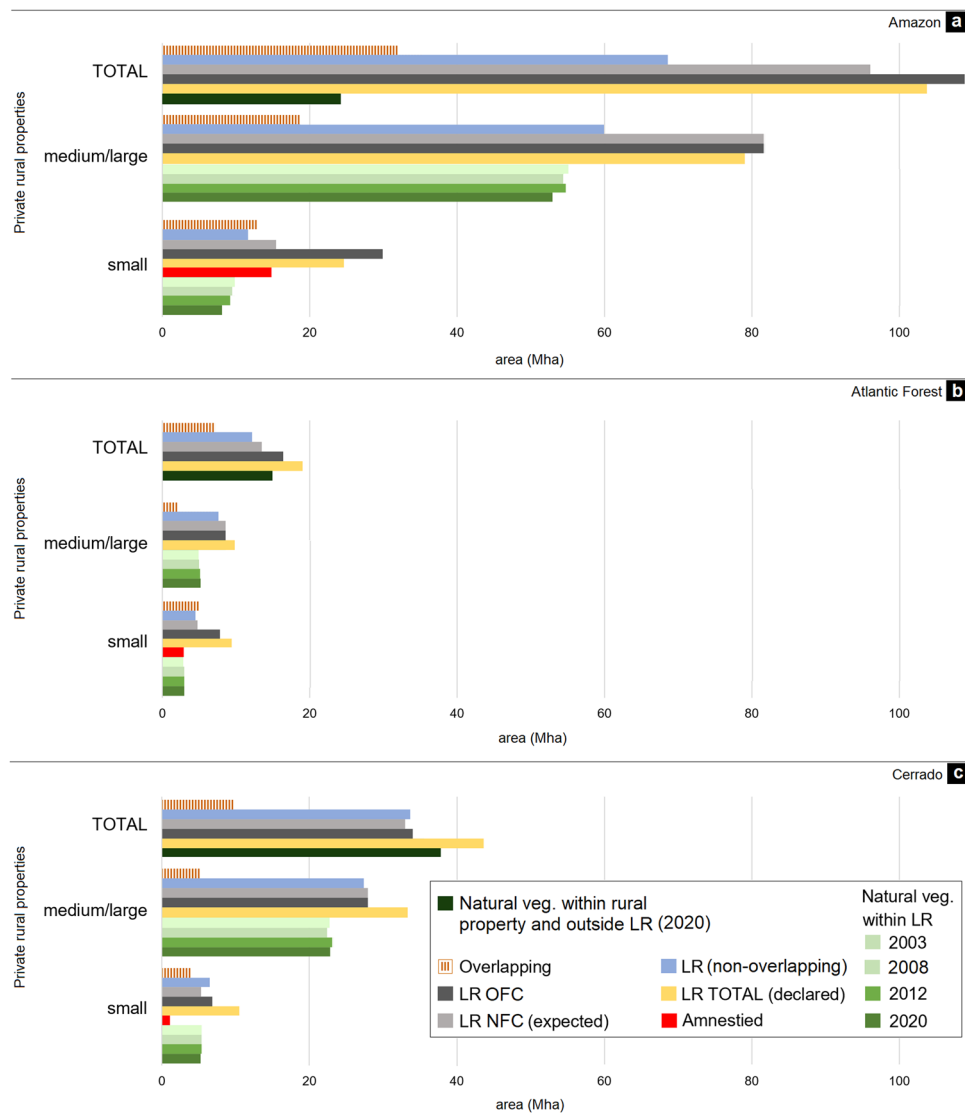


Fig. 2 Legal reserves (LR) within private rural properties and LR area according to the New Forest Code of 2012 and the old Forest Code of 1965. **a** Amazon biome; **b** Atlantic Forest biome; **c** Cerrado biome. The horizontal bars depict different situations with regards to the area required to be protected as LR between the old Forest Code (LR OFC) and in the New Forest Code of 2012 (LR NFC). Also depicted is the area declared by landowners (LR TOTAL), the overlapping areas among LR (Overlapping), the current area under LR within the rural properties without overlapping (LR), and the area released from the obligation to be recovered, i.e., expected by the old Code but spared in the new one (Amnestied). Natural vegetation cover is presented according to the rural properties' group size (i.e., small and medium/large), for 2003, 2012, and 2020. The data presented in Fig. 2 is provided in supplementary information (Supplementary Table 2). The calculations consider legal Articles 12 (without implementing potential flexibilities for LR in Amazon) and 67 (which institutes the “tolerant” regime) of the NFC (see in “Methods”).

32.7 Mha in the Atlantic Forest, and 99.6 Mha in the Cerrado. From our calculations (considering the biome level), we have found 345 Mha, 33.4 Mha, and 103.1 Mha, respectively. These results denote the consistency in our methods to analyze such a large dataset.

Legal reserves and impacts of the NFC on carbon stocks. In cases where the minimum area to be declared as LR by a private property does not match what was included (declared) in the CAR system, we define this as an “LR deficit” (i.e., minimum area required by the legislation in relation to the area self-declared by landowners). In the Amazon biome, where a total LR deficit of 25.5 Mha was found (22 Mha of which was in medium/large rural properties), 2020 LULC data indicate that 27% (23.7 Mha) of native vegetation within rural private properties are found on land not declared as LR, while 12% of declared LR is not covered

by natural vegetation (Fig. 2a). The LR deficit in small rural properties was calculated based on the 2008 natural vegetation cover (see Methods). Although the Cerrado biome exhibits a lower LR deficit (0.4 Mha), 19% of LR is not covered by natural vegetation (Fig. 2c), while less than half of the total natural vegetation within rural properties in this biome is found on land declared as LR (44%). The Atlantic Forest has a LR deficit of 1.3 Mha (Fig. 2b) and exhibits a lower natural vegetation cover within the areas declared as LR (68%). Additionally, the natural vegetation within LR in the Atlantic Forest in 2020 corresponded to 36% of that class in rural private properties. Deforestation was observed within LR in the Amazon and Cerrado biomes. In the Cerrado, this process accounted for 7.5% of the deforestation on private lands in 2012–2020, while in the Amazon it accounted for 54%. In the Atlantic Forest, natural vegetation in LR increased 4% in 2003–2012 and 1% in 2012–2020.

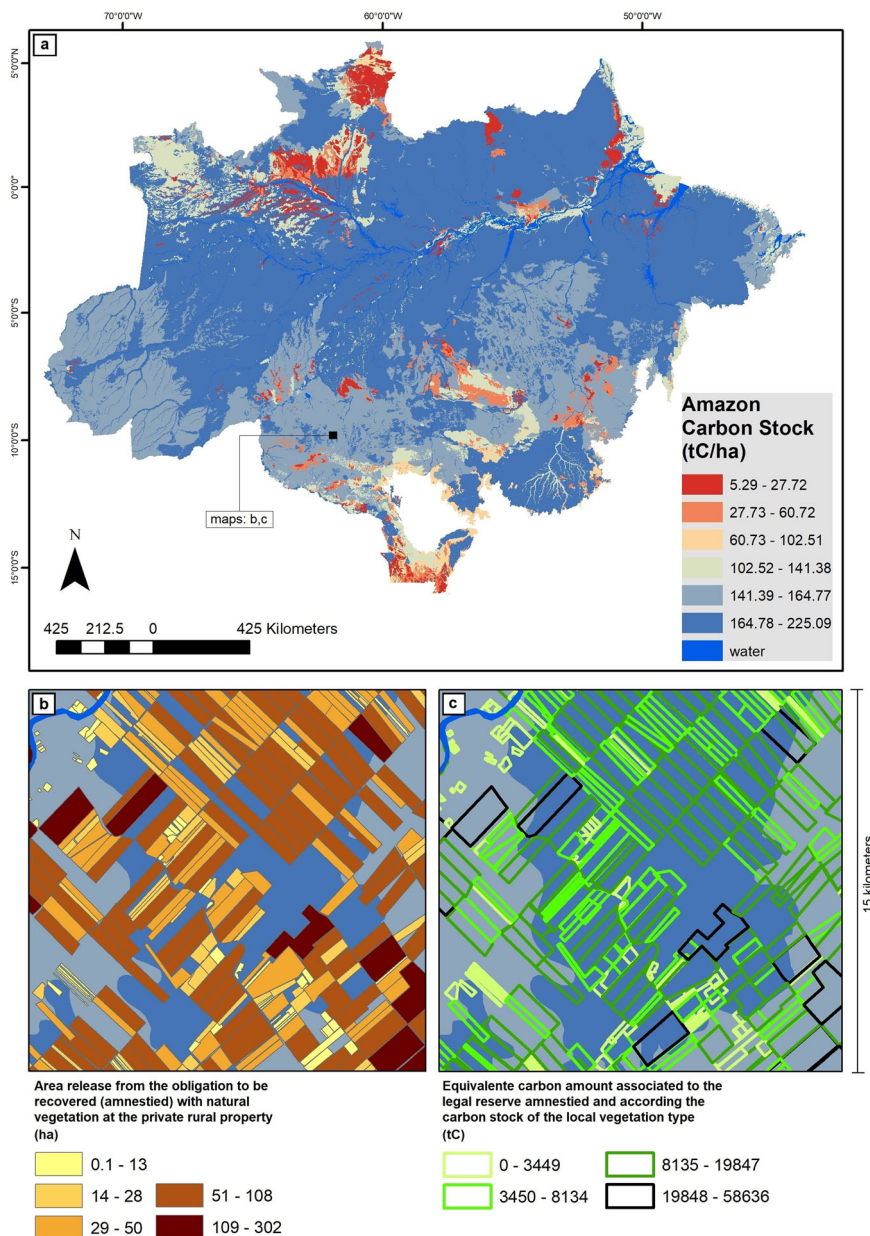


Fig. 3 Spatial distribution of small private rural properties and reference values for carbon stocks according to natural vegetation types in the Amazon biome. **a** The Amazon biome map shows the carbon stocks (tC/ha—i.e., total carbon stock: above- and below-ground, litter, and dead wood) per vegetation type that naturally occurs across the region [see “Methods” for a description of the procedures used]; **b** the polygons represent small rural properties in the Amazon and the colors of each polygon indicate the area (ha) that the property was in LR deficit but amnestied; **c** the colors of each polygon (i.e., private property) represent the equivalent amount of carbon that would be potentially stored in natural vegetation cover if it was recovered. Color slices in these maps were created using Natural Breaks (Jenks).

Based on the previous 1965 Forest Code, when the NFC was introduced in 2012 many “small” private property owners would have found themselves with insufficient natural vegetation on their land to meet the new requirements for legal reserves. Due to the political influence of the agribusiness sector during the Forest Code’s review, small property owners in this legal debt were granted an amnesty such that they were not obliged to recover natural vegetation (from productive land) for LR. We found that 511,658 private properties (80% of small properties) were amnestied in the Amazon biome, corresponding to a total of 14.6 Mha (Fig. 2a), with an average of 30 ± 35 ha per private property. In the Atlantic Forest 1,451,321 private properties (59% of small properties) were amnestied, sparing these landowners from the obligation to recover 3 Mha of natural

vegetation (with an average of 2 ± 20 ha per rural private property). The Cerrado was the biome least affected by the NFC in this regard, with 241,271 rural properties (27% of small properties) amnestied, totaling 1 Mha of natural vegetation released from the obligation to be recovered (with an average of 5 ± 9 ha per rural property).

In the Amazon, the potential carbon stock that could have been held in natural vegetation (including above- and below-ground, litter, and dead wood) had landowners not been amnestied, was 2.4 Gt of carbon (Fig. 3a–c). For the Atlantic Forest biome this stock was found to be 341 Mt of carbon, and only 76 Mt for the Cerrado biome (Supplementary Fig. 2 and Fig. 3). Despite the negative impacts on carbon stocks given the NFC amnesty, we estimate that the decelerated deforestation trends between the

periods 2003–2012 and 2012–2020 within private properties in the Amazon (less 3.2 Mha compared to previous period) and Cerrado (1.1 Mha) biomes, prevented the release of at least 601 Mt of carbon to the atmosphere (using weighted average carbon stocks at the biome level—171.39 tC/ha Amazon, 109.9 tC/ha Atlantic Forest, and 47.77 tC/ha Cerrado).

Considering the potential implementation of *Article 12* § 4⁰ of the NFC (the private properties eligible to reduce LR obligations from 80% to 50% of its area—see “Methods”), the LR deficit in the Amazon biome would be reduced by 32%, from 25.5 Mha to 17.1 Mha (in Supplementary Notes 2 we provide additional data—see Potential Impacts of *Article 12* § 4⁰ and 5⁰). Hence, a potential impact of minus 8.3 Mha of natural vegetation cover that Brazil would give-up to conserve—which constitutes an additional impact to the 19 Mha amnesty. From the set of private properties that would fall within this benefit, we found a potential carbon stock of 1.4 Gt (weighted average carbon stocks). We also evaluated the potential impact of the *Article 15* of the NFC (which allows landowners to include natural vegetation areas within PPA in the computing of LR—see “Methods”) in total area of LR deficit. If the natural vegetation cover within PPA declared in the CAR data is accounted as LR in the Amazon biome, the deficit will decrease by 8.9 Mha (1.5 Gt of carbon). Hence, if we account the potential impacts from articles 12 § 4⁰ and 15, the Amazon LR deficit (Fig. 2a) would be reduced to 8.2 Mha (i.e., 67% reduction). In the Atlantic Forest we found 4.2 Mha of natural vegetation (470 Mt of carbon) within PPA. Hence, the *Article 15* may release landowners from the obligation to restore the 1.3 Mha of LR deficit found (Fig. 2b). For the Cerrado biome, a total 5.3 Mha of natural vegetation (235 million t of carbon) was found within PPA. Considering the situation of non LR deficit at the biome level, *Article 15* would not have a strong impact in the Cerrado. Our validation approach to assess the accuracy of the LR data analysis (see Methods) showed that natural vegetation cover represented 86.11% of a 10% sample of LR polygons in the Amazon, similar to the relative value of 88.45% obtained for the total LR dataset at the biome level. We also found a 24% LR deficit in the Amazon from a sample of 151,566 private properties, which is a relative value close to the 26% found for the total dataset (Fig. 2a).

Private lands in indigenous territories and conservation units.

Conservation units (CU—with full protection, such as National Parks) and indigenous territories (IT) combined, represent 49%, 7%, and 3% of the Amazon, Cerrado and Atlantic Forest biomes, respectively. Although the Amazon is covered by the greatest proportion under a protected designation, it is in the Cerrado and Atlantic Forest biomes that we found the highest proportion of private properties declared within the limits of those protected areas (i.e., overlapping polygons of CU or IT with rural properties). In the Atlantic Forest we found 42% (1.5 Mha) of the areas in CU and IT registered as private property on the CAR. This proportion reached 25% (3.5 Mha) in the Cerrado and 10% (20.5 Mha) in the Amazon. Interestingly, the higher proportions of overlapping areas between private lands and protected areas occur for CU, with 85% in the Amazon and Atlantic Forest biomes, and 76% in the Cerrado. Deforestation in CU and IT was not observed in the Atlantic Forest, but rather a positive (though small) increase in natural vegetation of 0.3% and 0.4% in 2003–2012 and 2012–2020, respectively. Additionally, a 0.4% and 0.3% increase in natural vegetation was observed in private properties within CU and IT, in the same periods, respectively. In the areas declared as private properties within CU and IT in the Amazon, deforestation decreased between the 2003–2012 and 2012–2020 periods, but exhibited 5- and 2-fold higher

proportions, respectively, when compared to total CU and IT areas in the same periods. In contrast, in the Cerrado biome, deforestation increased not only across the CU and IT, but also in private rural properties within CU and IT. Similar to the Amazon biome, the deforestation was higher within the areas declared as private lands (2.3- and 1.7-fold higher in 2003–2012 and 2012–2020, respectively).

Discussion

Governing natural resources. Implementation of environmental policies occurs at local scales (e.g., individual parcels of land), yet their effects are felt not only at these scales but across regions, countries, continents and the entire world⁴⁵. Thus, it is important to evaluate the effects at the scale of individual land parcels (e.g., private rural property), to understand the effectiveness of the implementation of environmental policies⁴. However, due to the lack of appropriate data², most previous analyses have neglected evaluating the effects at those local scales⁴. Using a dataset created by individual private rural property owners (i.e., CAR data), here we evaluated natural vegetation cover change and its effects on carbon stocks on lands within private properties. Such information is crucial for improving national policies and governance structures, as it allows understanding the spatial (e.g., across biomes, private land size) and temporal variance in implementation and in outcomes among individual parcels. Given the large size of Brazil and its extensive natural vegetation areas, understanding the effectiveness of policies like the NFC is important both locally and globally. Furthermore, the CAR system has the potential to provide suitable data for envisioning new ideas to manage and govern forest resources within private lands, which will be vital for achieving global ambitions such as reducing greenhouse gas emissions (e.g., Paris Agreement), conserve biological diversity (e.g., Convention on Biological Diversity, UN Decade on Ecosystem Restoration), and support the achievement of UN Sustainable Development Goals—e.g., 13 and 15. Our findings support previous studies that highlight the importance of considering private lands in conservation strategies, including carbon storage and biodiversity conservation^{2–6}, while filling important research gaps (significance of private lands for the conservation of a global biodiversity hotspot) in current assessments³.

A contentious interaction among stakeholder groups including rural producers, NGOs, and scientists, in defining minimum conservation areas inside rural properties in the NFC, culminated with an amnesty on recovering natural vegetation given to small private rural^{20,46}. This relative success of the agribusiness sector, according to Kröger²², placed the sector as a major actor at the center of decision-making processes at the national scale. Nevertheless, as found in this study, by conceding amnesty to 50% of the landowners of rural private properties in the Amazon, Atlantic Forest and Cerrado biomes, the NFC foreclosed the need to recover around 19 Mha of natural vegetation in these biomes. A previous study suggested that the NFC would favor 90% of rural properties in Brazil⁴⁷, but we found that that just half (50.7%) received the benefit of the amnesty. We estimate that the recovery of these areas would have sequestered around 3 Gt of carbon. Targeting private lands of highest biodiversity and carbon value will be most effective for achieving conservation goals^{1,5}. This has important consequences on the Brazilian commitments assumed by the National Determined Contribution (NDC 2015) under the Paris Agreement³⁸ to recover 12 Mha of natural areas and to reduce greenhouse gas emissions by 43% by 2030 (based on 2005 emissions). If not under the NFC, the targets assumed by Brazil would more likely have been achieved just by enforcing the previous Forest Code of 1965, without relying on extra efforts.

These efforts, which may still be complementary, include mechanisms for restoration and carbon offset (e.g., REDD + and other financial instruments), and additional policies (e.g., Agricultural Policy for Planted Forests, Law 8375/2014) to foster the implementation of National Determined Contribution commitments⁴⁸. The Amazon biome was most affected by the changes brought by the NFC. While this biome exhibited a decrease in deforestation rates from 2012, it exhibited the largest share of natural vegetation loss within LR—54% of the total observed within rural properties. The deforestation trend observed in LR in the Amazon also highlights the inefficiency of the NFC, previously suggested by Azevedo et al.³⁹, to conserve natural vegetation in private lands without complementary efforts of law enforcement, surveillance, and supply chain agreements. Since 2003, the Brazilian government developed a series of strategies at the federal level to address deforestation in Amazon, through the “Plano de Prevenção e Controle do Desmatamento na Amazônia” (PPCDAm), a public policy with a high degree of success⁴⁹, but which lost capacity and implementation through different segments of the Federal Public agenda in recent years. Here we recall the importance of multi-level/polycentric environmental governance approaches in which public policies may be strengthened by private and non-governmental agreements to foster sustainability into global supply chains^{27,50}. This context highlights the impacts of telecouplings on Brazilian ecosystems that have been developing over the last few decades, mainly driven by the increase in trade of soybean with China and Europe^{34,51,52}.

Despite the considerable amount of natural vegetation cover that Brazil gave-up by giving amnesty to landowners (19 Mha), the actual LR deficit in the Amazon (25.5 Mha) is higher (although if *Article 12 § 4^o* was considered, Brazil would give-up 27 Mha thereby reducing LR deficits in the Amazon to 17.1 Mha). This scenario indicates that by enforcing the NFC and demanding landowners to comply with the legislation would considerably increase Brazilian carbon stocks, necessary to offset the country's emissions. For instance, a 100% natural vegetation cover within LR could be a demand by stakeholders of global supply chains (e.g., companies and retailer markets in importing countries) as a mandatory requirement for rural properties willing to engage into global trade. Such a measure could be strengthened by a “Zero LR deficit” policy to drive landowners to fill the LR deficits. This measure would be especially important for the Amazon, with the largest LR deficit and a larger potential to sequester carbon into its natural vegetation. Although the strong political influence of agribusiness stakeholders enabled the amnesty to landowners²², it may also have supported non-compliance behaviors towards the NFC, as we observed through deforestation within LR.

This study obtained crucial knowledge on the land use/cover impacts of a forest policy instrument designed to improve environmental governance and terrestrial intelligence at the private property level. In this regard, by analyzing individual land parcels, our study advances the knowledge obtained by previous studies^{24,41,53} by pin-pointing private properties in compliance or non-compliance with national legislation, while also assessing the scale of the impacts of policy change on Brazilian carbon stocks. For example, not only did we find portions of LR areas with non-natural vegetation cover (Fig. 2), but also considerable portions of natural vegetation cover within private lands that are outside declared LR areas. Landowners have the legal right (according to the NFC) to decide where to conserve natural vegetation as LR within their properties. Our analysis shows that this right is open to abuse and that landowners do not always set their actual natural vegetation areas for conservation but rather declare LR in areas appropriate for human use. By doing this, landowners may create “artificial surpluses” of natural vegetation, which can be

legally deforested or traded for LR compensation with non-compliant landowners within the same biome. In addition, they may not be preserving the minimum area specified by the NFC [e.g., discounting natural vegetation cover from PPA in each biome from natural vegetation outside LR (Fig. 2), leads to a surplus of 61 Mha]. Such action elicits considerable negative effects on carbon stocks and biodiversity conservation by exchanging old-growth natural vegetation with restored vegetation on cleared areas within LR—i.e., lower carbon stocks and biodiversity values compared to pristine areas⁵³. These findings could not be obtained using modeling and/or satellite remotely sensed data^{54,55}.

We argue that this new knowledge capacity provided through the CAR under the NFC, allows policymakers and stakeholders to anticipate impacts according potential propositions for additional changes in the Forest Code, as well as to engage individual landowners into conservation and restoration programs according to their respective geographic location [e.g., private lands with high potential to sequester carbon through natural vegetation cover could be prioritized by national policies⁵] or natural vegetation cover deficits. This individual level of analysis can also support more efficient strategies to monitor land cover changes for specific supply chains [e.g., cellulose pulp from eucalyptus²⁷], as trading companies and retailers may build their own cadastres of the rural properties of interest and keep track of natural vegetation cover through time using high spatial resolution satellite imagery (which would be unfeasible, or at least very expensive, for large scale census-style assessments on an annual basis). Such strategies at the property level could work as complementary efforts to current government policies (e.g., Low-Carbon Agriculture—ABC Program) to monitor and evaluate restoration of degraded pastures [± 132 Mha within the study area⁵⁶], or water use efficiency through biomass productivity into integrated crop-livestock-forestry systems⁵⁷. These strategies may also improve the traceability of major Brazilian food-commodities associated with deforestation, such as beef⁵⁸.

Forest Code analysis and caveats. Our study provides new analysis of the NFC by quantifying the actual impact of the amnesty on forest recovery (on LR) in private lands of the three major forest biomes in Brazil. This quantification includes the land extent impacted, the number of rural properties, and the consequences for carbon stocks. We additionally analyzed how effective the LR is for protecting natural vegetation and measured the current LR deficit across biomes. While previous studies have analyzed the land change impacts of the Forest Code, they have used different time scales and/or different units of analysis (e.g., states, municipalities), which do not allow fair comparisons with the results of this study. However, to provide a measure of certainty in our results based on the results obtained by prior studies, we obtained key findings from some of these prior studies to be compared with those from our study. Such a comparison highlights that our data demonstrate reasonably comparable results. For example, whereas Soares-Filho et al.²⁵ found the area under protection from the NFC to be 193 Mha (LR and PPA—entire country), here we find 144 Mha (only LR—Amazon, Atlantic Forest and Cerrado biomes—around 175 Mha if considered LR plus PPA). In addition, after considering all flexibilities in the NFC they concluded that Brazil gave up 21 Mha of protected area within private properties, while we found 19 Mha (considering just the “tolerant” regime).

Soares-Filho et al.²⁵ also found a surplus of natural vegetation of 88 Mha (entire country), whereas we found it to be 57.4 Mha (natural vegetation outside declared LR and PPA). Furthermore, in Vieira et al.⁵⁹, the authors found a surplus of natural vegetation

cover of 39 Mha in the Cerrado considering the NFC, while we found a 37.5 Mha surplus outside LR areas (Fig. 2c)—32.3 Mha if considered LR and PPA. From Faria et al.²⁴, the most comprehensive analysis of NFC in the Atlantic Forest biome until now, the authors found a total of 22.6 Mha of natural vegetation within private properties where we found 22.9 Mha. These authors²⁴ also observed a total 2.8 million private properties in the Atlantic Forest, whereas we found 2.6 million, with both studies demonstrating that small properties account for 94% of the total private properties in the biome. Considering the data analyzed by Faria et al.²⁴, the authors found 78% of the Atlantic Forest in private lands, while we found 73%. In supplementary information we compare our results (Supplementary Table 3) to those of previous studies (Supplementary References). The uncertainties highlighted by this comparison demonstrate the importance of continued efforts to empirically study the Brazilian Forest Code, given its importance for conservation purposes.

As previously noted by Soares-Filho et al.²⁵, the measurement and accurate allocation of Permanent Preservation Areas (PPA) within rural properties is challenging and may lead to uncertainties, especially when working at the scale of biomes. Hence, in this study we decided to focus on the rural property level and the Legal Reserves (LR) to measure total land-use and natural vegetation changes, together with the impacts of the NFC on a major policy instrument [i.e., LR^{23,60}] for environmental conservation on private lands. According to the FC of 1965, the PPA and LR were not interchangeable (i.e., rural properties must have both), but in the NFC PPA and LR can be interchangeable (under specific situations, such as in *Article 15*). This leads to potential uncertainties in our calculations as our results do not account for the deficit of PPA, an issue that needs to be tackled in future studies. However, we accounted only the areas declared into the CAR system (known as SICAR) as PPA to assess natural vegetation cover to evaluate potential impacts on LR deficits—i.e., by including natural vegetation within PPA as part of LR in private properties will reduce the total area required to be protected as LR, then reducing conservation areas in Brazilian private lands.

The CAR system and future prospects. Despite being a self-declaratory system, which caused the polygon overlapping issues observed (Supplementary Results and Supplementary Fig. 1), the CAR data provides a useful overview of NFC compliance, contributing to the production of strategic data for assessing compliance with the NFC Brazil. However, the discrepancies between the declared areas and the “non-overlapping” areas among private rural properties (Supplementary Results) represent an important source of error. Additionally, the overlap between private areas and protected areas (CU and IT) reveals potential land conflicts since, according to specialists on Brazilian environmental policies, the CAR created a new instrument for people willing to take advantage of the NFC by using the self-declaratory system as “legal land titling” to claim land rights within CU and IT²⁸. This may additionally foster natural vegetation loss⁶¹, thus requiring attention from public authorities. Our results highlight the need for high-precision terrestrial positioning tools for land declaration purposes²⁸, a situation evidenced by the discrepancies between the CAR and other georeferenced data sources²⁹. To provide a more accurate assessment of the “non-overlapping” situation of private rural properties in Brazilian biomes, the CAR data (which have just been updated following the extended December 2022 deadline set by the NFC) still needs to be analyzed and properly cleaned by data professionals in charge of the maintenance and management of the SICAR. However, the analysis of such a large

dataset may take a relatively long time (decades), if changes are not implemented towards automatic analysis⁶². Our results strengthen the argument that private lands are key for biodiversity conservation and carbon sequestration^{2–6}. Additionally, we highlight that public authorities (e.g., policymakers, managers) and stakeholders representing different types of environmental governance (e.g., sustainable supply chain agreements, which may work complementary to public policies) should motivate landowners to use their actual natural vegetation cover as LR instead of self-declaring other areas with lower conservation value as LR. This measure will avoid potential ongoing legal deforestation over old-growth vegetation while increasing compliance with the NFC. This suggests that national governments worldwide need to consider the design of policies that regulate private lands, while creating spatial data at the scale of individual ownership parcels. Even in countries such as China that do not allow private lands but require ecosystem services and biodiversity conservation^{63–65} the methods and results from this study may also provide useful insights. The CAR system provides a fundamental entry point to implement surveillance, credit policies, and other multi-level/polycentric environmental governance approaches.

Methods

Study area. This study applies a series of descriptive statistics together with spatial analysis on a geospatial vector dataset and temporal time series (2003–2020) of thematic maps of LULC. The study area is the Amazon, Atlantic Forest and Cerrado biomes. These biomes are representative of different natural vegetation formations in Brazil⁶⁶, and encompass 85% of the country's territory [Amazon (419 Mha), Atlantic Forest (111 Mha) and Cerrado (203 Mha)]. Additionally, the Amazon and Cerrado biomes are the most active agricultural frontiers in Brazil³⁵, while the Atlantic Forest has relatively stable LULC dynamics¹⁷.

The Forest Code (background). The Brazilian Forest Code (Law 23793/1934) was created in 1934, when the country was entering a period of industrialization, mainly the transformation of the metallurgy sector, which favored the growth of mining operations. Given this context, the prediction of future demand of raw materials for the industry, such as wood charcoal (used as fuel used for industrial mineral transformations), prompted the government to develop a set of policies to regulate the use and exploration of natural resources, including a law to protect and regulate natural forests¹⁹. However, in the 1934 Forest Code, there was a lack of clear norms regulating the conservation of natural vegetation areas within private lands, a problem addressed by the revised Forest Code of 1965 (Law 4771/1965), which instituted the Legal Reserves (LR) and Permanent Preservation Areas (PPA). Both LR and PPA represent portions of land within rural private properties destined to conserve local natural vegetation, biodiversity, and to protect water resources, steep slopes and dunes. The 1965 Forest Code defined LR as 50% of each individual private rural property in the Amazon biome, compared to 20% in the other two biomes evaluated.

Despite the advances of the Forest Code of 1965, in 1989 a new regulation implemented clear rules to demarcate PPA, such as defining the degree to which slopes must be permanently protected with natural vegetation cover (i.e., 45 degrees), or the minimum radial distance around water springs (set at 50 meters) to be covered by natural vegetation. Given the alarming deforestation rates in the Amazon during the 1990s, international and national pressure (e.g., NGOs, multilateral institutions, universities) influenced the Brazilian Government to increase LR in the Amazon from 50% to 80% (presidential Decree 1511/1996). Additionally, LR in the Cerrado biome was increased to 35% of private lands within the Legal Amazon²⁰. Soon after (in 1999), the chamber of deputies (the lower house of the National Congress) began discussions for a review of the Forest Code, which culminated with the NFC of 2012 (Law 12651/2012).

After more than a decade of discussions, which were highly criticized by the scientific community and environmentalists^{20,22}, the NFC was sanctioned in 2012, creating the CAR and adopting two judicial regimes to regulate natural vegetation cover within private lands. The first regime was one of “tolerant,” bestowing amnesty for deforestation actions up to 2008, while the second was “stringent,” condemning all deforestation actions after 2008. Under the first regime, the NFC instituted more flexible regulations for small landowners⁴⁶, the group directly benefiting from the “tolerant” regime^{25,39}. Additionally, the NFC gives an opportunity, although still not fully implemented, (i) for reducing the LR from 80% to 50% of the area of protected areas in Amazon municipalities, and (ii) the possibility for landowners to account the natural vegetation within declared PPA as part of the LR—which will decrease the total LR areas compared to previous version of the FC, before 2012⁶⁷.

To define the group of rural properties considered for tolerant vs stringent regimes, the NFC used the number of fiscal modules (FM) of each property²⁵.

The FM is a land policy implemented in 1979 (Law 6746/1979) which defines the minimum rural property size considered economically viable. This area varies from 5 to 110 ha depending on the Brazilian region⁴⁶. The Agrarian Reform Law (Law 8629/1993) established that a small rural property has ≤ 4 FM [i.e., family farming according the Family Farming Law (Law 11326/2006)]. These were the rural properties benefiting from the “tolerant” regime in the NFC⁴⁶. Additionally, this group was not required to recover PPA with the same standards defined by the NFC for rural properties > 4 FM. Considering the large variation in FM area across the country (from 5 to 110 ha), the NFC may negatively impact the amount of native vegetation cover^{18,25}. For example, a rural property with 4 FM in the municipality of Alta Floresta (Amazon biome), Mato Grosso state, has an area of 400 ha. If that property does not have natural vegetation areas in 2008, it would be released from the obligation of recovering 320 ha of natural vegetation (i.e., 80% of total property area). Herein lies one of the major criticisms from the scientific and environmental communities during the discussions of the NFC—the “amnesty” to deforesters^{20,22,25}.

To examine the major changes brought by the NFC, our study explicitly adopted two specific articles of the law to model our spatial analysis: *Article 12*—which defines the percentage (ranging from 20% to 80%) of LR in private properties according each biome; and *Article 67*—which defines the “tolerant” regime. *Article 67* was the most controversial during the Forest Code’s 2012 review because of the major potential impacts to natural vegetation in Brazil and was therefore a primary interest in our study. However, we also analyzed two additional scenarios that considered the adoption of § 4^o and § 5^o of *Article 12*, and *Article 15*. The § 4^o states that municipalities in the Amazon biome with more than 50% of its area protected could reduce LR from 80% to 50%. The § 5^o states that Amazonian States with more than 65% of their territory protected could reduce LR from 80% to 50%. The *Article 15* creates the possibility for landowners to include the natural vegetation areas within declared PPA in the calculation of LR. This article will potentially decrease the LR deficits and the total conservation areas within private properties if fully implemented⁶⁷. *Article 68* may impact the accounting of LR deficits but is not considered in this study. This article does not establish a general rule for all rural properties but considered specific situations of LR compliance according to previous versions of the Code, which required documentary proof from landowners. In this case, *Article 68* brings a specific rule that needs to be evaluated case-by-case, making it complex to be analyzed in a regional context.

Dataset. Since 2015 the MapBiomias initiative is providing land use land cover (LULC) maps for the entire Brazil with accuracies of over 80% and comprising classes such as natural forest, grassland, agriculture and urban areas. For the purpose of this study, we applied a series of statistical and spatial analysis over the MapBiomias collection v.6.0 (<https://mapbiomas.org>) issued in 2021 (which exhibited an accuracy of 90.8% for level 1 (L1) products [LULC classes: forest, non-forest natural formation, farming, non-vegetated area, water]). The class “forest” is represented by different types of natural forest, including the Atlantic and Amazon forests but also the typical Cerrado vegetation, known as savanna formation (i.e., “forest formation,” “savanna,” “mangrove,” “wooded restinga”). “Non forest natural formation” includes the sub-class “grassland.” Therefore, the class “forest” and the sub-class “grassland” were reclassified as a single cover class named “natural vegetation,” which represents the land-cover subject of protection by the NFC. All the other LULC classes remained unchanged. The study used LULC maps for the years 2003, 2008, 2012 and 2020. By taking this multi-temporal approach, we were able to detect changes in natural vegetation cover before the implementation of the NFC in 2012 (2003–2012), and on a similar period after its creation (2012–2020), to evaluate if the change trajectories (e.g., rates of natural vegetation loss/increase) were affected by the NFC.

The multi-temporal analysis was performed at the scale of individual rural private properties, and on a per biome basis. From the CAR system, known as SICAR (<https://www.car.gov.br>), we downloaded the vector files storing the geometric location and attribute information of around 6 million rural properties included in the system until April 2021. Among the information of each rural property included in the CAR dataset landowners provide (i.e., self-declared) the area covered by natural vegetation, the LR and the PPA. Additionally, it includes the number of fiscal modules (FM) based on rural property size (ha).

Information on indigenous territories (IT) and conservation units (CU) are provided by the Brazilian Government and were downloaded from online repositories. CU data were provided by the Ministry of Environment (<https://www.gov.br/mma/pt-br>), and IT by the National Indian Foundation (<https://www.gov.br/funai/pt-br>). Considering the Brazilian National System for Conservation Units (Law 9985 of 2000), we excluded “environmental protection areas” from the analysis, since they were categorized as sustainable use areas and hence legally occupied by rural private properties⁶⁸. We also excluded “private national heritage reserves,” which are conservation units of integral protection but inside rural private properties⁶⁹.

For the carbon stock analysis, we obtained the vegetation map (v.2021, scale 1:250,000) developed by the Brazilian Institute of Geography and Statistics⁷⁰, which describes the spatial distribution of different vegetation types in association to edaphoclimatic factors (i.e., phytophysiology) across the country (<https://www.ibge.gov.br/geociencias/informacoes-ambientais/vegetacao.html>). The dataset was processed and analyzed through a Geographic Information System (GIS) using the

Albers Equal Area Conic Projection (grid cells at 30 m resolution), suitable for area calculation of large land masses and also the system adopted by the IBGE for official measurements⁷¹.

Data analysis. For some analyses conducted in this study, we considered the group of rural properties ≤ 4 FM as separate from the rest of the rural properties (to evaluate the impact of the NFC “tolerant” regime on the natural vegetation cover and its trajectory between 2012 and 2020). Therefore, we analyzed rural properties as a whole and also split in two groups according to the Agrarian Reform Law (“small” ≤ 4 FM, “medium/large” > 4 FM) and in each biome of interest (Amazon, Atlantic Forest, and Cerrado). As the CAR is a self-declaratory tool, there was some overlapping between neighboring rural properties [due to imprecision in the self-declaratory registry, since the geo-web system does not demand high position accuracy²⁵, but also due to potential land conflicts among farmers, as well as land speculation^{22,29,72}]. Such overlap represents a problem for spatial analysis^{26,28,73}. To overcome this issue, we merged the rural properties (i.e., the rural properties’ boundaries) in each group (small, and medium/large) to obtain a total “non-overlapping” area. This procedure was conducted by merging all polygons of rural properties into a single polygon. By doing this we could also obtain a measure of the overlapping area among rural properties, while also obtaining the total area declared by landowners.

In the CAR data, boundaries of communal areas, known as rural settlements (assentamento—AST), traditional people’s lands (povos comunidade tradicionais—PCT), and public national forests (cadastro nacional de florestas públicas—CNFP) were also included in the system, as well as the individual land parcels of each group member/family of the respective communal areas. For the purpose of this study, we did not account for the land designated as communal areas and public forests, but only the private rural properties (imóveis rurais—IRU). Additionally, according to the CAR system, the rural property information inserted into the system can be active (AT), pending approval (PE), suspended (SU), or canceled (CA). In this last case the official authorities reject the information provided to the system and this rural property is no longer valid. Hence, we also did not consider properties with CA status.

Natural vegetation cover changes in private lands. Improvements in environmental quality are expected when people involved in any process with a negative environmental impact (e.g., agricultural production) engage with environmental policies or other sustainability governance systems^{74,75}. Thus, in the Amazon biome, where conservation policies and international agreements are in place [e.g., Soy Moratorium⁷⁶; Beef zero deforestation⁵³], we expect a decrease in the rates of deforestation in rural properties, as they tend to avoid legal and economic sanctions, but not in the Cerrado, a major agricultural producer biome that is not subject to the same agreements. Additionally, private lands in the Cerrado biome still have a surplus of natural vegetation cover (i.e., over the minimum required by the NFC), allowing continual deforestation for the expansion of agricultural production. Using the rural properties’ merged boundaries (i.e., non-overlapping), the LULC class “natural vegetation” was analyzed through time to evaluate changes in the temporal trajectory (i.e., loss, gain, or stability) at the rural property and biome levels. Here we consider rural properties from the CAR as the “treatment” group, while the biome areas outside CAR are the “control” group. Through this process we can evaluate if changes at the rural property level are consistent (or different) with those at the biome level. To test if natural vegetation changes were significantly different in both periods, we applied statistical *Wilcoxon* tests (with rural properties as units of analysis), ideal for paired samples⁷⁷. The *Wilcoxon* test was chosen after rejecting ($p < 0.01$) the non-normal distribution of the data through an *Anderson-Darling* test⁷⁸.

Legal reserves. Based on the total area occupied by non-overlapping rural properties, first we calculated the relative (percentage) area that should be covered by natural vegetation as LR for rural properties > 4 FM (i.e., Amazon 80%, Cerrado 35% within the Legal Amazon and 20% in Cerrado outside Legal Amazon, and Atlantic Forest 20%). Second, we calculated the natural vegetation cover area for each small rural property (≤ 4 FM) in 2008. If natural cover was lower than the minimum required before the NFC, we considered the 2008 cover as the minimum LR for that property. However, for properties with natural vegetation cover higher than the minimum established by 1965 Forest Code, we considered the same percentage used for medium/large properties (> 4 FM). By taking this approach, our method enables accounting for the number of rural properties annulled by the NFC in each biome and measurement of the area released from the obligation to be recovered. We compared the results with the total LR area declared in the CAR. This approach allowed us to evaluate the LR deficit at the biome level, and the extent of natural vegetation cover that should have been recovered according to the 1965 Forest Code, but released from this obligation under the New Forest Code in 2012 (i.e., amnesty). Hence, we were able to measure the real impact of the NFC on the area and change of natural vegetation cover within private lands. Second, the LULC data were used to evaluate the presence of natural vegetation cover within the declared LR, which by law does not necessarily need to be covered by natural vegetation at the moment of the declaration, but has to be recovered in future. A

LULC change analysis was performed to assess if the area of natural vegetation cover changed over the periods 2003–2012 and 2012–2020.

In addition to evaluating potential impacts of the changes to the NFC, we considered a situation where § 4^o of *Article 12* is fully implemented. In this case we considered the full set of medium/large rural private properties (we did not consider small properties because they already largely benefit from the “tolerant” regime) of the Amazon biome. Hence, we first calculated the total protected area (the sum of CU and IT) at the municipality level and estimated the percentage occupied in each respective municipality’s territory. Second, from the set of municipalities suitable to enjoy the benefit of *Article 12* § 4^o, (i.e., over 50% of its territory under protected area), we calculated the necessary area of LR if just 50% was necessary. To consider the impacts of § 5^o of *Article 12*, we conducted the same approach at the municipality level, but focusing on state-level data and considering eligible states, those with more than 65% of their territories protected. Third, to evaluate potential impacts of *Article 15* we calculated the total natural vegetation cover of 2020 within the polygons declared by landowners as PPA. Hence, if this article is implemented in future, landowners will have the right to use those areas in the calculation of LR.

Rural properties within conservation units and indigenous territories. We extracted and analyzed all private rural properties from the CAR data that overlapped CU and IT. The overlapping areas were quantified by types of protected areas (CU or IT) and natural vegetation cover change was assessed at both levels—i.e., protected areas and private rural properties within (i.e., overlapping) protected areas.

Carbon stock analysis. Carbon stocks in tropical forests are known to be of high importance to offset anthropogenic greenhouse gas emissions and to cope with climate change⁷⁹. Based on the most up-to-date references on carbon stocks for different vegetation types in Brazilian biomes⁸⁰ from the Third National Inventory⁸¹, we calculated the impacts of the NFC on carbon stocks, considering the total area released from the obligation to recover with natural vegetation, given the “tolerant” regime applied to small rural properties. This allowed a more accurate assessment of the effects of the NFC on carbon stocks, as we were able to evaluate the effects at the level of rural private property—i.e., the number of hectares released from the obligation to be recovered and the corresponding carbon stock (tC/ha—i.e., total carbon stock: above- and below-ground, litter, and dead wood) based on the respective vegetation type involved (see Fig. 3 and Supplementary Figs. 2 and 3). For this purpose, we considered a scenario in which carbon stocks would be restored (i.e., sequestered) over the long-run [20 to 100 years⁸²] through natural vegetation cover in small rural properties according to the previous Forest Code of 1965. To accomplish this task, our methods applied the carbon stock references (tC/ha) from the Third National Inventory⁸¹, according to each vegetation type described in the IBGE vegetation map v.2021 (Supplementary Methods, and Supplementary Fig. 4—in the supplementary file we provide details on the methods used to refine carbon stocks information according to vegetation types and biomes). The resulting carbon stocks map (Supplementary Fig. 5), according to vegetation type, was used to compare carbon stock values within the boundaries of small rural properties without the minimum LR area in 2008—i.e., released from obligation to recover natural vegetation by the NFC—and a reference carbon stock value of each rural property extracted from the carbon map by using the “majority” zonal statistics⁸³. Therefore, for each rural property, and according to the carbon stock based on the vegetation type, the area to be recovered (according to the LR percentages for each biome) was used to calculate the equivalent carbon sequestration amount that the country lost (i.e., “gave-up”).

Validation of the results. To assess the confidence of the results obtained in the study, we designed four validation approaches and implemented them in the Amazon biome. (i) In the first approach, we evaluated the overlaps among private properties using a stratified random sample through three steps. The first step was to randomly collect 100 samples (i.e., private properties) in each of the two groups of property size (i.e., small, and medium/large). In the second step, for each private property in the sample we created a buffer of 30 km. In the third step we extracted all private properties within the buffer. For the samples in each property size group, we calculated the total area declared and the area occupied without overlaps. Finally, we also measured the overlaps among private properties. (ii) In the second approach we evaluated deforestation trends within private properties. For this, we created a random sample consisting of 10% of the properties in each size group (i.e., 63,962 small properties, and 6,414 medium/large). The natural vegetation cover was measured for 2003, 2012, and 2020. Results of both of these approaches are reported as percentages, to place them within the context of the total set of private properties in the Amazon biome. (iii) Our third approach evaluated a 10% random sample of declared LR in each size group (i.e., 48,999 polygons in small properties, and 4,823 in medium/large) and the percentage of natural vegetation cover in 2020, to compare with the values found in the total LR at the biome level. The percentage of natural vegetation cover was calculated from the LR “real situation” area (Fig. 2a). (iv) In the fourth validation approach we used the same sampling method applied in the first approach, but by selecting LR first. We then used the selected LR sample to extract the respective private property boundaries.

With this selected dataset we assessed the LR deficits for each private property size group considering non-overlapping areas, and compared the results obtained with the data found using the full data set at the biome level.

Data availability

The datasets utilized in this study are freely available through their respective public repositories [the respective online repositories are also provided in “Methods, Dataset”—<https://mapbiomas.org>; <https://www.car.gov.br>; <https://www.gov.br/mma/pt-br>; <https://www.gov.br/funai/pt-br>; <https://www.ibge.gov.br/geociencias/informacoes-ambientais/vegetacao.html>]. The Supplementary Information—Supplementary Tables 1 and 2—is available through a free online data repository at: <https://doi.org/10.17605/OSF.IO/S87VF>.

Code availability

All methods and procedures are fully described in the “Methods” section.

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R.F.B.d.S. led the manuscript conceptualization, methodology, data gathering, software, investigation, formal analysis, and the writing—original draft, writing—review and editing. D.d.C.V., F.A.N., E.F.M., J.L., A.V., M.B., S.A.V., and J.D.A.M. contributed to the investigation and conceptual framework of analysis, commented on the manuscript, writing—review and editing.

Competing interests

The authors declare no competing interests.

Additional information

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