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Impact of land tenure on deforestation control and forest restoration in Brazilian Amazonia

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Abstract

This study examines how land tenure constrains Brazil's ability to meet its deforestation control and forest restoration goals in its Amazonia biome. Our findings are based on an updated assessment of land tenure and land use in the region. Between 2019 and 2021, 44% of deforestation in Amazonia occurred in private lands, while forest removal in settlements ranged from 31% to 27% of the total. Deforestation in undesignated public lands increased from 11% in 2008 to 18% in 2021. Deforestation is highly concentrated, with 1% of properties accounting for 82.5% of forest cuts in 2021. In Amazonia, there is considerable non-compliance with the legal reserve provisions set by Brazil's Forest Code. Legal reserve deficits in private lands sum up to 18.17 Mha (million hectares), compared with 12.49 Mha of legal reserve surpluses. Even if all forest surpluses are offered in the forest credits market set in the Forest Code, farmers still need to restore 5.67 Mha to comply with the law. Large-scale cattle ranchers have a legal reserve deficit of 10.35 Mha (34% of their area). Most crop farming occurs in medium and large properties (4.63 Mha) with a large proportion of legal reserve deficits (45%). Given the political power and financial resources of large ranchers and crop producers, Brazil faces major challenges in inducing these farmers to meet their legal obligations. Therefore, Brazil needs to combine robust command-and-control strategies with market-based policies to achieve its deforestation and forest restoration goals. The government should tailor forest protection and restoration policies to the needs of different landowners, considering their land use practices, technical capacity, and financial resources.

1. Introduction

Deforestation in the Brazilian Amazonia biome has cut 76.85 million hectares (Mha) from the original forest cover of 390.2 Mha, according to data from Brazil's National Institute for Space Research (INPE) [1]. Strong action by the Brazilian government led to an 84% drop in deforestation, falling from 2.77 Mha in 2004 to 0.46 Mha in 2012 [1]. Since then, deforestation has been increasing, rising to 0.59 Mha in 2013 and reaching 0.70 Mha in 2018 with an yearly average of 0.66 Mha. During the Bolsonaro government from 2019 to 2022, environmental protection agencies were dismantled resulting in 4.54 Mha of forest cuts, and the yearly average rate doubled to 1.14 Mha. This situation requires urgent action. Brazil needs sound public policies to reverse the current trends and regain control over Amazonia.

The legal framework for land policy in Brazil is the Forest Code (Law 12 651/2012), which regulates private land use. In the Amazonia biome, the law requires landowners to set aside 80% of their property as a legal reserve to preserve natural vegetation, with some exemptions. The code also prohibits removal of natural vegetation on hilltops and near streams (areas of permanent preservation, APP) to safeguard water resources and protect the soil. Chiavari and Lopes [2] compare forest policies enacted by Brazil, Argentina, Canada, China, France, Germany, and the United States of America. Brazil is unique in mandating compulsory protection of private lands.

According to Brazil's Forest Code, landowners who fail to meet the legal reserve requirement accrue a natural vegetation deficit. Farmers with deficits before 22 July 2008, must restore natural vegetation on their lands to meet legal limits. Removing natural vegetation inside the legal reserve after this date is prohibited and subject to fines. Farmers can earn a surplus if they use less land than allowed by law, which can be converted into environmental reserve quotas. Farmers with deficits can offset them by purchasing quotas from properties with surpluses within the same biome. Thus, the Forest Code provides measures for avoiding deforestation, restoring forests, and creating a forest credits market.

In 2015, Brazil submitted its nationally determined contribution (NDC) to the UN Framework Convention on Climate Change, pledging to reach zero illegal deforestation by 2030 and compensate for greenhouse gas emissions from legal suppression of vegetation by 2030. Additionally, Brazil committed to restoring and reforesting 12 Mha of forests by 2030 [3]. Recent scientific studies argue that compliance with the Forest Code is crucial for Brazil to achieve its emissions reduction and forest restoration goals set in its NDC [3, 4].

In UNFCCC COP 27, held in Egypt in 2022, newly-elected president Lula committed to completely halt new deforestation in the Brazilian Amazonia by 2030 and to make a strong effort to fulfill Brazil's NDC commitments [5]. To meet these pledges, decision makers in Brazil need science-based evidence. In line with previous authors [6–10], we consider that existing land tenure arrangements constrain Brazil's capacity to achieve its deforestation control and forest restoration goals. With this motivation, the authors produced an updated assessment of land tenure and land use in Amazonia. Using this new data, we examine the limitations posed by land occupation on deforestation control and forest restoration, exploring the following questions:

(a) How are forest cuts related to the different types of land tenure?
(b) How much deforestation in Amazonia is legal?
(c) How concentrated is deforestation in Amazonia?
(d) How much legal reserve deficits and surpluses exist in private properties and settlements in Amazonia?
(e) How do land use practices constrain forest restoration and what are the consequences for public policy?

Our results use up-to-date information on land tenure, deforestation, and land use. This work complements and extends earlier research [4, 9, 11–15] by using new data sets produced after these papers were published. Our new findings are relevant to inform public policy making and to enable Brazil to better meet its NDC, deforestation control, and forest restoration goals.

2. Methods

2.1. Data sources

To produce an updated assessment of land tenure in Amazonia, we used public datasets produced by Brazilian institutions, as shown in table 1.

The National Foundation for Indigenous People (FUNAI) provides data on indigenous lands. The 1988 Brazilian Constitution assures the right of pre-Columbian populations to exclusive use of their territories.

The Chico Mendes Institute for Biodiversity Conservation (ICMBio) has data on conservation units, including areas of full protection and sustainable use. No land use is allowed in the first case. Sustainable use units allow private lands inside them under strict land management plans [16].

The National Institute for Colonization and Agrarian Reform (INCRA) provides the following databases:

(a) Quilombola lands occupied by descendants of people who resisted the slavery regime whose land rights are recognized by the Brazilian Constitution.
(b) Rural settlement data. Settlements in Amazonia started during military rule in the 1970s to reduce social tension and allocate landless people far from urban areas. Most settlers lacked farming skills and had no access to credit, markets, and technical support [17]. The result was a strong increase in deforestation in those areas. For this reason, settlements created after the 2000s have to follow sustainable use rules [18].
(c) Private land tenure: (i) SNCI, which holds records from 2004 to 2018; (ii) SIGEF, which has data ranging from 2013 up to 2021; and (iii) Terra Legal, created in 2009 to certify land for small farmers in public areas. These records are accurate but incomplete.

To fill the current gaps in land tenure data, the 2012 Forest Code created the Rural Environmental Registry (CAR) maintained by the Brazilian Forestry Service (SFB). The code mandates all landowners to self-register their properties in the CAR. However, the CAR is currently incomplete and contains many conflicts and overlaps. SFB also provides the National Cadastre of Public Forests (CNFP), which has two types of data: (a) public forests defined as conservation units, indigenous lands, military lands, and other sustainable use areas; (b) identified areas yet to be designated to a tenure category by federal or state governments.

Table 1. List of land databases for Brazil.

Type	Description	Source	Year
Public land tenure	Indigenous lands	FUNAI	2021
	Conservation units	ICMBio	2021
	Quilombola lands	INCRA	2021
	Rural settlements	INCRA	2021
	Public forests	CNFP	2016
Private land tenure	SIGEF (rural properties)	INCRA	2021
	SNCI (rural properties)	INCRA	2021
	Terra Legal (rural properties)	INCRA	2019
	CAR (Self-declared cadastre)	SFB	2021
Land use and land cover	PRODES (deforestation)	INPE	2021
	MapBiomas Amazonia	MapBiomas	2022
	TerraClass	INPE/Embrapa	2020
Ecological economic zones	SIAGEO (areas where legal reserve is reduced)	Embrapa	2022

Brazil's INPE has provided annual assessments of deforestation by clear-cuts in Amazonia since 1988 using the PRODES system. INPE and the Brazilian Agricultural Research Corporation (Embrapa) produce the TerraClass land use map for the biome [19]. Embrapa also provides the Interactive System of Geospatial Analysis of the Legal Amazonia (SIAGEO), which lists initiatives of ecological-economic zoning in the region [20].

MapBiomas is a collaborative platform that uses satellite data and machine learning to map and monitor land use and land cover changes in Brazil [21]. Created in 2015 by a consortium of NGOs and research labs, MapBiomas uses Google Earth Engine to provide annual maps of land use and land cover in Brazil from 1985 to the present.

2.2. Building maps of public and private land tenure

Our analysis requires maps of public and private land tenure. The public land tenure map contains protected areas set by Law. To solve overlaps, we used an order of precedence: (a) indigenous lands from FUNAI; (b) quilombola lands from INCRA; (c) fully protected conservation units from ICMBio; (d) military areas from CNFP; (e) sustainable use conservation units from ICMBio; (f) public forests from CNFP. Table 2 shows the public land tenure data.

To obtain the private land tenure map, we used data from INCRA (SIGEF, SNCI, and TerraLegal) and CAR. Conflicts between properties registered more than once were fixed by taking one data source as a reference and removing overlaps from the other. Since its records are certified, INCRA is a reliable source of private land tenure. Thus, SIGEF and SNCI have the highest priority, followed by TerraLegal. Since the CAR has self-declared records, it has the lowest priority. This ranking allowed us to use the best information first and to reduce the work on data cleaning.

Table 2. Public land tenure in Amazonia.

Category	Amount	Total Area (Mha)
Indigenous lands	357	108.6
Quilombola lands	128	1.7
Fully protected conservation units	116	35.7
Sustainable use conservation units	232	41.2
Military use	1	2.2
Public forests		61.6
Total		251.0

We set up five rules to create the private land tenure map (see figure 1). The first two rules apply to INCRA's data. Rule (A) refers to conflicts between SIGEF and SNCI. New entries in these cadastres can be added without removing previous ones that cover the same area. We consider these cases to result from land sales and take the newest registered property as the valid one. Rule (B) takes the resulting data and includes entries from the TerraLegal cadastre that do not conflict with the joined SIGEF and SNCI data. The result is a clean dataset based on INCRA's data.

Next, we use rule (C) to remove overlaps between CAR self-declarations. When the CAR was set into law, its proponents expected it to solve the gaps and issues of land tenure in Brazil [22]. However, entries provided by owners in the CAR have many conflicts and errors [23], including duplicate entries, geometric inconsistencies (such as overlaps and gaps), legal incompatibilities, and missing or conflicting information. To make matters worse, state authorities have been slow in solving such problems and creating a clean cadastre. As a result, most CAR records are pending validation [11].

To resolve conflicts in the current CAR version, we assume legitimate owners are rigorous in their declarations. Entries with many overlaps are more likely to result from illicit claims than those without

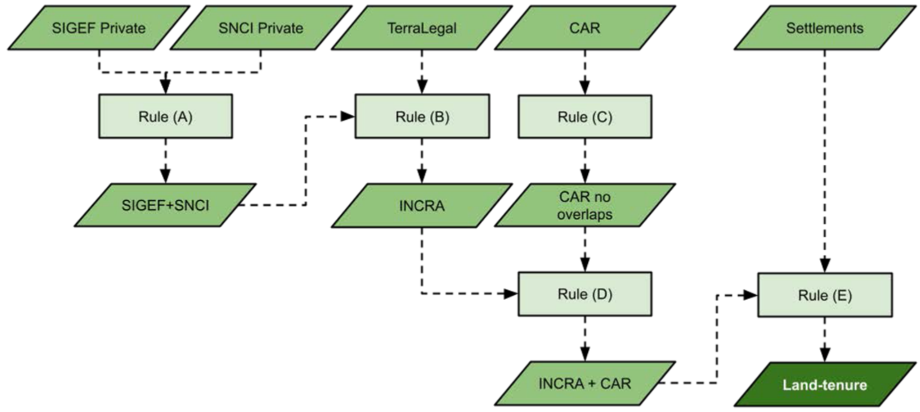

Figure 1. Steps to generate the private land tenure map.

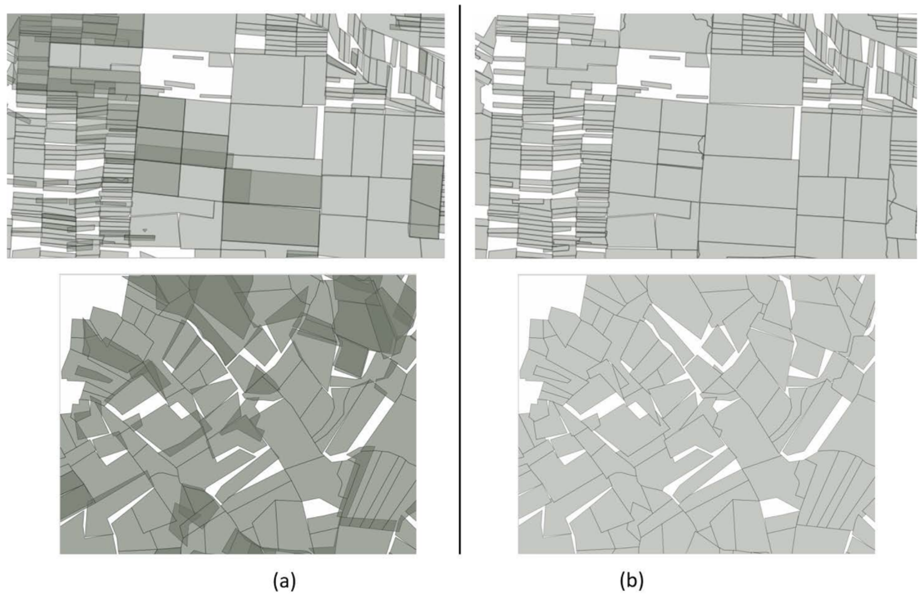

Figure 2. Resolving overlaps in CAR using rule (C) (a) before correction; and (b) after removals and adjustments. Dark areas in the left images denote overlapping property claims in CAR. The result is a spatially consistent map.

intersections. The conflict-resolution algorithm used by the authors is available together with the data used in the study (see 'Data Availability Statement'). This algorithm provides a systematic approach to address conflicts in the CAR. Figure 2 illustrates corrections made in two distinct regions of Amazonia.

After applying the algorithm to all CAR items, we use rule (D) to match the clean INCRA dataset with the cleaned CAR. In case of conflicts between INCRA and CAR entries, properties listed by INCRA have priority over those in CAR. We get a register of private rural properties without intersections or conflicting information.

The final step includes rural settlements. Our study takes all properties inside a settlement as a single entity. Thus, we define rule (E), which dissolves all boundaries of individual farms inside a settlement. These rules produce a consistent private land tenure map. The resulting dataset has 489 795 unique private lands outside settlements covering 128.1 Mha; there are 2333 settlements covering 32.9 Mha. Figure 3 shows private properties and settlements in Amazonia by size class.

2.3. Mapping forest protection mandates

To assess legal compliance by private landowners, we need to match the private land tenure map with information on forest protection mandates. To obtain this information, we considered rulings related to public land tenure areas and those that apply to private lands.

We first built a map of protection mandates in public areas. Indigenous lands, fully protected conservation units, and quilombola areas have a 100% forest protection mandate. Sustainable conservation units and sustainable settlements follow an 80% protection mandate. Considering the unclear status of the undesignated forests in Amazonia, we assigned an 80% protection level to them.

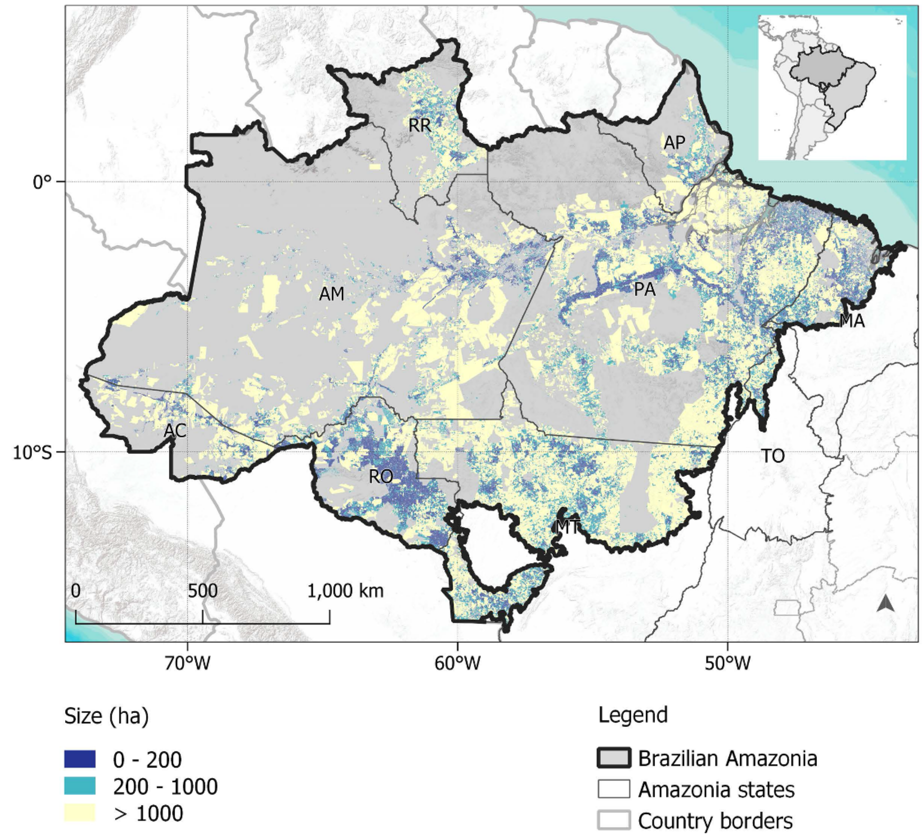

Figure 3. Rural properties and settlements in Amazonia by size (ha). Small properties (200 ha or less) are more frequent in Rondônia (RO), Northeastern Pará (PA), along the Trans-Amazonian highway, and in Maranhão (MA). Most of these areas were occupied before the 2000 s. In Mato Grosso (MT), the Southern portion of PA, and Southeastern Amazonas (AM), most properties date from the 2000 s and later; most have medium (200 to 1000 ha) and large (over 1000 ha) sizes.

Regarding forest protection mandates in private properties, the Forest Code states that owners must set aside 80% of their forest area as legal reserve. However, the code has several exceptions and waivers. In the appendix, we provide a detailed discussion of how the authors interpreted the provisions of the Forest Code to assign forest protection mandates in private lands. Combining all legal provisions of the Forest Code, we produced a map of forest protection mandates, shown in figure 4.

2.4. Obtaining areas of permanent preservation

The next step was to get the map of areas of permanent preservation (APPs) in Amazonia. Since we used a 30-meter grid for our maps, we considered two cases. For rivers wider than 30 m, we used the water mask provided by INPE [1] and the Forest Code rules to assign the grid cells that will be part of the APP. To include rivers narrower than 30 m, we computed a drainage network for Amazonia as proposed by Rosim and Rennó [24]. Comparative studies show drainage networks computed using this method are suitable to define APPs [25]. Based on the drainage network, we inferred the location and extent of narrow streams and riparian areas to estimate the fraction of each cell assigned as an APP. The final step was to use the Forest Code rules and deforestation maps to establish the areas that must be restored for each property listed in our land tenure map.

2.5. Defining legal and illegal deforestation

To measure legal and illegal deforestation in different land tenure regimes in Amazonia, we considered the preservation requirements set by the Forest Code. Our analysis considers deforestation is illegal anywhere inside fully protected areas, indigenous lands. Deforestation is also illegal in undesignated public areas and sustainable conservation units outside the private land tenure map. Rural properties inside sustainable conservation units have to abide by an 80% legal reserve limit. Other rural properties and settlements can only cut forests legally if they respect the legal reserve limit and do not remove APP.

2.6. Defining secondary vegetation

Secondary vegetation areas typically arise from forest clear-cuts that have been abandoned. Over time, these areas of secondary forest will gradually evolve into a native vegetation area if left undisturbed [26]. However, many secondary forests are temporary and are not intentionally included in forest restoration efforts [7, 27, 28].

A recent study by Wang *et al* [29] found that removal of secondary forests decreases with age.

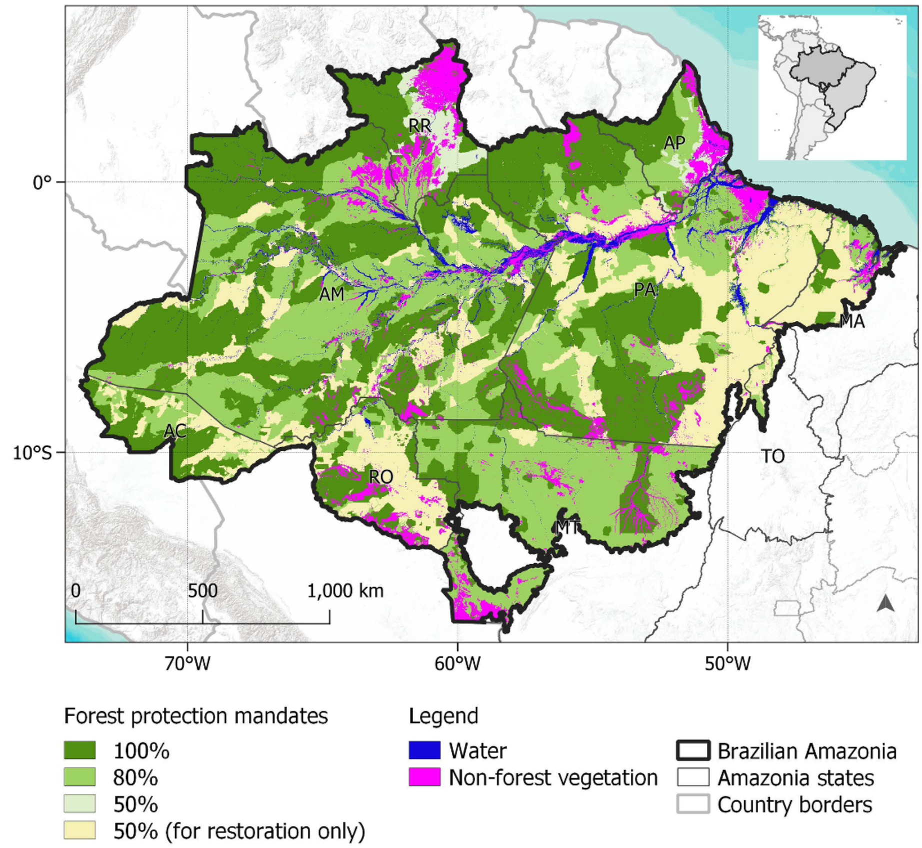

Figure 4. Map of forest protection mandates, including inland water areas and non-forest vegetation. The methods to produce the map are described in the appendix.

Based on these results, we assume that secondary vegetation areas that have not been cut since 2014 indicate that farmers are interested in recovering native vegetation. We thus add these long-term secondary vegetation areas to the native forest areas for purposes of measuring legal reserve deficits and surpluses.

3. Results

3.1. Trends in deforestation in Amazonia: 2008–2021

We measured deforestation in private properties, settlements, conservation units, indigenous lands, and undesignated public lands. Figure 5 shows the annual deforestation by land tenure type from 2008 to 2021. Deforestation inside private lands accounts for about 45% of the total. Cuts in private areas inside conservation units amount to about 4% of the total. Forest removal in settlements decreased from 31% of the total in 2008–2012 to 27% in recent years (2019–2021). Deforestation in undesignated public lands increased from 11% in 2008 to 18% in 2021.

The extent of legal and illegal deforestation for 2008–2021 is shown in figure 6. Except for 2008, the proportion of illegal deforestation ranges between 81% and 86%. The outlier for 2008 is due to the exemption granted by the Forest Code to small properties deforested before July 2008.

How concentrated is deforestation in Amazonia? To address this question, we measured the cumulative distribution of deforestation on properties and settlements, as shown in figure 7. Entries in the private land tenure map are ordered from highest to lowest annual deforestation. The graph excludes cuts in undesignated public lands, conservation units, and indigenous lands, which amount to between 20% and 25% of total yearly deforestation. The graph follows a power law. In general, only about 5% of the private properties and settlements are responsible for 100% of the forest cuts each year within the areas registered in the CAR.

From 2008 to 2012, a time of strong government action, about 1% of the properties carried out 75% of the forest cuts. During 2018–2021, when enforcement was strongly reduced, about 0.5% of the properties did 75% of the cuts. Figure 8 shows the location of all properties and settlements in the private land tenure map. We highlight the 1% of properties that account for 82.5% of forest cuts in registered areas in 2021. Such extreme concentration has important consequences for law enforcement actions, with the potential to significantly reduce deforestation by targeting those responsible for most of the damage.

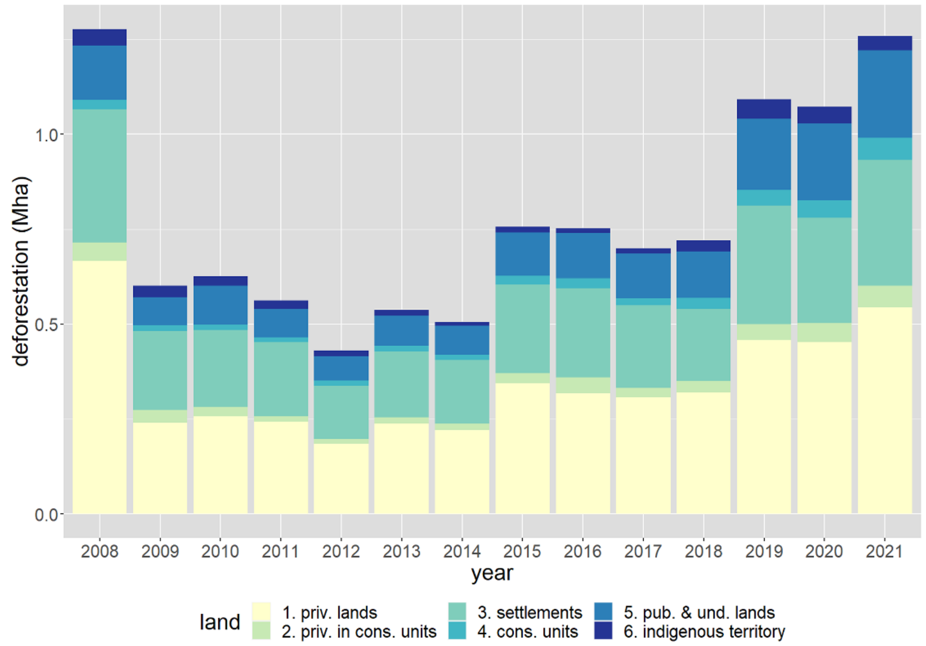

Figure 5. Deforestation area by land tenure type (2008–2021): (1) Private lands; (2) Private lands inside conservation units; (3) Settlements; (4) Conservation units; (5) Public and undesignated lands; (6) Indigenous territories.

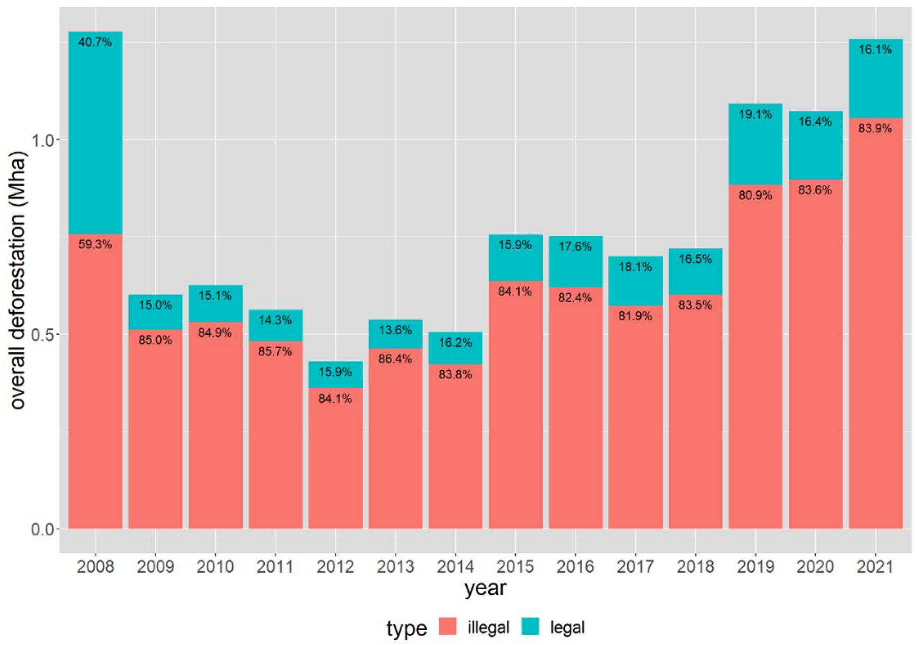

Figure 6. Legal and illegal deforestation in Amazonia biome (2008–2021).

3.2. Land use and forest restoration

To estimate how much legal reserve deficits and surpluses exist in private properties and settlements in Amazonia, we used INPE's PRODES deforestation maps. Comparing the current forest area for each property with the expected forest cover based on the Forest Code, we obtained values of deficit or surplus for each property. The individual values were added for each group of properties by type and size to obtain the data shown in table 3 as of 2021.

The results in table 4 show that, even if all forest surpluses are offered in the forest credits market, farmers still need to restore 5.67 Mha in Amazonia to comply with the Forest Code. Furthermore, there are many obstacles to ensuring farmers' compliance with the Forest Code. To better understand these

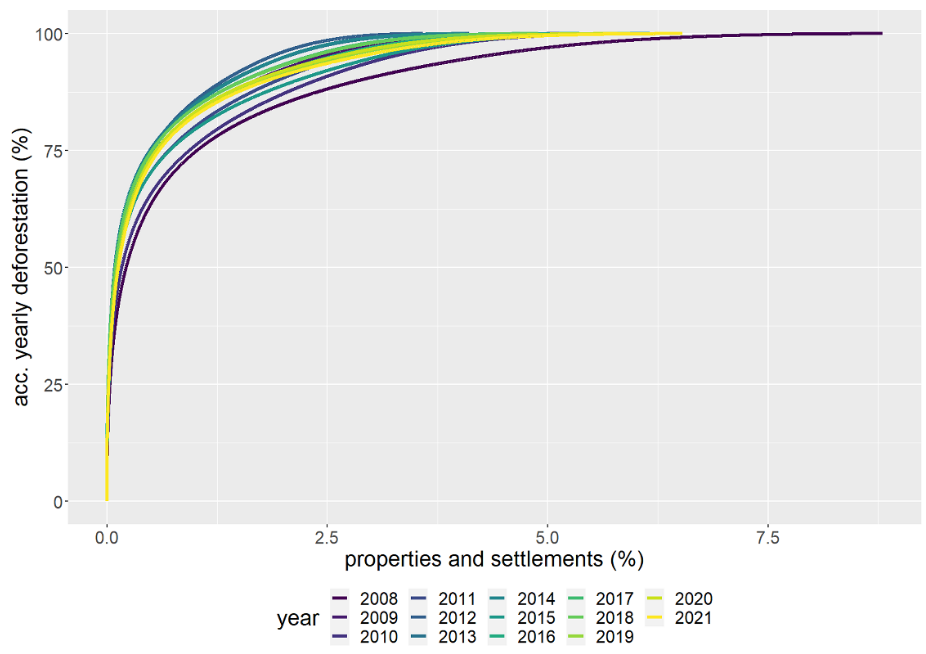

Figure 7. Cumulative distribution of deforestation on properties and settlements.

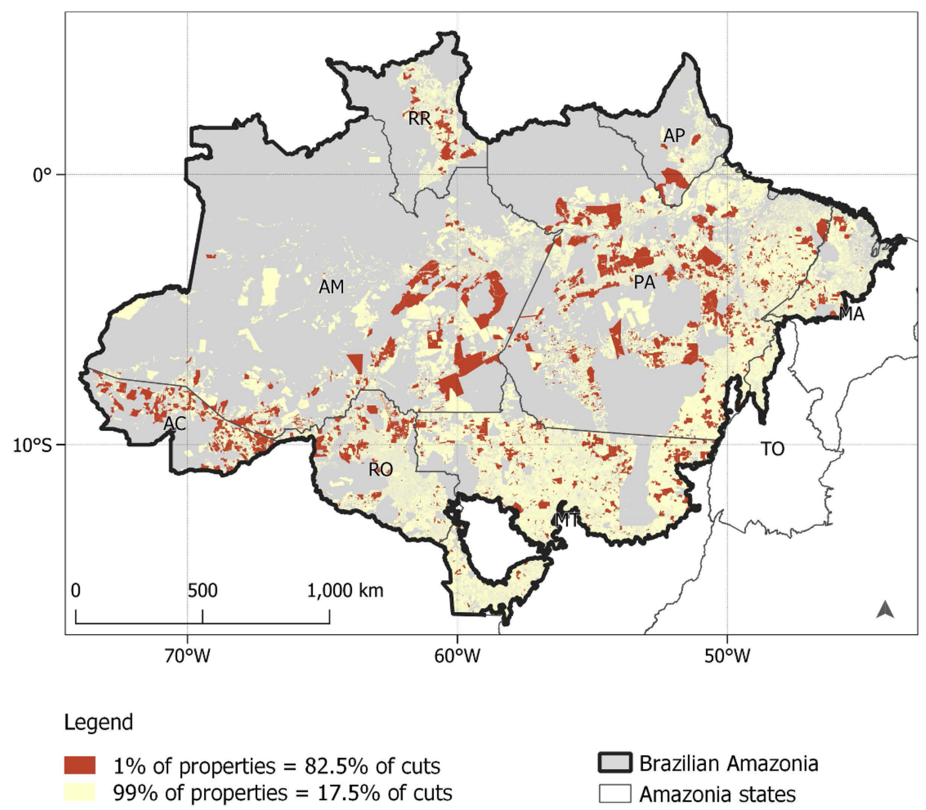

Figure 8. Private land tenure in Amazonia, showing 4737 properties (1%) responsible for 82.5% of deforestation inside private lands and settlements in 2021.

challenges, we need to consider how the type of land use in deforested areas affects farmers' reluctance to legal compliance.

To calculate the legal reserve deficits associated with each land use type, we used the 2020 TerraClass land use map for the Amazonia biome [19]. The most relevant land use classes identified in TerraClass are: (a) secondary forests; (b) herbaceous pasture with grasses; (c) shrubby pasture combining woody vegetation and grasses; (d) single-crop farming, mostly

Table 3. Total current forest area in private lands and legal reserve surpluses and deficit per property size for year 2021. Surplus refers to areas in private lands that exceed the forest protection mandate for such lands. Deficits refer to areas in private lands that need to be restored to comply with forest protection mandates set by Brazil's Forest Code.

Farm Type	Farm Size	Total Forest (Mha)	Deficit (Mha)	Surplus (Mha)
Private properties	0–200 ha	19.0	0.99	0.48
	200–1000 ha	22.8	3.81	1.55
	>1000 ha	65.1	7.67	8.20
Settlements		30.6	5.70	2.26
Total		137.5	18.17	12.49

Table 4. Area and legal reserve deficits per land use and farm size on private land tenure properties in Amazonia.

Land use	Farm type	Farm Size (ha)	Area (Mha)	Deficit (Mha)
Secondary forests	private	0–200	1.29	0.10
		200–1000	1.15	0.32
		>1000	2.07	0.65
	settlements		1.35	0.51
Total			5.86	1.58
Herbaceous pasture	private	0–200	7.68	0.59
		200–1000	6.80	2.28
		>1000	10.69	4.45
	settlements		7.66	3.57
Total			32.83	10.89
Shrubby pasture	private	0–200	2.65	0.26
		200–1000	1.84	0.60
		>1000	2.63	0.89
	settlements		3.50	1.37
Total			10.62	3.12
Single–crop farming	private	0–200	0.10	0.01
		200–1000	0.20	0.08
		>1000	0.37	0.16
	settlements		0.07	0.03
Total			0.74	0.28
Multi–crop farming	private	0–200	0.50	0.02
		200–1000	1.30	0.45
		>1000	2.76	1.37
	settlements		0.27	0.19
Total			4.83	2.03

soybeans; (e) multi-crop farming, mostly soy-corn or soy-cotton. Table 4 shows farm areas by land use type and associated legal reserve deficits.

As shown in table 4, there are 5.86 Mha of secondary forests in Amazonia, with a surplus of 4.28 Mha. These are areas that have been cut after 2014 and thus have less than seven years of recovery. Secondary forests have the lowest opportunity costs for forest restoration.

TerraClass maps provide information on herbaceous and shrubby pastures separately. Herbaceous pastures are areas where farmers invested in exogenous grasses that allow for a greater stocking rate. Shrubby pastures emerge as part of a pasture degradation process; if not enough money is spent on renewing pasture grasses, natural regeneration will occur, leading to a mixed land cover with grasses and shrubs [26]. As shown by Uhl *et al* [26], planted pasture grasses lose vigor after three to four years. A 1994 study by Mattos and Uhl [30] estimates that restoring a degraded forest costs US\$ 260 ha^{-1} (US\$ 560 in 2022 values). In a 2017 study, Garcia *et al* [31] state that maintaining high-yield pastures in Amazonia has an average yearly cost of US\$ 1335 ha^{-1}. Thus, maintaining good-quality herbaceous pastures requires continuous capital investment, favoring medium and large farmers.

Herbaceous pastures (90% or more of grasses) cover 32.83 Mha, mostly associated with big herds on medium and large farms. About 34% of these areas (10.89 Mha) have legal reserve deficits. Shrubby pastures occupy a smaller area than herbaceous pastures (10.62 Mha), but also one-third (3.12 Mha) of those should be reforested to comply with the law. Such low-quality pastures occur most frequently (58% of the total) in small farms and settlements in Amazonia. Small-scale farmers and settlers have 6.15 Mha of shrubby pastures, of which 1.63 Mha (27%) correspond to legal reserve deficits. This distribution is consistent with the significant investment required to keep good quality pastures in Amazonia, favoring economies of scale.

Most single-crop and multi-crop farming occurs in medium and large properties (4.63 Mha), with an associated deficit of 2.06 Mha (45%). Such a deficit is substantial; thus, it will require strong public action for crop producers to become compliant with the Forest Code.

4. Discussion

Brazil faces a significant challenge in addressing deforestation in Amazonia, as more than 80% of it is illegal. The country needs robust command and control strategies, with strict law enforcement being essential for reducing illicit activities in the region. Moreover, only a small proportion of farmers and settlers carry out most forest cuts on private lands (see figure 8). In the past, the lack of such detailed information led to blanket measures that punished all owners in a region, regardless of the legality of their actions [32]. Knowing that deforestation is concentrated in a few actors allows the government to run targeted control actions to prevent illegal deforestation.

Large-scale cattle ranching is a particular area of concern, as shown by the 10.35 Mha of forest reserve deficit (one-third of their area) reported in table 4 in farms with herbaceous pasture. The government must enforce the law to ensure ranchers comply with legal reserve requirements and prevent impunity. Full compliance would require ranchers to increase their stocking rate by over 50%, a significant intensification over their current practices. Since the industry has a strong political presence in the region and Congress, ranchers will likely push for incentives and payments for environmental services resulting from restoration. To make progress, Brazil should combine intelligent credit policies with new livestock production technologies and strong Forest Code compliance requirements.

Small farmers and settlers linked to cattle raising face unique challenges when complying with the Forest Code. Out of the 10.62 Mha of shrubby pastures, 3.12 Mha must be restored or compensated (cf table 4). However, forest restoration in shrubby pasture areas requires significant investment; maintaining high-yield pastures is not viable for small farms [31]. Small farmers and settlements cannot maintain profitable livestock farms that abide by the law. Since they lack capital, buying environmental reserve quotas is impossible for them. Therefore, the government must establish an incentive regime to encourage small farmers and settlers to restore their land. This will require careful design to promote both legal compliance and social justice.

High-yield crop producing areas have the largest extent of legal reserve deficits (42% of total area) and high economic value [33, 34]. Crop farmers are more likely to buy environmental reserve quotas than to use their lands for restoration. Since most crop production in Amazonia is for export [35], pressure from international markets could induce Brazilian producers to comply with the law. This presents an opportunity to set up a viable forest credits market, but the government must ensure that it promotes forest protection and social justice [36].

Considering there are 18.17 Mha of legal reserve deficits in Amazonia and 12.49 Mha of legal reserve surpluses (as per table 3), the forest credits market is not sufficient to meet the legal demands of the Forest Code in Amazonia. An additional 5.67 Mha must be restored to comply with the law. This situation challenges the Brazilian government, which needs to combine market-driven policies with strict law enforcement. To control deforestation and achieve Brazil's forest restoration targets, government actions must address landowners' resistance to compliance. Targeted strategies will be necessary, with restoration and market policies designed according to land use, farm size, and access to credit and technology.

5. Conclusions

This study provides new insights into the challenges of deforestation control and forest restoration in the Brazilian Amazon. We propose a set of methods to produce a clean version of the Cadastro Ambiental Rural (CAR) and to estimate landowners's compliance with the Forest Code. We show that a reliable private land tenure cadastre is essential to meet Brazil's targets of reducing land use emissions and promoting forest restoration.

Once the CAR is complete, the government can establish a forest credits market based on environmental reserve quotas. Large-scale crop producers and cattle ranchers could use these quotas to meet legal reserve deficits. To meet this demand, forest credits would be offered to small farmers and settlements who restore their lands and use the resulting surpluses in the quota market to compensate for their foregone opportunity costs. By validating the CAR, targeting the few landowners who deforest the most, using public credits to enforce forest restoration, and establishing a viable credits market, Brazil can protect the Amazon rainforest with a stable arrangement that balances production with protection.

Our study demonstrates the key role land tenure arrangements play in deforestation and forest restoration processes within Amazonia. For Brazil to attain its deforestation reduction and forest restoration objectives, it must balance command-and-control actions and market-based incentives. Policies should be tailored to address the distinct needs of various landowners, considering their land use practices, technical capacity, and financial resources.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://figshare.com/articles/dataset/Forest_restoration_challenges_in_Brazilian_Amazonia_Data_and_code/22129325.

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Conflict of interest

The authors declare no competing interest.

Author contributions

G C conceived and designed the study, interpreted the results, and was the main writer of the manuscript. R S, H R, and P A produced the maps of land tenure, forest protection, and APP, developed scripts for data analysis, discussed the results, and supported writing of the manuscript; A S and F R supported the study conception and revised the manuscript at various stages; R R and M S performed additional data analysis; C A and L M produced the deforestation maps, analyzed the results, and revised the final drafts; I S, A C, J E, J A, A V, M A produced the land use map, analyzed the results and revised the final drafts. All authors reviewed the results and approved the final version of the manuscript.

Appendix. Obtaining the land tenure map for Amazonia based on the Forest Code

This appendix explains in detail how the authors have interpreted the provisions of the Forest Code and other applicable legislation to produce the private land tenure map for Brazilian Amazonia. The Forest Code states that owners must set aside 80% of their forest area as legal reserve. However, the Code has several exceptions and waivers. There are two cases where the Law grants absolute reduction of legal reserve:

- Article 12 section 5 provides a special condition for states with over 65% of their area occupied by conservation units and indigenous lands. Private properties in those states benefit from an unconstrained legal reserve reduction from 80% to 50%.
- Article 67 provides a waiver for small rural properties. For these lands, the legal reserve is taken as the remaining forest area as of 22 July 2008. The Law grants this amnesty if owners did not deforest their lands after that date.

Including these articles on the forest, the protection map is straightforward. Article 12 section 5 applies only to Roraima (RR) and Amapá (AP) states. To include the exemptions of Article 67, we identified all small properties covered by this provision. We used the INPE PRODES maps from 2008 to 2021 to find which properties had not cut forests since 2008.

Other provisions of the Forest Code allow reducing the legal reserve from 80% to 50% for restoration purposes only, as follows:

- Article 12 section 4 singles out municipalities where more than 50% of its area is taken by conservation units and indigenous lands.
- Article 13 allows states to define special areas of ecological-economic zoning where the legal reserve is to be reduced.
- Article 68 considers rural properties that had cut forests up to 25 July 1996 respecting the legal reserve limit of 50% valid before that date and that have not deforested their lands ever since.

To include Article 12 section 4, we matched data on conservation units and indigenous lands, municipal boundaries, and the location of rural properties. As for Article 13, we used data on ecological-economic zoning provided by Embrapa’s SIAGEO database [20] to identify which subregions in Amazonia qualify for a reduction in legal reserve.

The final step was to determine whether a rural property was eligible for the exception granted by Article 68. To do so, we had to estimate the extent of deforestation on the property by July 1996. Because the INPE PRODES deforestation maps are only available from 2008 onwards, we used the MapBiomas annual maps from 1985 to 1998 [21]. Our analysis requires that primary and secondary forests are mapped as different classes. Unlike PRODES, MapBiomas annual maps have a single forest class that includes both cases. For this reason, we combined the PRODES and MapBiomas maps to get a land cover map for 1996 where natural forests are split from secondary forests. The resulting map allowed us to determine which properties meet the requirements of Article 68 of the Forest Code.

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References

[1] INPE 2022 Amazon deforestation monitoring project (PRODES) *Technical Report* (Brazil: National Institute for Space Research)
[2] Chiavari J and Lopes C L 2017 Forest and land use policies on private lands: an international comparison *Technical Report* (Climate Policy Initiative/PUC-Rio)
[3] Soterroni A C *et al* 2018 Future environmental and agricultural impacts of Brazil's Forest Code *Environ. Res. Lett.* **13** 074021
[4] Stabile M C C, Guimarães A L, Silva D S, Ribeiro V, Macedo M N, Coe M T, Pinto E, Moutinho P and Alencar A 2020 Solving Brazil's land use puzzle: increasing production and slowing Amazon deforestation *Land Use Policy* **91** 104362
[5] Greenfield P and Harvey F 2022 Lula vows to undo environmental degradation and halt deforestation *The Guardian*
[6] Sparovek G, Barreto A G O P, Matsumoto M and Berndes G 2015 Effects of governance on availability of land for agriculture and conservation in Brazil *Environ. Sci. Technol.* **49** 10285–93
[7] Schielein J and Borner J 2018 Recent transformations of land-use and land-cover dynamics across different deforestation frontiers in the Brazilian Amazon *Land Use Policy* **76** 81–94
[8] Silva F d F, Perrin R K and Fulginiti L E 2019 The opportunity cost of preserving the Brazilian Amazon forest *Agric. Econ.* **50** 219–27
[9] Rajão R *et al* 2020 The rotten apples of Brazil's agribusiness *Science* **369** 246–8
[10] Azevedo-Ramos C, Moutinho P, Arruda V L d S, Stabile M C C, Alencar A, Castro I and Ribeiro J P 2020 Lawless land in no man's land: the undesignated public forests in the Brazilian Amazon *Land Use Policy* **99** 104863
[11] Chiavari J, Lopes C and Araujo J 2021 Onde estamos na implementação do código florestal? Radiografia do CAR e do PRA nos Estados Brasileiros (implementation of Forest Code - current status) *Technical Report* (Climate Policy Initiative/PUC-Rio)
[12] Soares-Filho B, Rajao R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H and Alencar A 2014 Cracking Brazil's Forest Code *Science* **344** 363–4
[13] Guidotti V, Ferraz S F d B, Pinto L F G, Sparovek G, Taniwaki R H, Garcia L G and Brancalion P H S 2020 Changes in Brazil's Forest Code can erode the potential of riparian buffers to supply watershed services *Land Use Policy* **94** 104511
[14] Brites A and Mello K 2021 O Avanco da implementacao do codigo-florestal no Brasil (progress in Forest Code implementation in Brazil) *Technical Report* (Observatorio do Codigo Florestal)
[15] CSR 2022 Panorama codigo florestal Brasileiro (status of Brazil's Forest Code) *Technical Report* (Centro de Sensoriamento Remoto, UFMG)
[16] Drummond J A, Franco J L d A and Ninis A B 2009 Brazilian federal conservation units: a historical overview of their creation and of their current status *Environ. Hist.* **15** 463–91
[17] Foresta R A 1992 Amazonia and the politics of geopolitics *Geogr. Rev.* **82** 128–42
[18] Pereira A S A d P, dos Santos V J, Alves S d C, Amaral e Silva A, da Silva C G and Calijuri M L 2022 Contribution of rural settlements to the deforestation dynamics in the Legal Amazon *Land Use Policy* **115** 106039
[19] Almeida C, Coutinho A, Esquerdo J, Adami M, Venturieri A, Diniz C, Dessay N, Durieux L and Gomes A 2016 High spatial resolution land use and land cover mapping of the Brazilian legal Amazon in 2008 using Landsat-5/TM and MODIS data *Acta Amazonica* **46** 291–302
[20] EMBRAPA 2022 SIAGEO Amazônia (sistema interativo de Análise geoespacial da Amazônia legal) (available at: www.amazonia.cnptia.embrapa.br/)
[21] Souza C M Jr *et al* 2020 Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat archive and earth engine *Remote Sens.* **12** 2735
[22] Azevedo A A, Rajão R, Costa M A, Stabile M C C, Macedo M N, dos Reis T N P, Alencar A, Soares-Filho B S and Pacheco R 2017 Limits of Brazil's Forest Code as a means to end illegal deforestation *Proc. Natl Acad. Sci.* **114** 7653–8
[23] Dockendorff C, Fuss S, Agra R, Guye V, Herrera D and Kraxner F 2022 Committed to restoring tropical forests: an overview of Brazil's and Indonesia's restoration targets and policies *Environ. Res. Lett.* **17** 093002
[24] Rosim S and Rennó C D 2013 TerraHidro: a distributed hydrology modelling system with high quality drainage extraction *GEOProcessing 2013 : The 5th Int. Conf. on Advanced Geographic Information Systems, Applications and Services* p 7
[25] da Costa F R, de Souza R F and da Silva S M P 2016 Análise comparativa de metodologias aplicadas à delimitação da bacia hidrográfica do Rio Doce - RN (Comparative analysis of methodologies applied to the demarcation of the basin of Rio Doce - RN) *Soc. Nat.* **28** 429
[26] Uhl C, Buschbacher R and Serrao E A S 1988 Abandoned pastures in Eastern Amazonia. I. Patterns of plant succession *J. Ecol.* **76** 663–81
[27] Tyukavina A, Hansen M C, Potapov P V, Stehman S V, Smith-Rodriguez K, Okpa C and Aguilar R 2017 Types and rates of forest disturbance in Brazilian Legal Amazon, 2000–2013 *Sci. Adv.* **3** e1601047
[28] Picoli M C A, Rorato A, Leitão P, Camara G, Maciel A, Hostert P and Sanches I D 2020 Impacts of public and private sector policies on soybean and pasture expansion in Mato Grosso—Brazil from 2001 to 2017 *Land* **9** 20
[29] Wang Y, Ziv G, Adami M, de Almeida C A, Antunes J F G, Coutinho A C, Esquerdo J C D M, Gomes A R and Galbraith D 2020 Upturn in secondary forest clearing buffers primary forest loss in the Brazilian Amazon *Nat. Sustain.* **3** 290–5
[30] Mattos M M and Uhl C 1994 Economic and ecological perspectives on ranching in the Eastern Amazon *World Dev.* **22** 145–58
[31] Garcia E, Ramos Filho F S V, Mallmann G M and Fonseca F 2017 Costs, benefits and challenges of sustainable livestock intensification in a major deforestation frontier in the Brazilian Amazon *Sustainability* **9** 158

[32] Cruz D C, Benayas J M R, Ferreira G C, Santos S R and Schwartz G 2021 An overview of forest loss and restoration in the Brazilian Amazon *New Forests* **52** 1–16

[33] Börner J and Wunder S 2008 Paying for avoided deforestation in the Brazilian Amazon: from cost assessment to scheme design *Int. Forestry Rev.* **10** 496–511

[34] Spera S A, Cohn A S, VanWey L K, Mustard J F, Rudorff B F, Risso J and Adami M 2014 Recent cropping frequency, expansion and abandonment in Mato Grosso, Brazil had selective land characteristics *Environ. Res. Lett.* **9** 064010

[35] zu Ermgassen E K H J *et al* 2020 Using supply chain data to monitor zero deforestation commitments: an assessment of progress in the Brazilian soy sector *Environ. Res. Lett.* **15** 035003

[36] May P H, Bernasconi P, Wunder S and Lubowski R 2015 Environmental reserve quotas in Brazil's new forest legislation: an ex ante appraisal *Technical Report* (Center for International Forestry Research (CIFOR))