



How vegetation classification and mapping may influence conservation: The example of Brazil's Native Vegetation Protection Law

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ABSTRACT

The way vegetation is officially named, classified, and identified has critical implications for ecosystems and biodiversity conservation. Yet little attention is given to how such issues hinder the efficacy of laws mandating environmental conservation on private land. In the Brazilian Amazon where half of the land is now already under private tenure or is available for future land-uses, differences in vegetation mapping and interpretation directly affect the level of protection in private rural properties, especially in transition areas where forest and savanna areas intermingle. Since Brazil's Native Vegetation Protection Law (NVPL) attaches a higher percentage of protection to forest-located properties, landowners may be tempted to use conflicting mappings and different vegetation classifications to claim their properties are located in areas other than forests to reduce their conservation requirements. In this paper, we compare three official vegetation databases and examine different law interpretation scenarios to assess the extent to which the level of private conservation may fluctuate. We found a difference of up to 430,000 km² of protected vegetation (an area the size of Iraq) according to the database and vegetation characteristics chosen. This technical ambiguity may lead to make additional deforestation legal or reduce sharply the amount of vegetation to be restored for these areas, if left unaddressed. Clarifying the database and criteria used to define forest is critical, especially as Brazilian states may make different choices in that regard, and cases in which loopholes are exploited occurred in the recent past. Given the importance of this region for global biodiversity conservation and climate, we highlight the urgent need to: (1) support additional research to clarify vegetation characteristics and location; (2) agree on a harmonized methodology to determine forests for NVPL implementation, and (3) explore alternative criteria for defining forests when databases conflict.

1. Introduction

The way vegetation is conceptualized and named by scientists and governments may have important global implications for the conservation of ecosystems, both for publicly and privately protected areas (Dryflor et al., 2016; Overbeck et al., 2015; Marques et al., 2011). Conservation laws regulating privately-held areas typically depend on forest classifications to apply (Marques et al., 2019). The forest definition used may thus influence the extent of area protected.

Brazil's Native Vegetation Protection Law (NVPL) is a paramount example in this respect. It imposes private landowners to protect a Legal Reserve (LR) consisting of a certain percentage of their areas, which varies depending on the vegetation: 80% for Amazonian forests and either 35% or 20% depending on vegetation type and location in Brazil. As a result, Brazilian private landowners are currently responsible for the management of about 30% of the country's above-ground carbon stock, two thirds of which are protected under the NVPL (Freitas et al., 2018). As the 2012 revision of the NVPL states that properties

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containing different vegetation types can have differentiated LR rates in function of their respective area, the question of how vegetation types are identified at property-level and which reference cartography to use is crucial.

These apparently technical questions can very significantly impact the overall conservation of the Legal Amazon region of Brazil. As we demonstrate in this paper, the total area which could potentially be protected under the LR varies from 1.74 million km² (Mkm²) to 1.31 Mkm² in function of the reference used, a 430,000 km² difference (equivalent to the area of Iraq). In order to demonstrate how vegetation cartography may have such a dramatic impact, we provide a comparison of three conservation scenarios using different official vegetation maps and vegetation reference, especially influenced by the nature of areas where savannas and forests coalesce (called “transition”). We then estimate how a change of map and vegetation reference would make a difference in the areas to be potentially protected as LR. We end by a discussion of how uncertainties about forest definition create loopholes that may either lead to more deforestation being legally allowed or a reduction in the amount of vegetation to be restored. Recent cases prove that this concern is all but theoretical.

Since choosing a particular dataset interpretation leads to critically different levels of forest protection, the choice of forest definition is inherently political. Several land use policy measures could solve this situation: (1) an agreement on which database(s) to use as the main reference for defining forests; (2) the creation of official forest definition guidelines for NVPL implementation; and (3) strengthening state environment agencies’ capacity (*secretarias de meio ambiente*) to conduct forest cover analyses and address landowners’ claims.

Although the challenge for forest definition has been known to Brazilian states for years, it has taken a new dimension with the 2012 NVPL reform and the creation of an environmental registry system whereby landowners must declare land cover information of their property. Without a clear forest definition, it becomes harder to verify such declarations and assess the level of forest protection and restoration in some areas, let alone target monitoring and enforcement activities toward illegal deforestation activities. Given the recent lack of support to environmental policies in Brazil, it appears essential to resolve potential ambiguities around the delineation of forest areas, as these can influence the amount of vegetation effectively protected and restored.

2. Context

2.1. The Legal Amazon as a critical region for conservation

The Legal Amazon region of Brazil⁴ is a geographical area containing native vegetation that plays a key role for biodiversity (Hubbell et al., 2008; Steege et al., 2013; Forzza et al., 2012), the regulation of South America’s water regimes, and the global climate (Nobre et al., 2016; Coe et al., 2016). Covering an area of 5 million (m) square kilometers (km²), it is split into two biomes: on the one hand the Brazilian share of the Amazon biome (4.19 m km², of which 16.4% has been cleared), mostly (but not exclusively) dominated by dense ombrophiles forests, and on the other hand part of the Cerrado biome (0.75 m km², of which 36.4% has been cleared) (Carneiro et al., 2018; Klink and Ricardo, 2005; INPE, 2020b, 2020a), characterized by the presence of extensive savannas.⁵ Far from being uniform both biomes are mosaics of different vegetation

⁴ The Legal Amazon is an administrative region created in 1953 to administer development subsidies and includes the following states: Acre, Amazonas, Roraima, Rondônia, Mato Grosso, Pará, Amapá, Tocantins and part of Maranhão.

⁵ In Brazil, the word *cerrado* can refer both to the biome and to the savanna formations. For the sake of clarity, in this text, we will use Cerrado only as a reference to the biome, while we will use “savanna” as a reference to savanna-like vegetation types.

types (Fig. 1). Several of these are gradual “transitions” between forests and savannas (“forest-savanna transitions”, hereafter FST).

Intense land-use change in this region (i.e. deforestation primarily for cattle-ranching or agriculture) has depleted the carbon stock of the Amazon, which is now estimated to capture 58.62 ± 12.81 billion (bn) tons of carbon (C) (Nogueira et al., 2015), and has led experts to question the role of the Amazon forest as a net absorber (or emitter) of carbon (Fearnside, 2018). Similarly, experts have highlighted the high clearing rates in the Cerrado biome (Strassburg et al., 2017; Aubertin and Pinton, 2013), the conservation of which underpins that of the Amazon rainforest (Malhado et al., 2010). Deforestation rates have known a short-lived but significant decline in the 2004–2012 period due to a combination of market forces (Gibbs et al., 2015, 2016; Massoca et al., 2017), agricultural intensification (Arvor et al., 2012), innovative environmental policies (Assunção et al., 2015; Nepstad et al., 2014) and heavy-handed law enforcement.⁶ Deforestation has since been on the rise again, oscillating between 5000 and 10,000 km² in the Amazon biome (INPE, 2020a) and between 6000 and 14,000 km² per year in the Cerrado biome (INPE, 2020b).

Due to these critical changes in land cover, scientists have warned of the possible and irreversible “savannization” of the Amazon if a tipping point of 40% of its original cover was to disappear (Lovejoy and Nobre, 2018; Nobre et al., 2016; Silvério et al., 2013). Such a transformation would have critical impacts at the regional and the global level given the role of the Amazon in climatic stabilization and biodiversity conservation (Nobre et al., 2016; Coe et al., 2016).

2.2. Private properties, Legal Reserves and the Native Vegetation Protection Law

Slightly less than half of the Legal Amazon area is preserved through protected areas and indigenous reserves (Nogueira et al., 2018). The other part is either under federal or state ownership as “undefined use” lands or under private tenure. New recent efforts to promote or regularize the privatization of public lands, like the *Terra legal* program, will probably increase the proportion of the latter in the next years (Campbell, 2015; Lipscomb and Prabakaran, 2020).

Private properties are regulated by one of the centerpieces of Brazilian environmental policies: the Native Vegetation Protection Law (NVPL) (Daugeard, 2021). The NVPL imposes private landowners to preserve a percentage of native vegetation cover on their properties under two categories. The first category is the Permanent Protection Areas (PPA) covering riparian areas, hilltops, and steep slopes in order to conserve water resources and prevent soil erosion. The second category, more controversial because it is also much more significant in terms of area, is the Legal Reserve (LR), a share of the property placed under strict land-use controls. It is currently estimated that as much as one third of all remaining native vegetation in Brazil is contained in LRs of private rural properties (Metzger et al., 2019).

The LR mechanism has been at the center of an intense controversy since the 1990 s. Up to this time, the LR percentage was set to 50% for the north and center-west of Brazil and between 20% and 50% for the other regions, following the region-based criterion of the 1965 Forest Code. The gradual switch to a vegetation-based criterion in 1989, and the increased protection of forest areas to a 80% LR in 1996, triggered a big uproar by the agricultural sector. Intense policy pressure in

⁶ We refer in particular to measures such as the 1998 Environmental Crimes Law (Law n°9.605 of February 12, 1998), the various enforcement plans by federal environmental authorities in the 2000 s (e.g. PPCDAm I & II), and the creation of the list of priority municipalities in 2007–2008 (Decree n°6.231 of December 21, 2007), all of which were interpreted by the agricultural sector as a “witch hunt” for farmers. Cunha and Mello-Théry (2017) show the role played by the *bancada ruralista* (i.e. agribusiness’ and landowners’ congressional lobby) in the leveling down of the FC in 2012.

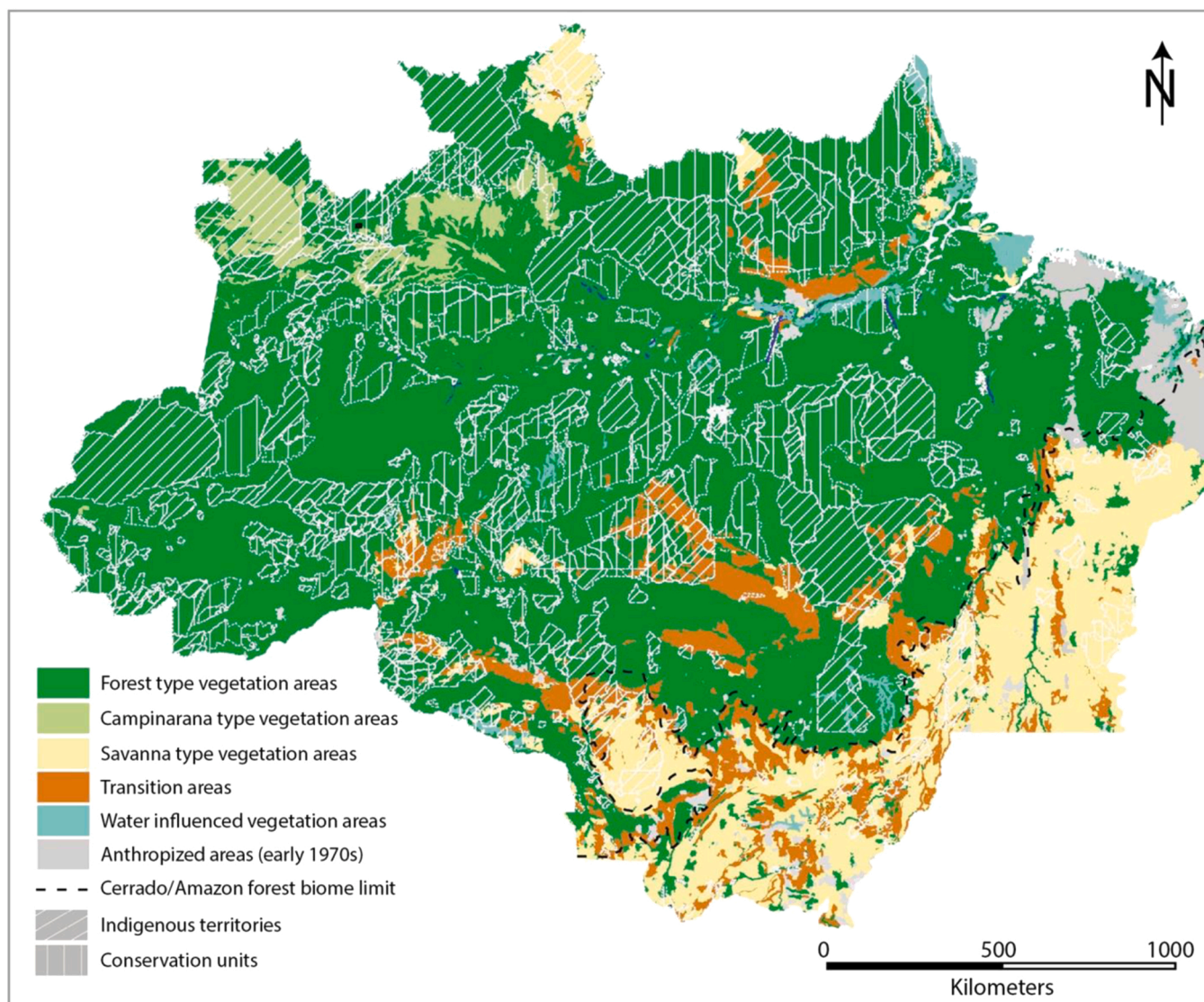


Fig. 1. Brazilian Amazon land cover according to RADAM and coverage of indigenous territories and protected areas. Vegetation cover in the Amazon is much less uniform than generally thought. This map highlights many transition vegetation types found in the original RADAM cartography, where intermingled forest and savanna patches might lead to a number of reduced environmental protection claims by landowners in the future. Landowners can claim reductions based on the property-level vegetation type survey that is required by the Native Vegetation Protection Law in order to determine the Legal Reserve percentage to be applied. Anthropized areas represent the situation of the early 1970 s when the RADAM project was initiated.

the following decade culminated in the reformulation of the NVPL in 2012. If, on the one hand, this revision was welcomed for maintaining the high LR percentages established recently, on the other hand, numerous exemptions to the rule were created for landowners, qualified by some as a general “amnesty” for illegal deforestation (Soares-Filho et al., 2014; Azevedo et al., 2017; Brancalion et al., 2016). Smallholders who have deforested until 2008 neither need to comply with LR requirement nor the obligation to restore the native vegetation covered by the LR missing on the property. The law nonetheless introduced the mandatory registration of private rural properties into a satellite-based environmental registry (called “*Cadastro Ambiental Rural*” – CAR) containing precise information about their land cover.

According to the 2012 NVPL, the LR percentage of protection in the Legal Amazon depends on the dominant vegetation type: 80% for “forest” vegetation areas and 35% for “cerrado” (i.e., savannas) vegetation areas. Instead of applying the LR percentage to entire properties, each vegetation area within a property is protected to different extents. As §2 of article 12 of the NVPL states: “*The percentage of the LR of properties located in zones of forest formations, savannas or steppes in the Legal*

*Amazon will be defined considering separately the indices defined in I [the different indices of LR]”.*⁷ Therefore, not all properties in the Amazon biome have a 80% LR and not all properties in the Cerrado have a 35% LR, contrary to what is casually assumed by many observers.

LR percentages may in fact vary *within* each property, depending upon the vegetation types present, and the total area protected ultimately has to be broken down by each vegetation area (Daugeard, 2021). This extremely significant specificity implies that landowners in the Amazon biome may clear savanna-like vegetation areas of their properties (or areas that they may claim to be such) up to 65% (as opposed to only 20% if we considered their whole area to be forests), making way for more legally-authorized deforestation. Conversely, this

⁷ English translation of article 12 by the authors. The original text in Portuguese is: “O percentual de Reserva Legal em imóvel situado em área de formações florestais, de cerrado ou de campos gerais na Amazônia Legal será definido considerando separadamente os índices contidos nas alíneas a, b e c do inciso I do caput”.

also implies that forest-like vegetation areas in the Cerrado biome should be preserved at 80%, which is rarely the case and could increase the “environmental debt” of Cerrado-located landowners.

2.3. The challenge to operationalize Brazilian vegetation classification

As we stressed, both the Amazon and the Cerrado biomes are not uniform in terms of vegetation cover. Rather, they present mosaics of finely intricated vegetation types, which explains the importance of the reference mapping that will be used to determine the extent and limits of each of them. The diversity of vegetation types in Brazil has been highlighted from the first attempts to classify and map them. Already in 1824, the Martius classification pointed out to two main formations, the Hiléia (forest) and the Oreads (savannas), in an area equivalent to today’s Legal Amazon. Later the 1908 Üle classification stressed the diversity of forest types within the Amazon as well as the existence of non-forest physiognomies within the Amazon biome (Joly et al., 1999). In the 1950 s, Duke and Blake proposed another classification, later completed by UNESCO. This work was later improved by the RADAM⁸ mapping initiative (1973–1983) led by the Ministry of Mines and Energy, which mapped the whole Amazon region at the scale of 1:250,000 by using side-looking airborne radar imagery cross-checked with vegetation inventories at more than 3500 points throughout the region (Fearnside and Ferraz, 1995). The final output were 1:250 000 topographic maps and 1:1000,000 thematic cartographies, among which vegetation maps distinguishing 92 different vegetation cover types and other land-uses for the Legal Amazon region. This work was later extended to the rest of Brazil and picked up by the Brazilian Institute of Geography and Statistics (IBGE) in 1985. IBGE modified this vegetation classification system in 1991 in order to create the official Brazilian vegetation classification system, which identifies 21 primary phyto-physiognomies, more than 160 vegetation sub-groups, and 18 types of “contacts” or transition between vegetation types (Joly et al., 1999). The RADAM still is one of the primary datasets used by institutions when assessing land classification.

Launched in 2004, The PROBIO⁹ project represented an update of the RADAM and followed a biome-based approach. Different institutions conducted the mapping effort in each biome, which relied on satellite imagery (LANDSAT and MODIS) of 2002 and visual interpretation to verify vegetation cover, producing 1:250,000 vegetation maps of all Brazilian biomes (Lúcio, 2014). If PROBIO has the same vegetation and transition classes than RADAM, it however classifies areas slightly differently: (1) it integrates land-use change that occurred since the RADAM was first published; (2) it adopts different parameters when determining each polygon’s vegetation type. As a result, it differs substantially from RADAM (see Results).

In all vegetation mapping efforts, the FST areas represent a particularly thorny classification issue. As one progresses southward or eastward from the Amazon biome, dense ombrophiles types are gradually replaced by drier, semi-deciduous mesophytic forests, the presence of which is influenced by the length and intensity of the dry season occurring in the Cerrado biome. This Zone of Ecological Tension contains diverse forest vegetation types that can be considered as “transition vegetation” (Fearnside and Barbosa, 2003), including for instance the so-called *cerradão* (“tall savannas” in Portuguese), but can extend even further down following the course of river streams representing a “hyperdynamic” area where forests retreat “into and out of the Cerrado region” (Marimon et al., 2014: 7). In such areas, forest and savanna vegetation formations intermingle, forming a “vegetational mosaic”

⁸ No translation available in English. In Portuguese, *Projeto Radar da Amazônia*, later expanded to *Projeto Radar do Brasil* (RADAMBRASIL).

⁹ Brazilian Biological Diversity Conservation and Sustainable Use Project (No official translation available in English). In Portuguese, *Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira*.

(Ackerly et al., 1989: 117) that is challenging if not impossible to classify as unique type.

Issues of vegetation identification and the almost impossibility to classify real ecosystems in clear-cut categories complicate the implementation of the NVPL. As the NVPL does not explicitly define which reference cartography shall be used for assessing the LR on each property, and as no particular vegetation mapping stand out as recognized by all actors, those who want to reduce environmental protection may legally argue that LR percentages should be smaller in their properties by claiming that they are located in a less protected vegetation class. This contestation of LR percentages through the re-qualification of vegetation type is particularly more likely to occur when landowners are wealthy,¹⁰ and in areas in the FST areas located in the Southeastern Legal Amazon at the limit of the Cerrado and Amazon biomes – currently forming the front where land conversion is massively taking place. As the concepts of “forest” and “savannas” are not defined precisely in the NVPL, and as the transition between one and the other is in general very gradual, there is significant room to interpret what is to be considered “forest area” (and bound to a 80% LR) and what is “savanna area” (bound to 35% LR) there. This concerns especially a large buffer located at the South of the Amazon biome where forest and savanna vegetation collide into each other in a zone 40–250 km-wide (Marques et al., 2019).

Given this relative uncertainty, the official PRODES deforestation monitoring project led by the National Institute for Space Research (INPE¹¹) may represent an alternative reference. To account for forest loss, the project required to settle on an initial delineation of the areas to be considered forests (a “forest/non-forest mask”), such that it could identify events of land-use change in later years. After consultation, the program managers decided to create an ad-hoc mask which would include all forest areas of the Legal Amazon (for both the Amazon and Cerrado biome areas within) (PRODES coordinator, personal communication, April 29, 2020). Even if it does not constitute a full vegetation mapping as RADAM and PROBIO, this dataset is worth considering in light of its use by Brazilian authorities for deforestation monitoring and control operations (based on the NVPL) and could possibly constitute an unambiguous reference for the implementation of the NVPL since it clearly defines forest and non-forest areas.

3. Materials and methods

3.1. Source datasets

The three vegetation datasets mentioned above were used in this study. The first two, RADAM and PROBIO, are complete vegetation mappings; the third one is the “forest/non forest” mask used by PRODES. In order to match deforestation against vegetation types in the different datasets, we used the PRODES dataset which recorded deforestation up to 2018 (INPE, 2020b, 2020a). Such data are released in two datasets, one counting deforestation of forests taking place in the Brazilian Amazon within the “forest mask”, and one depicting the deforestation of savannas areas within the Cerrado biome. Please refer to the [Supplementary Materials](#) for our approach for combining both datasets. For Amazon and Cerrado biome boundaries, we used the shapefile produced by IBGE and publicly available on website of the Ministry of Environment (MMA). Although the NVPL applies to all forms of land tenure, including Indigenous Territories or traditional communities that have collective use of their territory, we have excluded them and

¹⁰ This reclassification of LRs requires landowners to hire the services of a forestry engineer to justify the request to classify the legal reserve in another vegetation typology. These services are costly and it is thus less likely to be demanded by smallholders who have tighter financial constraints than large-scale landowners, especially since they are exempt from restoring LR vegetation cleared before 2008.

¹¹ In Portuguese, *Instituto Nacional de Pesquisas Espaciais*

protected areas from our calculations to focus primarily on private property and occupations using the datasets published by the Brazilian government (Ministério do Meio Ambiente, 2020; FUNAI, 2020) (See Supplementary Materials).

Maps about the tenure status of Brazil's land are either incomplete (cover partial areas of Brazil) or out of date (Sparovek et al., 2019). The CAR should theoretically provide an alternative but large shares of the data declared by individuals have not yet been validated by authorities (Roitman et al., 2018). Because the CAR is declaratory, property boundaries may present significant overlap, inconsistency, or may not even exist in some cases.¹² Although states are making progress on this matter, and it is difficult to get a transparent and timely picture of the CAR verification issue, the ValidaCar project estimated that only 7% of all CARs registered in the Amazon and Cerrado biomes had gone through a verification process as of November 2019 (Observatório do Código Florestal, 2019) although many states have made progress since then (Chiavari et al., 2021).

A team led by the IMAFLORA and other partners have however compiled all land tenure datasets available for Brazil (from about 20 different sources) to create a single land tenure database (Sparovek et al., 2019). Even imperfect, this map provides new insights into the extent of private land tenure in the country, we thus used it as a way to provide a big picture of vegetation classification issues in private properties. To do so, we regrouped the 18 categories of land tenure into 4: private properties, “undefined use” lands, protected areas and other (like urban, transportation network, water bodies, etc.). The areas where no tenure was identified in the database have been considered “undefined use” since we can ascertain that they are not protected areas (officially protected areas need to undergo a process in which their limits are clarified and published). These “gaps” probably constitute a mix of undeclared private properties and undesignated public lands. Hence, the reader should then keep in mind that our total for private properties is probably a lightly underestimated while the total for “undefined use” lands is probably lightly overestimated.

3.2. Hypotheses and rationale

The objective of this analysis was to determine how the use of different vegetation databases could influence the total area that should be protected under the LR in the Legal Amazon, especially in light of the property-level examination of vegetation types made possible by the NVPL and the uncertainties about the exact nature of FST areas which are not addressed as such by the NVPL. As the key question is to evaluate which areas are to be under either the 80% protection or the 35% protection, we examined three main scenarios, each one following one vegetation database. For the scenarios based on RADAM and PROBIO, we consider two possibilities based on the interpretation of FST areas: in one scenario we consider FST areas to be forests (e.g., 80% of LR), while we consider them to be savannas (e.g. 35% of LR) in the other. The third scenario used two hypothetical sub-scenarios. In the first one, we

¹² In one of the most advanced states for CAR verification, Mato Grosso, more than 45% rural properties presented overlaps (Observatório do Código Florestal, 2019). According to Brazil's Forest Service (SFB), an estimated 651 million (m) hectares (ha) of properties had been registered in the CAR by December 2021 while the area subject to registration in Brazil is only 397 m ha (Serviço Florestal Brasileiro, 2019, 2021). Over-declaration of rural properties is especially salient in states located in the Amazon biome which may have up to 8 times their CAR-eligible area registered. However, this situation is being corrected with the suspension of CAR overlapping indigenous lands (Chiavari et al., 2021).

examine the implications of using PRODES forest mask as the vegetation dataset to determine LR percentages.¹³ In the second one, we look at the implications of setting a 80% LR for the Amazon biome and a 35% LR for the Cerrado biome, a scenario which is frequently assumed in both scientific publications and newspaper articles but that is different the actual NVPL rule.

- **Scenario 1: RADAM** as the reference vegetation mapping
 - o **Scenario 1a:** FST areas of the RADAM mapping will be considered as forests
 - o **Scenario 1b:** RADAM FST areas deemed as savannas
- **Scenario 2: PROBIO** as the reference vegetation mapping
 - o **Scenario 2a:** FST areas of the PROBIO mapping as forests
 - o **Scenario 2b:** PROBIO FST areas deemed as savannas
- **Scenario 3:** Projections using hypothetical references
 - o **Scenario 3a:** PRODES forest/non-forest areas used for application of the NVPL. All areas within the “forest mask” of PRODES will be bound to 80% protection and all areas outside 35%¹⁴
 - o **Scenario 3b:** Use of biome limits for the determination of LR areas (Amazon biome at 80% LR and Cerrado biome at 35% LR)

Each scenario is examined first with a large focus, considering all the areas which are not under a protection status and are not water bodies, giving a calculation of the areas that could potentially be under LR status if all “undesigned lands” become private properties. We then propose a closer focus using the land tenure database in order to discriminate between areas effectively under private property status and still “undefined use” lands.

The rationale for each scenario is to explore different land-use policy options currently available to state environment agencies in charge of verifying landowners' CARs and their implications for conservation. For instance, they can choose to require landowners to respect the distribution of vegetation of the 1970 s as mapped by RADAM, because it corresponds roughly to what vegetation looked like in the Brazilian Amazon prior to the massive deforestation that took place in this region after the launch of state-backed development policies in the 1970 s and 1980 s (scenarios 1a & 1b). On the contrary, state environment agencies can choose to trust its latest update of vegetation distribution and use PROBIO (scenarios 2a & 2b). Using this basis however would prevent them from determining a baseline for NVPL compliance that is prior to 2002, which may favor landowners who settled in the region prior to this. Scenario 3a shows what would happen if state environment agencies choose PRODES to represent what counts as forests for NVPL compliance purposes, even though the PRODES forest mask distribution might differ slightly from RADAM and PROBIO since it was established in the late 1980 s. Finally, scenario 3b explores the implication of using an area-based criterion (i.e., biomes) to determine NVPL compliance, regardless the variation of vegetation types in and outside the Amazon biome. This option avoids the complex questions regarding forest classification, but significantly lowers the protection of forests in the Legal Amazon portion of the Cerrado biome, thus potentially undermining Brazil's efforts to protect carbon stocks. In practice, each state environment agencies may use one or more datasets to conduct their analyses of vegetation cover. Thus, the scenarios explored here serve to illustrate how widely their assessment of forests may vary depending on which database(s) they favor, and how massive the work of state

¹³ Note that one issue with this scenario is setting a 35% LR to all non-forest areas even though not all these areas are savannas. Since we are using this hypothesis simply to provide a “big picture” of the implications of using biomes as the reference, which is not what the FC states, we think this lack of precision is acceptable.

¹⁴ If this scenario resembles a “biome” interpretation of the FC, is important to note here that the limits of the PRODES forest mask differ sensibly from the limits of the Amazon biome.

environment agencies to reclassify forest areas is.

3.3. Data processing

As the crucial point is to differentiate which areas should be under the 80% rule and which should be under the 35% rule, we regrouped vegetation types of RADAM and PROBIO seven families based on their dominant feature: forests (comprising ombrophile forests and deciduous and semi-deciduous seasonal forests), *campinarana* vegetation (a mix of trees and grassland that neither fall into the forest nor savanna category), savannas, FST (based on the 7 types of contact specified in RADAM but discarding forest/forest or savanna/savanna contacts¹⁵), anthropized area (mainly agriculture and ranching), pioneer areas (like mangroves) and water bodies (Fig. 1).

We then calculated the total area for each category in each dataset and used the PRODES deforestation data to compute which proportion of each was deforested in 2018. We subsequently applied a mask of all protected areas and Indigenous Territories to exclude them from the analysis and to only consider areas under private property (already subject to the NVPL) and “undefined use” federal or state land (potentially subject to the NVPL in the future if they are privatized). Once the total unprotected area of each vegetation family established, we calculated the total area that should be protected under LR according to the percentage defined by the NVPL for vegetation types and the different scenarios. Finally, the RADAM, PROBIO and PRODES vegetation mapping were matched with the land tenure data in order to calculate the total area for each vegetation type under every tenure category. All geographic calculations were done using Geographic Information Software (GIS) ArcGis 10.7.

3.4. Limitations and scope of the analysis

The goal of this paper is to pinpoint the potential maximum variation in vegetation protection that can result from the use of different vegetation datasets to enforce the NVPL. The objective is neither to calculate precisely the exact extent of LR areas in private properties in the Legal Amazon nor to determine their compliance status with the NVPL, which would require to take into account property size, date of creation, and additional factors. Two caveats must be underlined. The first is that this analysis does not take into account the APP. As we said, these riparian areas have a much smaller extension and small private properties (under 4 fiscal modules) can include them within the LR for NVPL compliance purposes (to increase the percentage of vegetation preserved). As our focus was to provide a global estimate of the impact of vegetation mapping variation, we excluded APP from calculation. The second caveat is that our first round of calculation considers a worst-case scenario, in which all federal and state “undefined use” land would be converted into private properties. While this seems unlikely, due to national and international pressure to preserve what remains of Brazil’s Amazon forest cover, our analysis gives a sense of the scale concerned.

4. Results

4.1. Variation in vegetation types areas according to different mappings

4.1.1. Forest/savanna overall cover and deforestation

There are very significant differences between the vegetation datasets explored in this study (Table 1), which show how the interpretation of vegetation types can lead to rather different pictures of the Legal

¹⁵ Forest-to-forest (i.e., ombrophile forest mixed with seasonal tropical forests) and savanna-to-savanna transitions present very few risks of not being interpreted as forests or savannas and were thus considered in these categories. Thus, our classification represents the most conservative assessment of the extent to which transition categories can influence the interpretation of the law.

Amazon region’s land cover, even if some of the variation is due to land cover change that occurred because databases were produced years apart.

The total extent of forests originally mapped by the RADAM in the Amazon biome was 3.34 million km² (Mkm²), of which about 0.55 Mkm² were deforested. In PROBIO, forest area is reduced to 3.1 Mkm², of which 0.27 Mkm² were deforested. Both datasets thus point out to a remaining forest area of 2.8 Mkm². The reduction of the total forest area from the former dataset to the latter is mostly explained by a “transfer” of RADAM forests into the “anthropized areas” category in PROBIO (see Table 2 in Supplementary Materials). This means that if RADAM serves as the baseline to categorize areas, these “anthropized” areas will be subject to a much greater reforestation target under the NVPL because they were considered forests previously (see section 4.4). Consistent with this change, if 48% of the RADAM forest areas lay outside protected areas, this proportion lowers to 42% in PROBIO data. Forests are much less present in the Cerrado biome portion located in the Legal Amazon: they originally represented 45,560 km² in RADAM and only 14,322 km² in PROBIO. Most of them lay outside protected areas and the extent deforested is high (> 50%) independently of the dataset we consider. In both biomes, over 90% of deforestation occurred in non-protected areas, confirming the efficiency of protected areas (UCs and ITs) in conserving forests, which has to be nuanced by the fact they are often located in areas facing less land pressure (Pfaff et al., 2015).

The amount of savanna areas in the Legal Amazon also varies in RADAM and PROBIO. In the Cerrado biome, they amount to 0.53 Mkm² in the former and only 0.37 Mkm² in the latter, also as a reflection of land cover change since a large share of former savannas are now anthropized areas. Both datasets are in agreement regarding the proportion of non-protected savannas for this biome (81.3% for RADAM, 76.4% for PROBIO). Much less often spoken about, savannas in the Amazon biome cover 0.18 Mkm² according to RADAM, an area raised to 0.2 Mkm² in PROBIO, which reclassified about 20,000 km² of RADAM forest as such. Most of those savannas are unprotected (113,757 km² according to RADAM and 112,064 km² according to PROBIO). About 22% (RADAM) or 15% (PROBIO) of these savannas are located inside the PRODES forest mask, which leads to suspect that at least part of them is in fact composed by forests.

4.1.2. Variation in FST areas and deforestation

Forest-Savanna Transition (FST) areas originally represented 254,477 km² of the Amazon biome in the RADAM¹⁶ and shrunk to 85,174 km² in the PROBIO, making for one of the most dramatic differences between both datasets (Table 1). This large difference cannot be solely attributed to deforestation occurring between the dates of the two datasets since cross-check with the PRODES data show that only 24% of the area originally mapped as FST areas by RADAM has been deforested. The two mappings differ a lot about FST mapping in the Amazon biome: a striking 19% of FST areas in RADAM remained in the same category under PROBIO while 43.6% were reclassified as forests.¹⁷ This shows the extent to which much of RADAM transition areas may actually have been forests. Total FST cover in the Cerrado biome presents similar extents in the RADAM and PROBIO datasets (around 130,000 km²), but considerable variation between the two datasets also appears: only half of this area is considered FST in both datasets (Table S3, Supplementary Materials).

In sum, non-protected FST areas originally occupied 256,016 km² in the Legal Amazon according to RADAM (159,162 km² in PROBIO), 61% of which in the Amazon biome and 39% of which in the Cerrado biome. By 2018, however, about 40% had been cleared (107,133 km²

¹⁶ Some authors, as Marques et al. (2019), assessed the transition areas to be much larger than what the RADAM originally described.

¹⁷ Also 19% as savannas and 16% anthropized areas (See Table 2 in Supplementary Materials)

Table 1

Vegetation categories and deforestation for RADAM and PROBIO datasets. The table compares the total biome area with the biome area not protected by Conservation Units and Indigenous Territories. All numbers are in square kilometers (km²).

Biome	Category	RADAM				PROBIO			
AMAZONIA		Biome as a whole		Non-protected		Biome as a whole		Non-protected	
		Total	Deforested	Total	Deforested	Total	Deforested	Total	Deforested
	Forest	3,342,779	554,259	1,602,118	518,344	3,101,838	277,256	1,337,701	249,204
	Anthropized	97,791	80,252	83,172	68,451	475,673	408,018	441,648	384,840
	Campinarana	166,819	714	51,367	313	199,532	898	58,788	556
	Other (water)	94,015	5,636	67,422	4,406	84,848	2,579	61,437	1,833
	Pioneer	89,177	7,888	36,531	3,973	81,859	3,947	31,714	1,672
	Savannas	183,731	12,441	112,065	11,770	200,616	15,682	113,757	14,724
	FST	254,477	62,499	157,259	60,063	85,175	15,369	65,208	14,537
	TOTAL	4,228,788	723,689	2,109,934	667,320	4,229,540	723,749	2,110,253	667,366
CERRADO		Biome as a whole		Non-protected		Biome as a whole		Non-protected	
		Total	Deforested	Total	Deforested	Total	Deforested	Total	Deforested
	Forest	45,561	25,666	36,656	24,586	14,322	4,528	9,365	4,071
	Anthropized	43,196	–	42,012	32,679	238,528	184,093	226,042	175,840
	Campinarana	–	33,561	–	–	–	–	–	–
	Other (water)	5,336	631	3,685	562	4,217	270	3,194	247
	Pioneer	2,063	411	1,361	357	650	155	335	136
	Savannas	532,522	195,488	433,509	183,258	370,291	86,738	283,050	79,583
	FST	129,564	50,789	98,757	47,224	130,191	30,765	93,996	28,801
	TOTAL	758,242	306,545	615,980	288,664	758,201	306,548	615,982	288,679

remaining as of 2017) with a 38% cover loss in the Amazon biome and a 47% cover loss in the Cerrado biome. Today the remaining FST areas¹⁸ still represent significant shares of the non-protected biomes: 4.6% for the non-protected Amazon biome (95,009 km²) and 8.3% for the non-protected cerrado-biome portion of the Legal Amazon (51,534 km²).

4.1.3. PRODES “forest mask” vs PROBIO and RADAM

As Table 2 shows, PRODES’ forest cover classification does not fully align with RADAM nor PROBIO. If 97% of the non-protected area classified as forests by RADAM and PROBIO is identified as forest by PRODES in the Amazon biome, this proportion drops to 78–80% for the Cerrado biome.¹⁹ What is more, PRODES identify as forests large areas classified as savannas by RADAM and PROBIO: about 44,562 km² for RADAM and 38,726 km² for PROBIO (for both biomes). In terms of FST, PRODES classifies as forest 79% of the FST area mapped by RADAM and 72% of the FST area mapped by PROBIO in the Amazon biome. In the Cerrado biome, we find a different relationship: PRODES classifies as forests only 40% of the FST area mapped by RADAM, and 38% of the FST area mapped by PROBIO.

4.2. Global impact of variation in mapping on the Amazon according to scenarios

4.2.1. Scenarios 1 & 2 based on RADAM and PROBIO

The variation in vegetation classification between RADAM and PROBIO can have dramatic impacts when it comes to interpreting which LR percentage applies to private rural properties as per the NVPL. As Table 3 illustrates, the areas of forest or savanna native vegetation potentially protected under the LR varies a great deal depending on which is used and the scenario that will be used for FST areas.

Scenario 1a (using RADAM as vegetation data and considering all FST areas as forests) appears to be the best-case scenario, with a total potential LR area of 1.75 Mkm². Conversely, scenario 2b (using PROBIO as vegetation data and considering all FST areas as savannas) is the worst case, with only 1.32 Mkm². The 0.43 Mkm² difference between these scenarios, an area the size of Iraq²⁰ and representing 8.5% of the Legal Amazon area, underlines the scale of the potential uncertainty

over the protection or restoration of forests on private land.

Most of this variation comes from the difference in forest classification between the two datasets, which accounts for 0.2 Mkm² less protection between scenarios 1 based on RADAM and scenarios 2 based on PROBIO, just for the Amazon biome. Since this change is overwhelmingly due to PROBIO’s classification of RADAM forests into anthropized area, the question of which LR percentage should be applied to these areas arises (if RADAM’s precedent is recognized, these areas should be protected at 80% in all due logic, except for smallholders). No one will likely know this before the CAR mapping will be complete and validated by all Legal Amazon states, which may take several more years. The state of Mato Grosso, despite being considered at the forefront of the implementation of the CAR, had only validated around 3% of all registered CARs more than eight years after the 2012 NVPL revision (Ministério Público do Estado de Mato Grosso, 2020), despite recent progress. Furthermore, the dramatic diminution of FST areas in the Amazon biome in PROBIO also accounts for an important portion of the decreased protection between scenarios 1a and 2b: about 75,000 km² comparing scenario 1a to scenario 2a and about 53,000 km² comparing scenarios 1b to scenario 2b. Finally, reduction of the Cerrado savanna areas in the PROBIO also makes a difference, about 50,000 km² between total LR area for the Cerrado between scenarios 1a&b and scenarios 2a&b.

4.2.2. Idealized scenarios: PRODES mask (3a) and biomes (3b) as the defining criteria

The large discrepancies in native vegetation mapping show that trying to tie the NVPL enforcement to a precise vegetation database will probably lead to confusion. Landowners may call for revision of this cartography on the basis of new data such as locally tailored vegetation surveys provided by private consulting firms. It also opens the door for custom interpretations about what FST areas really are, which can also result in blurring the lines of areas under the 80% LR rule and areas under the 35% LR rule. One option to simplify the question would be to utilize the PRODES “forest mask” to determine which areas are forests and which are not. In doing so, one avoids the FST qualification problem since PRODES explicitly designate forest areas and non-forest areas. The downside of it, however, is that the same mask blends all areas not classified as forest or hydrography in a single class. Since it does not give a clear mapping of the areas of savannas and people may therefore claim that applying a 35% LR to all the “non-forest” areas overestimates somehow the amount of LR to be preserved.

Overall, the PRODES scenario is more favorable to forest protection,

¹⁸ As classified by the RADAM initiative.

¹⁹ These percentages are similar for the entire biome.

²⁰ The area of Iraq is 438,317 square kilometers (Central Intelligence Agency, 2020)

Table 2

Comparison RADAM and PROBIO vegetation mappings with PRODES' "forest mask." This table details which areas of both vegetation datasets have historically been identified as "forest" or "non-forest" by PRODES since its initial mapping. The "forest" category thus includes both forest areas still standing and areas that have been historically deforested. The "non-forest" category includes all vegetation types not recognized as forests (e.g. savannas) but also urban areas (although they represent a minor part of the total area of the Legal Amazon). All numbers are in square kilometers (km²).

Biome	Category	RADAM				PROBIO			
AMAZONIA		Biome as a whole		Non-protected		Biome as a whole		Non-protected	
		Within forest mask	Non-forest	Within forest mask	Non-forest	Within forest mask	Non-forest	Within forest mask	Non-forest
	Forest	3,265,968	76,811	1,556,299	45,819	3,038,949	65,998	1,301,160	37,903
	Anthropized	93,596	4,195	80,138	3,034	448,663	27,127	417,774	23,959
	Campinarana	130,885	35,934	32,474	18,892	158,616	41,218	37,597	21,299
	Other (water)	26,952	67,063	16,908	50,514	14,821	70,080	8,900	52,576
	Pioneer	31,045	58,132	13,764	22,767	20,738	61,663	8,524	23,488
	Savannas	41,092	142,639	23,659	88,406	57,983	143,927	30,245	84,458
	FST	205,261	49,216	125,029	32,230	61,451	24,139	47,488	18,052
	TOTAL	3,794,799	4,33,989	1,848,272	261,662	3,801,221	434,152	1,851,688	261,734
CERRADO		Biome as a whole		Non-protected		Biome as a whole		Non-protected	
		Within forest mask	Non-forest	Within forest mask	Non-forest	Within forest mask	Non-forest	Within forest mask	Non-forest
	Forest	36,022	9,424	28,811	7,845	11,931	2,395	7,580	1,785
	Anthropized	23,114	19,875	22,869	19,143	61,733	176,813	59,841	166,202
	Campinarana	–	–	–	–	–	–	–	–
	Other (water)	877	4,277	425	3,259	442	3,779	225	2,969
	Pioneer	521	1,495	178	1,183	173	477	146	189
	Savannas	25,717	504,302	20,905	412,604	11,272	359,023	9,428	273,623
	FST	54,173	74,478	39,825	58,933	55,116	75,085	35,780	58,215
	TOTAL	140,424	613,853	113,012	502,967	140,668	617,573	113,000	502,983

Table 3

Total unprotected area (private and undefined use land) and maximum Legal Reserve (LR) area for each biome under PROBIO, RADAM and PRODES relying on different scenarios (1a, 1b, 2a, 2b, 3a, and 3b). The total column gives the total native vegetation area (all types) protected by each scenario. Note: For scenarios 1 & 2, "a" = FST areas' LR at 80%; "b" = FST areas' LR at 35%; For scenarios 3, "a" = PRODES forest mask; and "b" = biome based scenario (80% for the Amazon and 35% for the Cerrado biome). All numbers are in square kilometers (km²). Note: *Campinarana* vegetation is assumed here to be protected with a 80% LR.

Biome	Category	RADAM			PROBIO			PRODES		
AMAZON		Total	RL Scen 1a	RL Scen 1b	Total	RL Scen 2a	RL Scen 2b	Total	RL Scen 3a	RL Scen 3b
	Forest	1,602,118	1,281,695	1,281,695	1,337,701	1,070,161	1,070,161	1,848,519	1,478,815	–
	Anthropized	83,172	–	–	441,648	–	–	–	–	–
	Campinarana	51,367	41,093	41,093	58,788	47,030	47,030	–	–	–
	Other (water)	67,422	–	–	61,437	–	–	66,407	0	–
	Pioneer	36,531	–	–	31,714	–	–	–	–	–
	Savannas	112,065	39,223	39,223	113,757	39,815	39,815	–	–	–
	FST	157,259	125,807	55,041	65,208	52,166	22,823	–	–	–
	Non-forest*	–	–	–	–	–	–	195,328	68,365	–
	TOTAL	2,109,934	1,487,818	1,417,051	2,110,253	1,209,173	1,179,829	2,110,253	1,547,180	1,688,202
CERRADO		Total	RL Scen 1a	RL Scen 1b	Total	RL Scen 2a	RL Scen 2b	Total	RL Scen 3a	RL Scen 3b
	Forest	36,656	29,325	29,325	9,365	7,492	7,492	112,299	89,839	–
	Anthropized	42,012	–	–	226,042	–	–	–	–	–
	Campinarana	–	–	–	–	–	–	–	–	–
	Other (water)	3,685	–	–	3,194	–	–	4,119	0	–
	Pioneer	1,361	–	–	335	–	–	–	–	–
	Savannas	433,509	151,728	151,728	283,050	99,068	99,068	–	–	–
	FST	98,757	79,006	34,565	93,996	75,196	32,898	–	–	–
	Non-forest*	–	–	–	–	–	–	498,863	174,602	–
	TOTAL	615,980	260,059	215,618	615,982	181,756	139,458	615,282	264,441	215,348
TOTAL	2,725,914	1,747,877	1,632,669	2,726,235	1,390,929	1,319,287	2,725,535	1,811,621	1,903,550	

yielding a total of 1.57 Mkm² for the whole Legal Amazon (Table 3). In terms of overall quantity of native vegetation in LR, the PRODES scenario seems superior to RADAM's best case scenario (1a) because it protects roughly the same quantity in the Cerrado biome (264,431 km² of LR against 260,059 km² in RADAM best case scenario) but far more in the Amazon (1.54 Mkm² against 1.46 Mkm² in RADAM). As we will develop later on, the use of PRODES could also have important consequences on environmental restoration, especially in the Cerrado biome.

The scenario based on LR percentages determined by biomes (3b) is the one that would create the largest LR requirement for private properties in the region. Because this fictional scenario is "blind" to differences in vegetation and land-cover categories it applies to the whole biome resulting in 1.90 Mkm² of protection (way over scenario 1a and 3a), but they hold different implications for each biome. Under such scenarios, the Amazon biome (including savannas) gets maximum

protection while the forests and FST areas of the Cerrado biome get the least protected of all scenarios (in this regard, this scenario is inferior to the maximum LR of scenario 1a and 3a for the Cerrado biome).

Fig. 2 summarizes the maximum gains or losses of LR protection depending on which scenario is adopted (excluding scenario 3a that gives a precise estimate of what would be under 80% LR and what would not). Within the RADAM dataset, just changing scenarios can result in up to 182,121 km² of variation in LR protection. This number is down to 127,046 km² of variation in LR protection if the PROBIO vegetation mapping serves as a reference.

4.3. Scenarios and tenure mapping

The use of the land tenure dataset allows to delve deeper into the implications of our calculations for both land already under private

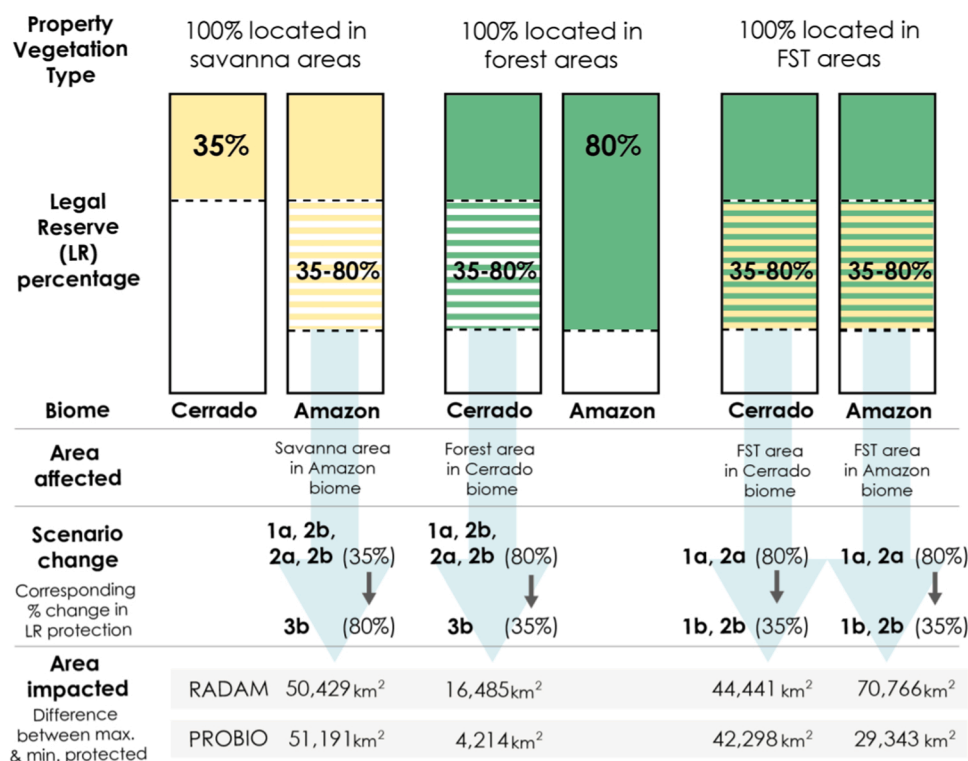


Fig. 2. Uncertainty around Native Vegetation Protection Law conservation requirements depending on vegetation types in the Legal Amazon. The upper half of this figure shows the different uncertainties in determining the percentage of Legal Reserve (LR) based on the type of vegetation present on private rural properties and the biome in which the property is located. The lower part of the figure indicates the total LR area (both for private and undefined land) that could be impacted by changes in protection levels based on the different scenarios analyzed in this paper. The total area impacted at the bottom of the figure has been calculated as follows: $Area\ impacted = (80\% \text{ area protected} - 35\% \text{ area protected})$.

property status and land that may be converted in the future. About 800,000 km² and 130,000 km² of land are still undefined in the Amazon and the Cerrado biome (Table 4), respectively, giving a rough idea of what the future stakes of environmental protection in the region are (Azevedo-Ramos et al., 2020). Interestingly, these undefined areas do not explain the difference of protection between scenarios 1a, 1b, 2a or 2b. Rather, most of the variation in these scenarios appear in private land tenure, which represent the dominant tenure category for FST areas (83% of RADAM FST unprotected areas; 82% of PROBIO unprotected FST areas). This means that their classification as “forest” or “savanna” have immediate implications for land currently managed privately. In scenario 3a, the brunt of the protection by LR still lays in the Amazon biome (1.6 Mkm² out of 1.91 Mkm²). In this scenario, the contribution of Cerrado-located LR peaks high over all other scenarios with 308,000 km² of LR. The biome-based scenario, in contrast, only results in 225,339 km² of LR for the Cerrado biome. Scenario 3b is however the one that results in most LR protection in the Amazon biome across all scenarios.

However, using PRODES as a basis to identify forest areas would be the best-case scenario for protecting forests on private land – it would result in recognizing 959,000 km² of forests in the Amazon and 72,518 km² in the Cerrado while others scenarios would identify less forests, in part (again) due to the uncertainty over the nature of FST areas.

5. Discussion

5.1. “Best-case” scenario is not likely to happen because of NVPL wording

Scenario 3a based on a simple discrimination between forest and non-forest derived from the PRODES program constantly gives the highest amount of forest protection (Fig. 3) (if we leave aside the biome-based scenario 3b). This “best case” scenario has to be nuanced by the fact that this scenario privileges forests over other types of vegetation like savannas, which are critical for biodiversity protection as well

(Klink and Ricardo, 2005; Strassburg et al., 2017). As shown in 2.1, the NVPL allows to determine different LR areas based on the area each vegetation type present within the property. This might seem a small detail, but the devil hides in the details because such phrasing opens the door to landowners challenging the LR percentage imposed by state environment agencies on a property-by-property basis. Many landowners have, or may claim they have, properties with “mixed” areas of vegetation (e.g., part forests, part savannas) and may thus claim certain patches should be under smaller LR percentages. This issue is even harder to solve considering that RADAM and PROBIO do not consistently classify areas, hence (in some cases) what may be a savanna under one database may be a forest in the other.

The LR requirement that different vegetation types be differentiated in a single property bears two consequences. First, scenarios 3a and 3b would probably be repelled in court as not attending the requirements laid out by the NVPL’s wording since they use binary forest/non-forest (or Amazon/Cerrado) criterion without considering the detail of vegetation types. Second, as most claims will be settled by state environment agencies (which handle private property areas), and as those are more often than not subject to the economic and political influence of large landowners, the PRODES database (scenario 3a) may not be used as it heavily limits the potential for future land use expansion over forest.²¹ The NVPL’s wording issue is so far-reaching that until vegetation cover mapping and registration of all rural properties in the Legal Amazon is completed, and the LR proportion applied to each property is known, it is virtually impossible to precisely evaluate the extent of native vegetation effectively protected by the NVPL.

5.2. FST as another potential loophole for minimizing LR requirements

As rich ecotones, FST areas are critical from an environmental point of view. They are, however, also the most threatened since they have

²¹ Especially since states are responsible for the identification of forest typologies, as well as the analysis and validation of landowner-declared CARs.

Table 4

RADAM, PROBIO and PRODES mappings compared against land tenure and using the different scenarios for determining LR percentages. All numbers are in square kilometers (km²). Notes: (1) there was no data in the “other” category for the Cerrado biome for scenarios 3a; (2) Slight differences in total area between this table using tenure data and other tables based on vegetation/protected areas databases are due to the fact APAs (Area of Environmental Protection) are classified as protected areas from an environmental viewpoint but are covered by private properties to a large extent as far as tenure is concerned.

		Lands				Scenarios 1a		Scenarios 1b	
		Private	Undefined use	Protected	Other	RL private	RL Undef	RL private	RL Undef
Scenarios 1a and 1b - RADAM / Land Tenure									
AMAZON	Forest	1,034,222	613,261	1,665,957	30,460	827,378	490,609	827,378	490,609
	Anthropized	54,394	35,584	4,478	3,340	–	–	–	–
	Campinarana	4,743	73,476	87,594	1,060	3,795	58,781	3,795	58,781
	Other (water)	8,433	14,502	10,287	60,859	–	–	–	–
	Pioneer	27,678	24,901	31,221	5,390	–	–	–	–
	Savannas	91,138	23,012	66,828	2,809	31,898	8,054	31,898	8,054
	Contact	121,240	23,253	107,760	2,254	96,992	18,602	42,434	8,139
	TOTAL	1,341,850	807,990	1,974,124	106,172	960,063	576,046	905,505	565,582
CERRADO	Forest	29,089	7,456	8,627	388	23,271	5,965	23,271	5,965
	Anthropized	28,866	12,658	869	799	–	–	–	–
	Campinarana	–	–	–	–	–	–	–	–
	Other (water)	1,413	625	824	2,468	–	–	–	–
	Pioneer	1,198	253	497	115	–	–	–	–
	Savannas	365,801	91,892	68,923	5,852	128,030	32,162	128,030	32,162
	Contact	87,442	17,121	23,513	1,473	69,954	13,696	30,605	5,992
	TOTAL	5,13,808	130,005	103,252	11,094	221,255	51,823	181,907	44,119
Scenarios 2a and 2b - PROBIO / Land Tenure									
		Lands				Scenarios 2a		Scenarios 2b	
		Private	Undefined use	Protected	Other	RL private	RL Undef	RL private	RL Undef
AMAZON	Forest	808,632	581,769	1,699,480	13,100	646,906	465,415	646,906	465,415
	Anthropized	358,722	85,732	20,234	11,055	–	–	–	–
	Campinarana	4,922	80,273	113,712	722	3,938	64,218	3,938	64,218
	Other (water)	2,216	5,093	2,610	75,002	–	–	–	–
	Pioneer	26,142	23,183	28,890	3,651	–	–	–	–
	Savannas	92,625	23,614	82,350	2,071	32,419	8,265	32,419	8,265
	Contact	48,649	8,551	27,310	696	38,919	6,841	17,027	2,993
	TOTAL	1,341,908	808,215	1,974,587	1,06,296	722,181	544,739	700,289	540,891
CERRADO	Forest	7,971	1,335	4,931	88	6,377	1,068	6,377	1,068
	Anthropized	186,913	42,544	5,277	3,794	–	–	–	–
	Campinarana	–	–	–	–	–	–	–	–
	Other (water)	585	392	246	2,986	–	–	–	–
	Pioneer	316	173	145	17	–	–	–	–
	Savannas	238,577	66,039	62,643	3,013	83,502	23,114	83,502	23,114
	Contact	79,459	19,522	30,012	1,196	63,567	15,618	27,811	6,833
	TOTAL	513,821	130,007	103,254	11,094	153,446	39,800	117,689	31,015
Scenario 3a - PRODES / Scenario 3b - BIOME / Land tenure									
		Lands				Scenarios 3a		Scenarios 3b	
		Private	Undefined use	Protected	Other	RL private	RL Undef	RL private	RL Undef
AMAZON	Forest	1,199,737	716,467	1,850,161	29,134	959,790	573,174	959,790	573,174
	Non-forest	138,127	79,005	115,404	8,870	48,344	27,652	110,502	63,204
	Others	3,997	12,489	8,061	68,247	–	–	3,197	9,991
	TOTAL	1,341,861	807,962	1,973,626	106,251	1,008,134	600,826	1,073,488	646,369
CERRADO	Forest	90,648	24,356	24,142	1,524	72,518	19,485	31,727	8,525
	Non-forest	423,173	105,651	79,113	9,569	179,837	36,978	148,110	36,978
	TOTAL	513,821	130,006	103,255	11,093	252,356	56,462	179,837	45,502

been deforested significantly more than forests. As transition areas are inherently difficult to delineate and classify in either forest or savanna vegetation types, they can be the object of contestation by landowners or even by state environment agencies in charge of enforcing LR percentages. The first may contend FST areas are savannas and therefore bound to a 35% LR rule, the latter may try to enforce 80% LR rule upon them.

Debate over the classification of FST areas already happened in the state of Mato Grosso. The local environmental agency, SEMA,²² has historically relied on various vegetation mappings to determine which vegetation type rural properties belong to and consequently which LR percentages apply. Because the RADAM made a distinction based on transition areas in both the Amazon and Cerrado biomes, SEMA has

²² State Secretariat of Environment (in Portuguese, “Secretaria de Estado do Meio Ambiente” - SEMA). Before 2005, this agency was called State Foundation of Environment (in Portuguese, “Fundação Estadual do Meio Ambiente” - FEMA).

traditionally applied them the same LR percentage as for forests (50% prior to 1996). However, when a 1996 federal measure increased forests’ LR percentage to 80%, SEMA maintained the same percentage for transition areas. Warned by the federal environment agency²³ that considered FST areas as forests (MMA, 2005), SEMA (FEMA at that time) was brought down in 2005 amid corruption scandals and the LR percentage of 80% was finally applied to FST areas (Azevedo, 2009; Stickler et al., 2013). Normative instruction published in 2005 also provided for the possibility for landowners to contest the typology in which the property is identified by the SEMA, and to request a visit by a technician (*vistoria*) at their expense. Demonstrating that the debate was apparently far from being over, Mato Grosso published in 2010 no less than 3 laws and a decree, bringing in turn clarifications (sometimes confusing) concerning the classification of “contact” areas in forest or cerrado

²³ The Brazilian Institute for the Environment – IBAMA (in Portuguese, “Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis”).

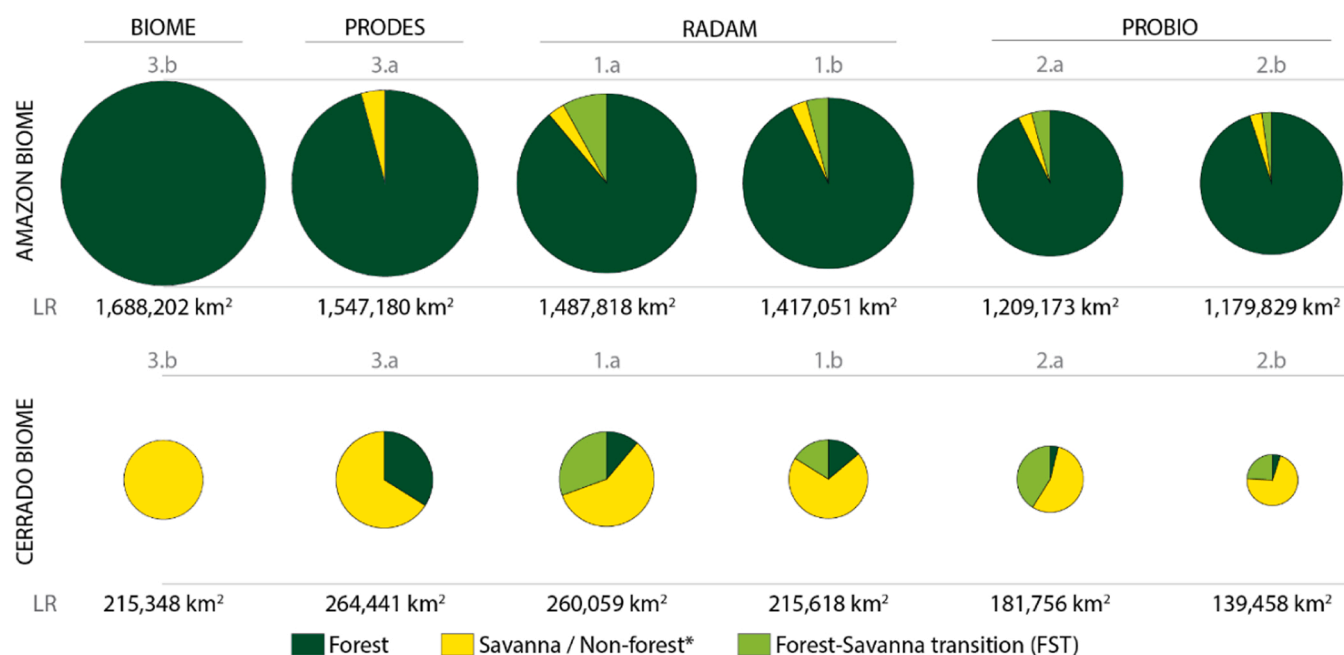


Fig. 3. Comparison of the maximum Legal Reserve (LR) under each scenario for the Amazon and Cerrado biomes in the Legal Amazon. Pie charts in this figure are at scale with the maximum LR under the “best-case” scenario 3.a. for the Amazon biome (1547,180 km²). For reference, the last pie chart on the bottom right corner is at 9% the size of the upper left pie chart. *In the PRODES scenario (3.a), the non-forest category should not be interpreted as being savannas, at least not entirely. Note: Campinarana vegetation is included in the “Forest” category here.

typology, and more or less clarified that all FST areas are forest areas (Daugeard, 2021).

Yet, despite the availability of legal recourse and despite these legal efforts, individuals have attempted to make fraudulent classification claims regarding the RL percentages on their rural properties. Following an anti-corruption operation in the second half of 2018 (Operation “Polygonum”), the head of SEMA and the Compliance and Environmental Monitoring team director were indicted²⁴ for having operated massive reclassifications of rural properties (about 600 properties in the state) from forest to savanna types, effectively lowering the LR percentage applying to such properties (Frederici, 2018; Favalezza, 2018). The scheme involved the participation of forest engineers from consulting firms who fraudulently classified forest vegetation into savanna vegetation in CAR declarations, hoping to allow their client (i.e., landowners) to “legally” clear a larger share of their properties.

The question of FST classification is not limited to Mato Grosso. It also concerns other states of the Legal Amazon like Tocantins, Maranhão, and Pará (Haidar et al., 2013). Despite the fact that some FST areas may quickly appear to be forests after examination by state authorities, fraudulent claims by landowners can theoretically “succeed” as long as state environment agencies have limited capacity to carry out property-by-property checks.

5.3. Savannas in the Amazon biome

Areas of genuine savannas embedded in the Amazon biome have also recently stirred controversy over their protection. States entirely included in the Amazon biome like Amapá and Roraima have important areas of savanna-like vegetation and the question of their status under the 2012 NVPL has recently been brought forward. While some may argue that the location of these savannas in the Amazon biome may result in their protection at 80% (which would go counter what the NVPL states), Amapá, for instance, has already decided setting the LR of savannas to 35%, and these areas have been disproportionately less

protected compared to forests (only 9% of savannas are under some kind of protection) many of which have protected area status (Hilário et al., 2017).²⁵

The interpretation of the NVPL by states also raise the question about how Amazonian savannas will be considered in the future, but this time at the property level, and authors have pointed out that they are at risk of being more heavily cleared (Carvalho and Mustin, 2017; Nogueira et al., 2018) since they can potentially be assimilated to savanna-like vegetation and be cleared up to 65% despite being located in the Amazon biome. It is not at all a detail since such areas represent about 113,000 km² outside protected areas according to both RADAM and PRODES, 75% of which are under private property status, the rest being “undefined use lands”. A change in the shared understanding that savannas in the Amazon biome were protected at 80% LR, which has prevailed until now, to 35% would thus automatically lower the overall LR area of RADAM Amazonian savannas by about 50,000 km² (See Fig. 2).

5.4. Land-use policy implications

Defining vegetation types may appear as simply technical, but it is also a political choice. Since the total area of privately protected forests vary largely depending on the vegetation or deforestation dataset used, this choice has far-reaching implications for land-use policy implementation. The interpretation of what vegetation types the forest concept covers occurs during two stages. First, when the federal government and relevant agencies define which vegetation types to consider as forests. Second, when state government and local actors have to implement rules related to this definition on the ground. In Brazil, one state well may consider the forested savanna vegetation type (i.e. “savanna florestada”, Sd code in the RADAM) as forests (e.g. Mato Grosso) while another may consider them as savannas (e.g. Tocantins) (TOCANTINS, 2015).

²⁵ The ZSC differs from the Ecological-Economic Zoning (EEZ) that Brazilian states must do by 2017 for their entire area.

²⁴ They were removed on December 2018 and August 2018 respectively.

None of the vegetation datasets in this study alone satisfy both objectives of Brazil's land use policy with regards to NVPL implementation: (1) provide a baseline to assess historical land cover of properties; (2) provide fine-grained land cover data to assess the compliance of even the smallest rural properties. PRODES has the advantage of already identifying forests (for deforestation control) but it has a coarse resolution not suitable for assessing LRs in small properties and data started being available toward the mid 1980 s, which limits its use as a baseline for properties which have been cleared before that date. RADAM is better suited than PRODES to serve as a baseline but has an even coarser resolution which severely constrains the ability of state environment agencies to conduct a fine-grain analysis of properties' compliance with the NVPL. PROBIO is more precise, but our analysis demonstrated that it may not be suitable as a baseline since many areas classified as "anthropized" areas were considered native vegetation by RADAM.

Our work leads to several recommendations to address this land use policy challenge. First, more scientific research on land use and vegetation cover datasets is needed. As demonstrated in this paper, each database provides different estimates of vegetation cover, and sometimes even contradict each other. In addition, the need to have accurate vegetation cover data from the past is critical to provide the government with different baseline options to determine NVPL compliance and vegetation restoration goals. However, old databases may present flaws due to technology available at the time. Marques et al. (2019) found approximately 75,700 km² of ecotonal forests (*cerradão*) in areas previously mapped as savanna by RADAM, showing to what extent RADAM mapping, mostly used, can be challenged. In the state of São Paulo, where there has been a debate over whether the baseline date should be set to 1934 or 1965 (or an alternative date), researchers have used different proxies (location of agriculture, transport networks, climatic conditions) to estimate the vegetation cover distribution in 1934 in absence of accurate vegetation mapping (Tavares et al., 2021). Additional research may help clarify more precisely the distinction between forests and savannas.

Second, the federal and state governments can have a debate to determine which databases to use and how to use them. Ensuring the transparency and fairness (among landowners) in environmental policy implementation requires a harmonized methodology to determine forest cover across states. Several databases can be used in combination (as in the case of Mato Grosso), but clear criteria should be established in instances where the data conflicts otherwise the exact area of protected forests will be uncertain and left to local interpretation. Also, since each database is complex and has several classification codes which serve different purpose, the federal government and state environment agencies need to provide precise and transparent guidance about their use. Importantly, the choice of datasets influences the baseline that can be used to calculate the "environmental debt" of landowners (i.e., forest cover missing based on LR percentage), and the type of forest definition and monitoring that can be achieved by authorities. This harmonized methodology could take the form of forest definition guidelines elaborated jointly with competent agencies (IBGE or the Brazilian Forest Service) and be accompanied by a conformity assessment process to be executed by the competent state environment agencies. The added transparency may help avoiding landowners' attempts to discuss forest typology.

Third, alternative criteria for determining LR percentages could be explored when database conflict. Since no dataset alone can both help determine forest cover at property-level (spatial resolution challenge) and provide a baseline for evaluating landowners' conservation record (over a minimum of 40 years), an alternative could be to adopt an area-based criterion defining zones where forests are located and where they are not. This could help local actors to easily determine their compliance with LR requirement simply by checking whether their property fit into this area or not. An example would be to use PRODES' forest mask, with the major caveat that it only identifies forest and disregards other vegetation types. Another option would be to rely less on vegetation

types as a basis but on other forest cover characteristics. For example, the United Nations Food and Agricultural Organization defines forest cover as "Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. Such example of alternative criteria may present their own limitations, but offer alternative land use policy options for stakeholders if they wish to explore it.

6. Conclusion: clear vegetation identification criteria are also needed for reforestation

At first sight, the Brazilian NVPL seems to promise a strong protection of native vegetation in the Legal Amazon region, especially when it comes to forests, where LR must cover 80% of the properties. A closer look to the text however reveals that this percentage is not to be uniformly applied upon the whole region, and that case-by-case analysis looking at the vegetation types present in each property might be called for. As a result, the cartographic reference serving to identify the LR percentages laid out by the NVPL for the different vegetation types will be crucial. Our study shows that when calculating the total area potentially protected by LR in the Legal Amazon, simply switching of official datasets (RADAM and PROBIO) can lead to a difference in protected area of up to 430,000 km² (which is of the order of the size of Iraq or Uzbekistan). Changing the reference vegetation dataset can thus significantly reduce protection for forests under current or future private dominion (unallocated public lands) or reduce the amount of vegetation to be restored by landowners who have already cleared their area. Furthermore, the uncertainty about FST areas' status alone can result in a difference in protection of up to 100,000 km² across datasets.

The Brazilian case shows how a legal text for conservation based on "simple" ecological concepts such as forest or savanna can pose serious enforcement challenges. Controversies and corruption schemes based on such loopholes already existed, and landowners may challenge administrative decision more often when the CAR system will be more stringently enforced. A takeaway for policy-makers is that state-level and federal-level environmental bodies should, if not already done, consider (1) support additional research to clarify the vegetation characteristics and location of forests and savannas; (2) agree on a harmonized methodology to determine vegetation qualifying as forest for NVPL implementation (thus solving the FST area uncertainty) (3) explore alternative criteria for defining forests when databases conflict. Communicating this information to existing and future private rural landowners is key to the efficient implementation of the NVPL, as is the avoidance of ambiguous wording like the vegetation "area" criterion in the law.

The discrepancy in native vegetation protection estimates shown by this study is concerning for global biodiversity conservation and climate mitigation. The uncertainties found represent between 3% (for FST areas) and 14% (for vegetation datasets) of the size of protected areas added in the world between 2010 and 2018 (an additional 3 million km²) (Lewis et al., 2019). If protected areas increase to 30% of the world's area by 2030, as laid out by the draft document of the post-2020 Global Biodiversity Framework of the Convention on Biological Diversity, it is increasingly clear that public protected areas alone will not address biodiversity loss. Conservation on privately-held land, like by the Brazilian LR mechanism, is therefore one of the main challenges for successful biodiversity conservation (Kamal et al., 2015; Drescher and Brenner, 2018; Rissman et al., 2007). Laws and policies that foster protection within private lands are thus critical but, as our study demonstrates, need vegetation classification and reference maps as unambiguous as possible.

Declaration of interests statement

The authors declare no conflict of interests.

Data Availability

The data supporting the present analysis and findings are available at the following address: <https://visualizador.inde.gov.br/> (Last accessed September 2020).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.landusepol.2022.106380](https://doi.org/10.1016/j.landusepol.2022.106380).

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