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White Paper

How to enhance Atlantic Forest protection? Dealing with the shortcomings of successional stages classification

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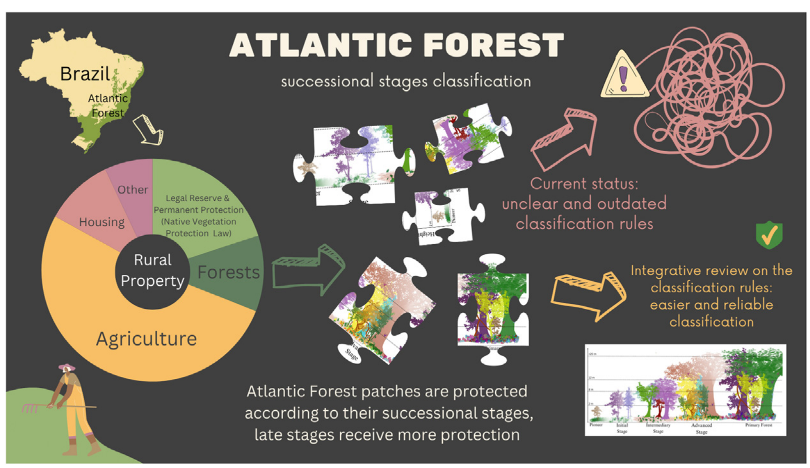
HIGHLIGHTS

- Since 1990, the intense threat faced by the Atlantic Forest pushed the enactment of dedicated laws safeguarding its native vegetation.
- Current successional stages' parameters are subjective and imprecise, hindering environmental permitting and related offset policies.
- We highlight the current classification's main limitations, propose specific improvements, and suggest creating a new inclusive framework.
- It is urgent to review, clarify, simplify, and increase the scientific reliability of the classification of successional stages.

GRAPHICAL ABSTRACT



Legal framework for the classification of Brazilian Atlantic Forest (AF) successional stages: Hypothetical land cover distribution of one rural property (doughnut graph), with forests beyond the protected areas (Native Vegetation Protection Law) under the jurisdiction of the AF Protection Law. The green arrow leads to the unsolved puzzle, representing the forests before being classified into successional stages. While the impreciseness of the current classification parameters leads to a tangled ball (top right), a law integrative review can lead to a solved puzzle (right bottom).

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ABSTRACT

The Atlantic Forest is a global biodiversity hotspot and a significant provider of ecosystem services to 65% of the Brazilian population. Due to being highly threatened, it is protected by federal law 11,428/2006, which establishes forest use restrictions based on native vegetation successional stages in the Atlantic Forest, with more advanced stages receiving more protection. The classification parameters are established at the state level. However, the parameters employed to classify forest fragments in different successional stages are subjective and imprecise, negatively impacting environmental permitting and related offset policies. Here, we critically assessed the major limitations in applying the 11,428/2006 law and presented alternatives for establishing a more transparent, applicable, legally safe, and effective protocol for identifying the conservation value of forest fragments. We also highlight problems related to sampling, indicators, and methodologies and present guidelines for revising the parameters for applying the Atlantic Forest law and associated state-level resolutions. We suggest an inclusive two-step analysis based on vegetation structure, forest cover history, biodiversity, ecosystem services (social), and landscape indicators. By employing a more technological approach and transferring part of the assessment responsibility to the state-level environmental agencies instead of allowing self-declared reports by landowners, our proposal focuses on the potential for evaluating ecological integrity among different successional classes by forest types. As nearly 90% of the remaining Brazilian Atlantic Forest is located within private lands, improving this legal instrument is essential for protecting the vulnerable biodiversity of this unique and threatened biome.

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Introduction

The Atlantic Forest is mainly composed of tropical and subtropical forests stretching across the Atlantic coast of South America over an area of 1,422,660 km^2, presenting high levels of biodiversity and endemism. With 92% of its area spanning across seventeen Brazilian states (extending into Argentina and Paraguay), the Atlantic Forest has been overexploited for centuries since the arrival of European colonists around 1500 AD. The biome's destruction has increased in the last century with the concentration of Brazil's main economic cycles, such as sugar cane and coffee, within its boundaries (da Fonseca, 1985; Dean, 1996; Victor et al., 2005). As a result, the Atlantic Forest is one of the world's most threatened hotspots for conservation priorities (Myers et al., 2000), with only a quarter of its original area remaining (Rezende et al., 2018). More than 80% of the remaining vegetation is composed of small fragments (<50 ha; Ribeiro et al., 2009), 82% of the tree species are endemic (Lima et al., 2024), and at least 23% of all endemic plant species are threatened with extinction in the biome (Brasil, 2022; Carvalho, 2023; Myers et al., 2000). At the same time, the Atlantic Forest harbours nearly 65% of the Brazilian population and 76% of the country's GDP (IBGE, 2023), supplying irreplaceable ecosystem services for human well-being and economic development (Joly et al., 2014; Rezende et al., 2018). This critical conservation scenario motivated a strong societal mobilisation in the 1980s and 1990s to protect its remaining forests, which resulted in its recognition as a national heritage (National Constitution of 1988, see Brasil, 1988). It also led to the enactment of protection decrees in the early 90s, culminating in the Atlantic Forest Protection Law (AFPL), the Federal Law 11,428/2006 (Brasil, 2006). The AFPL is a special law that overlaps or even supersedes other ruling laws.

The Atlantic Forest is the only biome in Brazil with a specific national-level protection law to date (Gaio, 2019). Other biomes have state-level legal protection, such as the Cerrado (Brazilian savanna) in São Paulo and the Pantanal in Mato Grosso do Sul. Other law projects for protecting specific biomes are also underway, as is the case of a national-level law project for safeguarding the Caatinga (Brazilian semiarid). The central premise of the AFPL is that the biome has been so degraded that intermediate to late-successional (advanced secondary or old-growth) forests should be specially protected, needing more restrictive conditions for forest conversion or management, such as timber exploitation. An overall decline in total native forest loss has been identified in the biome since the first protection initiatives in the late 80's (see Rosa et al., 2021).

Moreover, such protection mechanisms are partially ineffective since old forest remnants have been continuously cleared (Rosa et al., 2021). Theoretically, the AFPL also forbids forest removal when the fragments harbour threatened species, protect soils or waterbodies, form ecological corridors, present exceptional landscape value or in cases where the owner does not comply with the Native Vegetation Protection Law (Brancalion et al., 2016). Unfortunately, compliance with all the above-cited preconditions has not yet been operationally doable.

Since 1985, more than 8% of the old-growth Brazilian Atlantic Forest's remnants have been converted to alternative uses (Rosa et al., 2021). Furthermore, despite the increase in forest cover following restoration initiatives (Rezende et al., 2018), young forests (<20 years) have also been suppressed at alarming rates, with about one-third being cleared within less than eight years, preventing the creation of additional intermediate-/late-successional forests in the midterm (Piffer et al., 2022; Rosa et al., 2021). Tropical deforestation is a complex process with multiple drivers and challenging solutions (Armenteras et al., 2017; Freitas et al., 2010). One major issue in densely populated and economically developed regions such as the Atlantic Forest (Joly et al., 2014) is the pressure to boost economic development, requiring more land for agriculture and expansion of urban areas (Freitas et al., 2010; Daunt and Silva, 2019). Urban expansion is especially critical in its extensive coastal area, which houses nearly 25% of the Brazilian population (IBGE, 2023). Indeed, about 86.3% of deforestation alerts in the biome registered in 2021, which correspond to 26,000 ha deforested, have indications of illegality (Mapbiomas, 2023). Nevertheless, the illegal deforestation in the Atlantic Forest might be reduced in the near future after the creation of a permanent Interministerial Commission for the Prevention and Control of Deforestation and Wildfires in Brazil (Decree 11.367/23, Table S1). This promising initiative is creating a plan for reducing deforestation in the Atlantic Forest and other biomes. It is based on previous experiences from the same government in successfully reducing deforestation in the Amazon (PPCDAm). It is expected that, with the increase in policing and control of illegal deforestation, landowners will turn to legal means to obtain permissions for deforestation. However, problems in legisla-

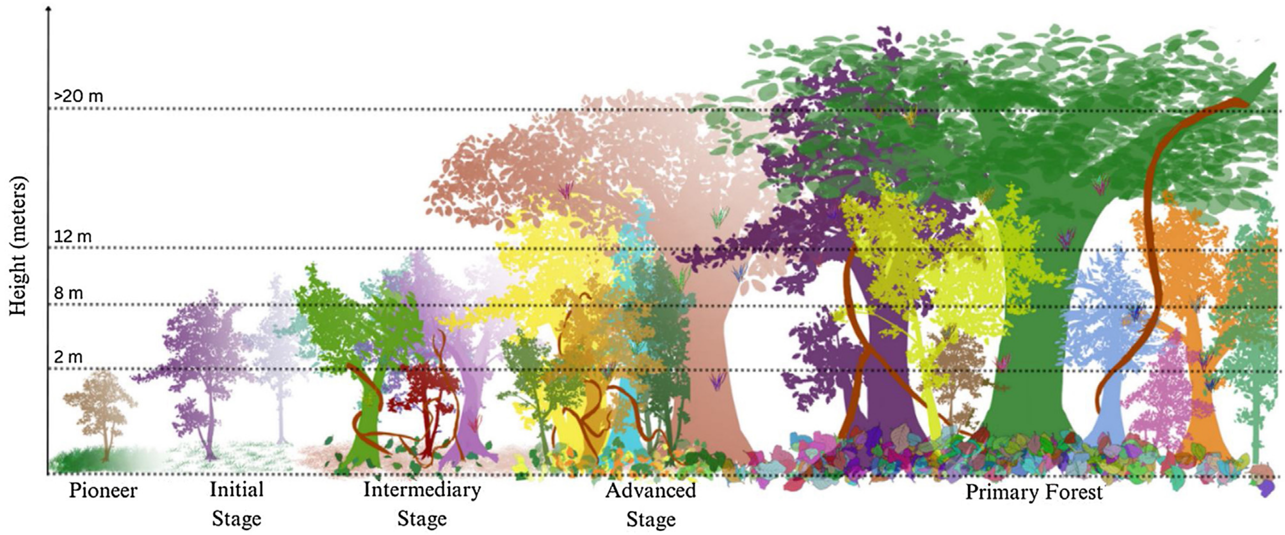

Fig. 1. Successional stages, determined by tree height, established by the São Paulo State resolution to implement the Atlantic Forest Protection Law.

tion framing may undermine the proper application of the AFPL and create opportunities for misclassification of Atlantic Forest's successional stages, allowing the legal cut of areas of high conservation value (Bressane et al., 2022; Siminski et al., 2013).

With the advances in remote sensing-derived data available in recent years, law enforcement can be substantially improved through remote monitoring (Almeida et al., 2020). Automated remote sensing-based systems designed for monitoring deforestation can improve national, biome and state-level monitoring, enabling the assessment of land use history and helping identify suspicious situations without requiring environmental technicians to squander time with uncomplicated cases. A great example is the MapBiomas project, a top-notch program designed to map annual land use and land cover change maps in Brazil since 1985, which produces national-level data on forest degradation (e.g., MapBiomas fire), deforestation or reforestation (www.mapbiomas.org). Other platforms like globalforestwatch.org and Google Earth Pro can be helpful since they quickly provide forest cover, land use-related layers, time-lapses, and high-resolution imagery, all publicly available. Such technologies can support decision-making by establishing remote metrics such as landscape composition and connectivity.

Here, we argue that the current criteria to classify forests in successional stages in the Atlantic Forest are too complex and vague, being difficult to implement. Determining the successional stage of a forest is a technically challenging activity, needing well-defined instructions to avoid misclassifications and further loss of Atlantic Forest fragments. Besides, many forests in the initial successional stages might not be as relevant today as in forests advanced stages. Still, they will reach advanced stages if allowed while providing essential ecosystem services and connecting old-growth fragments. Proving the successional stage through a self-declared technical report, as currently allowed, is susceptible to uncertainty and lack of compliance, as there are often strong financial interests in suppressing native vegetation in areas of high agricultural and real estate interest. The successional stage classification criteria established at the state-level by the Brazilian National Environment Council (CONAMA), with the São Paulo resolution being the first (CONAMA 01, 1994), is a problematic approach since almost no reference value is given for most parameters. Such problems create opportunities for the biased application of legal instruments to justify the removal of forests in areas of high economic value.

In this work, we critically assess the major limitations of the AFPL law and present alternatives for establishing more transparent, effective, and legally secure governance. Using the CONAMA 01/1994 resolution for the state of São Paulo as a case study, we verify the sources of misinterpretations in classifying the successional stages based on the current state-level resolution that regulates AFPL compliance in private properties. Finally, we propose improvements in the CONAMA parameters to avoid inconsistencies and enhance legal protection, including an optional framework that considers land use (forest cover) history, ecosystem services, and landscape indicators while using monitoring technologies. Finally, we provide general recommendations that can be used for law reviews in higher instances.

Forest succession

The AFPL is heavily based on ecological succession theories (see Fig. 1 for a description of the successional stages employed in the AFPL). Despite stage descriptions, the law has yet to have a specific forest succession concept. Such theoretical clarity is critical for ecological succession, a concept described in many different ways in the last century (Poorter et al., 2023), with significant consequences for practical applications. Ecological succession was first described as a cumulative, unidirectional process through which ecosystems gradually develop from lower to higher levels of diversity, structure, and composition complexity (Glenn-Lewin et al., 1992). This impression partially results from using chronosequences to study succession, an alternative and indirect approach to assess space-for-time substitution in plant communities (Walker et al., 2010). Regressions integrating plot age and ecological attributes give an impression of linearity and continuity. However, studies investigating succession in the same plots over time highlighted that this impression can be a statistical artefact since succession is commonly multidirectional in human-modified areas (Arroyo-Rodríguez et al., 2017). At the landscape level, the predictability is usually lower in landscapes with intermediate levels of forest cover (40–60%) due to the heterogeneity and complexity of ecological factors (Arroyo-Rodríguez et al., 2017).

Similarly, chronosequence studies performed in agricultural landscapes of the Atlantic Forest found that forest age has a marginal relationship with indicators of diversity, structure, and functioning recovery (Arroyo-Rodríguez et al., 2017, 2023; César et al., 2021). In contrast, the landscape's surrounding land use and forest cover have a major influence (Arroyo-Rodríguez et al., 2023; César et al., 2021). It is also important to consider that forest fragmentation and other anthropogenic factors leading to degradation can pervasively cause a retrogressive succession, leading to a *"secundarisation"* or degeneration of remnant fragments, where the structure and consequently the biomass of forests are modified (Santos et al., 2008; Tabarelli et al., 2008). It also affects the species composition, with rarefaction of some species and dominance of pioneers, ultimately leading to a biotic homogenisation (Joly et al., 2014; Santos et al., 2008; Tabarelli et al., 2008).

The concept of ecological integrity (Rosenfield et al., 2023), combined with the successional approach, can incorporate the conservation value of a forest remnant more clearly. The conservation value of a secondary forest fragment may be more important for legal protection than only its position across an ambiguous successional trajectory. It is then critical for legislation to clearly define the concepts employed, as they directly impact the metrics selected to classify successional stages and how their results are interpreted for compliance purposes.

Current Legal Framework for the Atlantic Forest Protection

Since 1934, Brazil has had a legal instrument for forest protection, reviewed in 1965 and 2012, culminating in the Native Vegetation Protection Law No. 12,651/2012 (Brasil, 2012; Brancalion et al., 2016). This law establishes special protection for native ecosystems in Areas of Permanent Preservation (e.g., riparian buffers, water springs, mountain tops) and Legal Reserves (i.e., a percentage of the landholding that must be protected or sustainably used). In principle, native vegetation under these protection statuses cannot be converted to alternative land uses (except for a few restrictive situations, mostly related to public infrastructure). Native vegetation outside these situations could be converted to alternative uses, conditioned by a permit. Despite the importance of the Forest Code, as the Native Vegetation Protection Law is commonly referred to, for forest protection, it was clear that additional legislation was needed to protect endangered biomes such as the Atlantic Forest.

After social and scientific movements aimed at highlighting the importance and imminent threats of the Atlantic Forest, the Brazilian Federal Constitution (Brasil, 1988, ref. in Table S1) declared the Atlantic Forest as a National Heritage. Actual protection was given in the form of decrees in the early 1990s. In 2006, a biome-level law was sanctioned for protecting the Atlantic Forest, with a regulation decree and an official law enforcement map released in 2008 (Brasil, 2008, ref. in Table S1). The Atlantic Forest Protection Law was designed to protect forests in late successional stages, such as old-growth (or primary) and secondary forests in intermediate and advanced successional stages (Brasil, 2006). The protection is higher in rural areas, surpassing the Native Vegetation Protection Law and protecting forests outside the Legal Reserves and Areas of Permanent Preservation (Fig. 2). Its implementation relied on successional stages classification, following nine parameters (see Supplementary Box 1) established in one Federal (CONAMA 10, 1993, validated in CONAMA 388, 2007, refs. in Table S1) or State-specific resolution. Given this, for 16 out of the 17 states comprising the Atlantic Forest territory, specific resolutions for successional stage classification were established by CONAMA since 1994. As the State of São Paulo and other state's resolutions (CONAMA 01, 1994 or SMA-SP & IBAMA 01, 1994 and CONAMA 07, 1996, refs. in Table S1) date from before the 2006 AFPL, they were validated in 2007 and are still used nowadays.

The AFPL currently in force maintained several aspects from the Decrees 99547/1990 and 750/1993 (Brasil, 1990 and 1993, ref. in Table S1), which were the first legal instruments to protect the biome. Protecting the lasting Atlantic Forest remnants is articulated around three factors: the successional stage of the forest fragment, removal purpose, and the patch's location within a rural or urban setting (Brasil, 2006). The legislation indicates that removing primary or secondary vegetation in the advanced successional stage can only be authorised for public utility cases. While for secondary vegetation in intermediate stage, the removal is allowed in cases of public utility and social interest. In both cases the state environmental agency is responsible for issuing the authorisations (AFPL arts. 14, 20, 21 and 23). Public utility and social interest are defined in Article 3 of the AFPL and generally involve national security initiatives, such as transportation, sanitation and energy infrastructure. Moreover, for every permit for the suppression of native forests in more advanced successional stages, an environmental compensation by allocating equivalent native vegetation to preserve or restore a degraded area to the same extent as the suppressed area within the same watershed is required (AFPL art. 17). Suppressing native vegetation in the initial stage of succession is allowed for any purpose, being exempt from environmental compensation (AFPL art. 25, Brasil, 2006). These conditions jeopardise the efforts to expand the forest cover in the biome. Consequently, there is still a risk for forest patches to be replaced by young fragments in areas with sub-optimal contributions to biodiversity conservation and ecosystem services provision.

Conversely, the state of São Paulo has established additional environmental compensation requirements via specific resolutions (SEMIL 02, 2024, ref. in Table S1), including for vegetation removal in the initial successional stage. The resolution establishes different compensation factors (multiplication values) depending on the successional stage and geographical location of the suppressed fragment in priority classes ranging from one (little priority) to four (very high priority). In the lowest compensation factor (initial stage and low priority class), every hectare of a deforested area must be compensated by restoring an area 1.25 times bigger. In contrast, for the highest compensation factor (advanced or primary stage at very high priority), the ratio is 1:6. Thus, in the state of São Paulo, the forest cover gain can be sustained if legal compliance is high. The resolution SEMIL 02/2024 may serve as inspiration for other states or even be integrated into the AFPL in a future review. Finally, environmental compensation via ecological restoration in the state of São Paulo is also in another regulation (SMA 32, 2014, ref. in Table S1) that aims to elaborate and monitor projects so that the restoration process results in resilient and self-sustainable ecosystems, attested by simple and integrative ecological indicators.

Both laws, the Native Vegetation Protection Law and AFPL, offer lower protection for forests in urban areas, as even forests in advanced stages can be suppressed. About 7% of the São Paulo State area is under the urban perimeter (IBGE, 2019). The combination of population growth, political power, and the potential influence that large developing companies exert over city councils is resulting in the expansion of urban areas in the Brazilian Atlantic Forest (Daunt and Silva, 2019). This expansion threatens forests and the associated ecosystem services in densely populated regions. About 54% of the deforestation (255 ha) identified in São Paulo in 2021 was due to urbanisation (MapBiomas, 2023; Souza et al., 2020). AFPL compensation rules apply to patches in rural properties, while specific directions are given for urban areas and metropolitan regions (articles 30 and 31). In consolidated urban perimeters (which were defined before the AFPL publication), it is possible to suppress forest vegetation in advanced stages for land parcelling or development, as well as the removal of vegetation in the intermediate and initial stages for the same purposes, with the conditioning of maintenance of part of the existing fragment in the property (Brasil, 2006). In the São Paulo state, the AFPL provisions for removing native vegetation in urban perimeters (Arts. 30 and 31) were detailed in SIMA Resolution (SIMA 80, 2020, ref. in Table S1, Fig. 2).

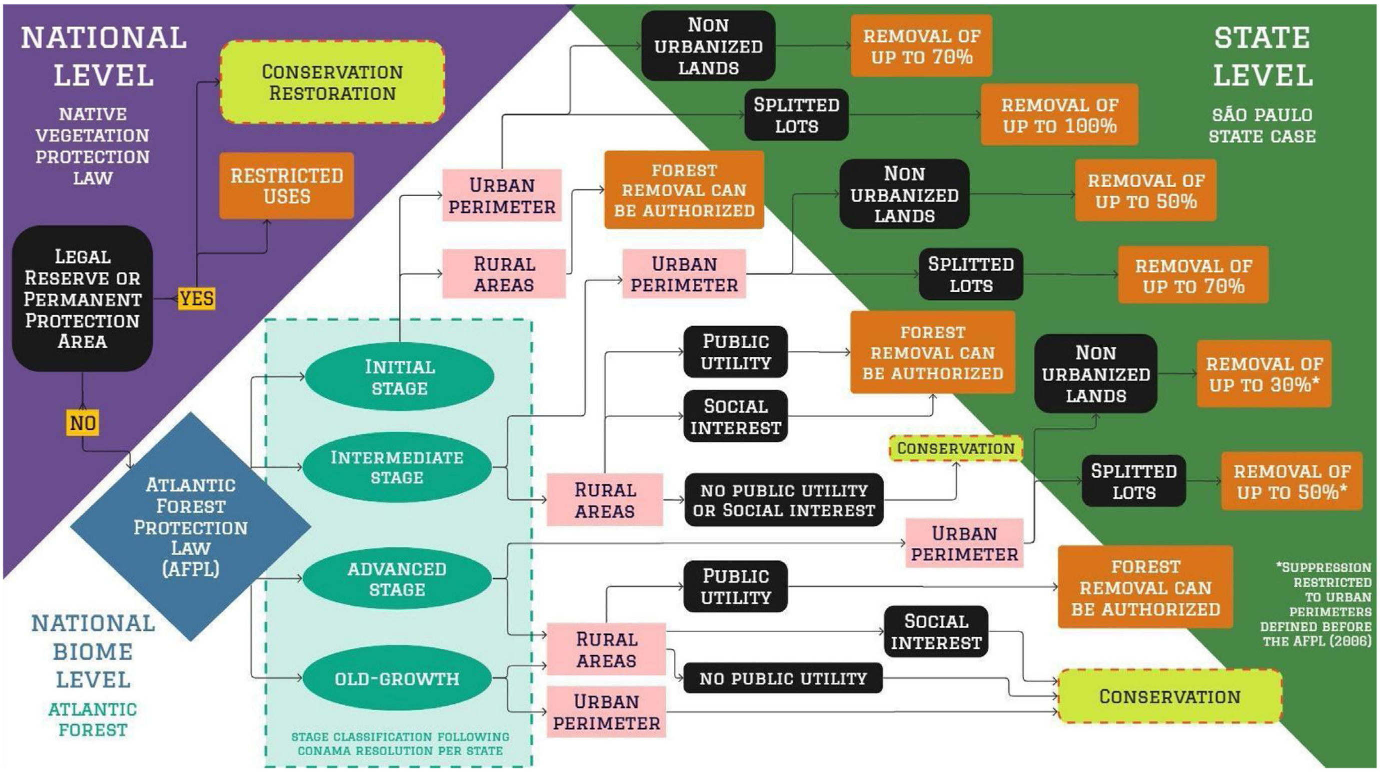

Fig. 2. Flowchart with the three main legislative levels for ruling forest protection within the Atlantic Forest. In the purple panel, we highlight the two main forms of protection of the Native Vegetation Protection Law. In the white panel, we show the Atlantic Forest Protection Law (AFPL) with a **light green box showing the successional stages classification, which is the bottleneck we deal with in this paper.** In the dark green panel, we depict the São Paulo State legislation regarding the forests in urban areas. It is important to notice that the AFPL is national and precedes all other laws (created with Miro).

If only the Forest Code were considered, in the absence of the AFPL, landowners could obtain legal authorisation to convert an old-growth forest remnant to agropastoral land use. As of 2009, nearly 90% of the remaining Atlantic Forest was in private lands (Ribeiro et al., 2009), highlighting the importance of the AFPL creation. Compared to other forest biomes in Brazil, the AFPL and associated legislation have successfully safeguarded essential remnants of the Atlantic Forest since the biome has maintained or even gained forest cover. On the other hand, biomes such as the Amazon or Cerrado lost about 10% and 12% of their net forest cover (after deducting forest gains) between 1991 and 2022 (MapBiomas, 2023). Even with the combinations of laws and protocols, the reduction in forest cover loss and further gains in forest cover observed after 1990 still hides the removal of old and young forests (Piffer et al., 2022; Rosa et al., 2021). The Secretary of Environment, Infrastructure and Logistics of the State of São Paulo (SEMIL), through the green panel platform (SEMIL, 2023, ref. in Table S1), reported for the period between January 2019 to April 2023, about 2,900 ha of legal forest removal and other 25,800 ha of illegal deforestation registered in the Atlantic Forest in the state. Such data shows that adopting the legal framework is still a challenge. A governmental plan in partnership with SOS Mata Atlântica NGO to combat illegal deforestation in the biome might boost the adoption of legal means to obtain permission to remove forests. Therefore, to avoid incorrectly allowing the suppression of important fragments, the legal instruments must be promptly reviewed and aligned by the environmental authorities.

In addition to stage classification resolutions, a legal framework at the state level provides formal authorisation for self-reported requests for forest removal. For practical purposes, to be granted authorisation for vegetation removal, the interested party or entity hires a consultant who visits the area, takes measurements, and prepares a report on the successional stage of existing forest fragments, which is submitted to the state environmental agency for analysis. In the State of São Paulo, this report must be prepared following specifications issued by its Environmental Company (CETESB). A similar process applies to all the other 16 states hosting Atlantic Forest.

Further details on the legislation for permitting the use or removal of native vegetation in the State of São Paulo can be found at the Environmental Company of the State of São Paulo (CETESB) digital platform at the link below:

https://cetesb.sp.gov.br/licenciamentoambiental/licenca-previa-documentacao-nescessaria/autorizacao-para-supressao-de-vegetacao-nativa-intervencao-em-areas-de-preservacao-permanente-legislacao/.

Shortcomings of the successional stages' classification (case study of São Paulo state)

Besides the AFPL providing nine parameters to be considered when classifying successional stages, basic sampling design guidelines and reference values are missing in the state's resolutions. In addition, even when the parameters are measurable, they still are extremely challenging to evaluate in the field without well-trained professionals. Based on the state of São Paulo's resolution for successional stages classification, we highlight the most critical shortcomings of the AFPL divided into three sections: i) the lack of differentiation of forest types and field sampling guidelines and the indication of inadequate ii) structural and iii) floristic parameters, as further described.

i) *Lack of differentiation of forest types and sampling guidelines*
   1) **Mixture of different forest types (phytophysiognomies) in state-level resolutions.** The state of São Paulo has seven recognised different forest types in the AFPL enforcement

map (Fig. S1): (1) seasonal semideciduous forest; (2) dense ombrophilous forest; (3) mixed ombrophilous forest; (4) savannah; (5) mixed and dense ombrophilous forest tension; (6) seasonal savannah tension; and (7) dense ombrophilous savannah tension, but only one resolution with the same descriptions for classifying all seasonal and ombrophilous forests (CONAMA 01, 1994, same as SMA-SP & IBAMA 01, 1994, see Table S1). The first AFPL parameter to be considered is called "physiognomy" and is interpreted in state resolutions as the general features of a given forest type (forest-like, plant size variation, canopy openness). Still, perhaps this item should refer to the forest formation types (phytophysiognomies) to start differentiating them. Alternatively, resolutions could be issued per phytophysiognomy or group of phytophysiognomy (including associated ecotones or transitions) as happens for *Restingas* (i.e., vegetation located in sandy deposits as beaches and dunes, scrublands or vegetation associated with swamps along the seashore) and native grasslands in high altitudes, where parameters are detailed in specific resolutions (CONAMA 07, 1996; CONAMA 417, 2009 and CONAMA 423, 2010, see Table S1).

2) **Lack of sampling area requirement in accordance with the total area of interest.** These crucial sampling guidelines must be given to guarantee sampling rigour and standardisation. An adequate sampling needs a minimum sampling size to represent the desired area, avoiding misestimations and improving accuracy (Viani et al., 2018; Oliveira et al., 2014). For example, a forest stage classification estimate based on a forest inventory of a plot of 25 m^2 or a plot of 10,000 m^2 (or multiple plots) will produce different results and possibly differences in stage classification when asking for authorisation to remove the vegetation of the same area. However, consultants in the State of São Paulo do not need to install forest plots since they evaluate forests using transects, as admitted by technical guides (CETESB, 2014; 2023, refs. in Table S1).
3) **Lack of plot allocation guidelines in the law.** It is known that the correct placement of one or more plots inside the area of interest can also affect the stage classification for heterogeneous fragments, which is the case in most Atlantic Forest landscapes (Costa et al., 2017). Fine-scale factors, including edge effect (Oliveira et al., 2004; Silva-Junior et al., 2020), topography, and soil factors (Alves et al., 2010; Rodrigues et al., 2020), will affect the forest structure and composition. Forests across the border may be in the initial stages while advanced in central portions of a larger fragment. A report relying on only one plot may not capture the entire area's complexity.
4) **Lack of a minimum diameter at breast height (DBH)**. No rule establishes whether someone should consider 5, 10 or 20 cm as the minimum DBH. The minimum DBH is a predetermined threshold to establish that all individuals above it should be inventoried. The higher the minimal DBH, the lower the number of individuals and stems, basal area, biomass, and species diversity, while the mean DBH and height are higher.

   Even in conserved forests with high biomass accumulation, such as the Serra do Mar (Ferreira et al., 2023), the observed average diameters and heights are low if the minimum diameter considered in inventories is below 10 cm. For instance, researchers studying conserved remnants and late secondary forests in Serra do Mar found values of an average of 12.7 cm in DBH and 9.1 m in height in conserved remnants when considering all individuals above 4.8 cm in diameter (Padgurschi et al., 2011), which would cause classifying old-growth forests as in initial or intermediate states if following the current CONAMA parameters. Some authors used creative solutions to overcome this issue by raising the minimum DBH a posteriori by considering the mean site DBH as a new minimum DBH and consequently increasing the forest mean DBH to consider only the adult trees and reach more plausible values for successional stages classification (Berveglieri et al., 2016).

   These statistical artefacts show how the lack of specific sampling guidelines can modify the results. Anyone with basic knowledge of forest inventory practices and conflicting interests can control the plot area, location, and minimum DBH to underestimate the conservation value of a given forest patch.

ii) *Structural parameters*

5) **Forest height reference values for successional stages are not specific for different phytophysiognomies.** Usually, wetter forests tend to be taller than drier forests, but they are mixed up in the same resolution. Still, forest height may vary in response to many other variables, such as soil, altitude and declivity, and regional climate (Potapov et al., 2021). In these terms, instead of indicating a single reference value for each successional stage, the Resolution could indicate a range of values, considering the different phytophysiognomies and average slope of the area under analysis (Alves et al., 2010).
6) **Tree and stem density, basal area and biomass parameters are not adequately foreseen.** These parameters are commonly used in practical or scientific studies to evaluate forests worldwide. There is an attempt to qualify biomass in the São Paulo state-level resolution for forest management. However, it is vague in the AFPL narrative and has no reference values (e.g., "reasonable woody product for the intermediate state" – in free translation). Nonetheless, some specific state resolutions provide controversial guidelines for the basal area (m^2/ha) and DBH reference values when classifying stages (e.g., states of Paraná, Rio Grande do Norte, and Paraíba). For estimating biomass, it is essential to give further directions. Biomass estimation can be based on several equations (e.g., Chave et al., 2014) using different parameters (e.g., DBH, tree height, mean wood density). If no clear directions are available, each one estimating biomass may have different results (Vieira et al., 2008).

iii) *Floristic parameters*

7) **Species inventory poses complex challenges.** The resolution lists species for each stage, including tree species, lianas, understory herbaceous plants, and epiphytes (the last ones are mostly at the family level). Apart from the composition unpredictability in successional pathways across diverse landscapes (Arroyo-Rodríguez et al., 2017), identifying plant species in megadiverse forests requires at least a small group of botanists very specialised in such groups, which is expensive and often not viable for a technical project. Conversely, the species list provided by technical reports can be a tool for recognising the existence of threatened tree species, but those species can be easily omitted in inventory outcomes. Moreover, São Paulo's resolution species lists have misspelt or non-existing names, such as an unknown plant family (Sapocindáceas) and wrong specific names (e.g., *Cascaria sylbestris* – instead of *Casearia sylvestris).* Some genera are misplaced among the stages (e.g., *Ficus* spp. and *Machaerium* spp. are placed in advanced stages but are common in all stages), which can affect the correct resolution use. The lists also present some exotic species (e.g., *Psidium guajava, Ricinus communis, Stenolobium stans*) and many outdated scientific names (e.g., *Pithecellobium urundeuva*).

Table 1
Atlantic Forest Protection Law, CONAMA resolutions parameters to be considered for successional stages classification.

	Direction/Parameter	Shortcomings	Recommendations
	Sampling area and location	Absent	- Provide directions on the sampling effort (area and a minimum number of plots per area) and the allocation of plots inside an area.
	Minimum DBH	Absent	- Define a minimum DBH (e.g., 5 cm).
1	Physiognomy	- Subjectiveness and lack of reference values lead each person to interpret differently.	- Add proper definitions for each term. - Add a range of reference values by forest type and by stage.
2	Woody strata		- Add basal area.
3	Woody product (biomass)	- Sampling biases occasioned by the lack of standardised methods.	- Add stem and tree density (number of individuals).
4	Diametric distribution		- Give variables and equations to be used for biomass estimative.
5	Litter		- Drop litter evaluation since it changes with seasonality.
6	Woody plants mean DBH and heights.	- Generalist phytophysiognomies in different conditions (e.g., climate and soil) can differ in sizes	- Add a range of reference values by forest type and stage, considering other factors such as average slope and altitude. - Allow the use of remote sensing-derived plot-level height (Lidar or photogrammetry clouds)
7	Epiphytes	- Require deep botanical knowledge.	- If possible, most of the floristic parameters should be removed.
8	Lianas	- No clarity on how to distinguish between conservation-valued and generalist lianas and epiphytes.	- Field photos made by a mobile phone with GPS could be enough to prove the existence or absence of Epiphytes, lianas or understory plants.
9	Understory plants		- The species list must be re-evaluated and names updated.
10	Biological diversity		- Environmental bodies should certify practical taxonomists to identify species in the field by applying a structured test made by recognised taxonomists.
11	Dominant species		- Provide a mobile app and booklets with a comprehensive database, including photos and reference values.
12	Abundant species list		

Recommendations

In our analysis, the Atlantic Forest Legal Framework needs an extensive revision in state-level CONAMA resolutions for the classification of successional stages. Moreover, a slight revision is required at the national level, introducing specific alterations to the AFPL concerning safeguarding successional stages and classification guidelines. In this paper, our recommendations primarily focus on the state-level resolutions, specifically addressing the context of the state of São Paulo and CONAMA 01/1994. Looking for a more modern and inclusive evaluation of the Atlantic Forest, we suggest, in the section “Inclusive Assessment Framework”, an optional outline with two tiers to facilitate the decision-making process while including more aspects such as ecosystem services and landscape features. Nevertheless, in the section “general recommendations”, we highlight some points within the AFPL that can benefit from modification.

Specific recommendations for state-level resolutions

Here, we develop ideas on adjustments that could improve the overall classification process, which may sometimes seem to complicate the process but result in greater benefits, simplifying it for landowners while giving more tools to decision-makers. Such suggestions must be considered for a resolution review that can be developed for a comprehensive classification protocol. We suggest a science-based reformulation on the successional stages' classification sampling directions and parameters presented by CONAMA. The suggestions are listed below:

1) **Separating forest types** (phytophysiognomies) in order to recognise the natural differences of such formations. This differentiation of forest types can be done by using tables or sections for each type in a resolution or by splitting it into several resolutions.
2) **Establishing a minimum sampling and plot areas** (suggestions based on (Viani et al., 2017), for Atlantic Forest Pact monitoring protocol).
   a. Forest fragments below 0.5 ha, sampling the entire area.
   b. Fragments between 0.5–4.99 ha, sampling 0.5 ha distributed among five plots of 0.1 ha.
   c. Areas above 5 ha, sampling 1% of the area – with one 0.1 ha plot per ha.
3) **Directions on the plot(s) allocation** must consider giving preference to central portions of each fragment while keeping a considerable distance between plots and distributing plots along an altitudinal gradient (Alves et al., 2010).
   a. For fragments above 5 ha, if possible, allocate plots at least 100 m from forest edges and keep a minimum distance of 100 m between plots.
4) **Minimum DBH for including trees in forest inventories**. This metric must be the same for the four forest stages ruled by AFPL (secondary growth in initial, intermediate, advanced stages and primary or old-growth forests). Given this, a minimum of 15 cm in circumference or 5 cm in diameter at breast height would be adequate for considering young and adult trees. Considering that with a minimum DBH of 5 cm, the mean plot DBH and height for late stages will drop, it is vital to review the given numbers and provide proper ranges by typology (Table 1).
5) **Properly reviewing the CONAMA parameters**. Every parameter must be reviewed to guarantee the proper application of the resolution. A suggestion for improving each parameter, along with the main shortcomings, is presented in Table 1.

Ultimately, the methodology must be standardised to allow comparisons with other areas, inventories delivered by different stakeholders and scientific studies. The Atlantic Forest Pact Protocol was created to monitor forest restoration in the biome (Viani et al., 2017). The São Paulo state has already implemented a methodology with a standardised sampling structure for monitoring the ecological development of restoration areas for legal compliance (Chaves et al., 2015, SIMA 32, 2014, SIMA ref. in Table S1), so it is feasible

Box 1

Box 1 – Alternative approach in case of a law review, with the assessment by tiers.

The inclusive tier-assessment proposal

We present a visual simplification of an assessment by tiers (Fig. 3), independent and in addition to the first recommendations on the respective CONAMA resolution. We suggest a first tier based only on the forest structure assessment (i.e., Basal Area, Stem and Tree Density ranges) provided by the landowner's report (threshold values must be defined by parameter and by forest type; e.g., Londe et al., 2020), combined with a land use history evaluation by the environmental body (freely available by MapBiomas or Google Earth Pro and Engine Timelapse tools). In this step, the georeferenced delimitation of the area of interest must be provided. This step can also include photos from the field to facilitate the decision-making process. Using both evaluations, the state environmental body technicians will be able to decide in the first instance if the fragment is in the early or late stage and determine if it is worth further evaluating the case by passing to the next tier (early stages). If late stages are detectd, it is already possible to veto the request and recommend conservation. For the second tier, we suggest considering the biodiversity assessment provided by a certified field taxonomist. After that, consider social aspects, adopting one or more ecosystem services as indicators, focusing not only on urban and general society (public interest) but on local peoples since both groups are directly affected by the clearance of forest fragments by losing several ecosystem services (e.g., water, well-being, climate regulation). For landscape analysis, spatially explicit landscape maps such as landscape composition, configuration and connectivity (Rosenfield et al., 2023; Tambosi et al., 2014) must be accessible as a reference during the decision-making processes.

to implement a similar approach for regulating successional stages classification.

We recommend simplifying the evaluation of the successional stage by reinterpreting most AFPL parameters, as highlighted in Table 1. It is possible to update (or replace) CONAMA resolutions defining measurable structural and floristic parameters by forest type in the form of plain tables and directions on how to interpret them (e.g., Viani et al., 2017, SIMA CBRN 1, 2015, SIMA ref. in Table S1). In the last 80 years, the scientific community in Brazil has produced and gathered comprehensive datasets from forest plots all along the Atlantic Forest (e.g., Lima et al., 2015; Londe et al., 2020), which can be used in a joined effort between decision makers and scientists to raise the correct reference values for reliable ecological and social indicators and allow the accurate inference of successional states by forest type. Removing some parameters (e.g., lianas, understory species list) would be the best solution, but in this case, a change in the AFPL would be necessary, which may not be so simple or quick. Ideally, state resolutions should adopt a more automated and remote approach that could indirectly encompass parameters outlined by the law, including more focused, science-based, and robust indicators, allowing a more straightforward, transparent, and effective way to monitor successional stages relying more on remote monitoring than on field visits.

It is paramount to notice that most of the problems observed for CONAMA 01/1994 are also present in all the other 17 resolutions approved in CONAMA 388/2007 (See Table S1) and posterior resolutions such as CONAMA 417/2009 and CONAMA 423/2010.

Inclusive assessment framework

While various challenges are associated with revising laws, whether through amendments or a complete replacement, we argue that a two-tier revision process (Box 1) is necessary, based not only on successional stages but also on forests' potential to provide ecosystem services (e.g., hydrological cycle regulation) and attributing its landscape importance (e.g., ecological corridors). This framework would be independent and additional to the previous recommendations on reviewing CONAMA resolutions.

The first step would be evaluating only structural parameters provided by the landowner's report, combined with the environmental body evaluation on forest cover history in the last four decades (freely available in a) MapBiomas land cover or b) by assessing Google Earth Engine timelapse tool or c) Google Earth Pro historical imagery), which would allow a good first assessment. The first step will distinguish fragments between initial (pioneer or initial) and advanced (intermediate to advanced) states, which in the second case is automatically designated for protection (saved for exceptional cases). The second part of the process includes assessments performed by a person or entity accredited by a competent environmental agency. It includes biodiversity assessment (richness, presence of endemic, presence of threatened species), landscape aspects (as landscape connectivity, e.g., Joly et al., 2010) and ecosystem services (water and climate regulation or cultural services for traditional peoples) indicators (also previously assessed and available in the form of maps commissioned by official bodies). Given that the provision of services is inherently centred on the demands emanating from society, the very act of considering service provision encompasses a social dimension. Examples of landscape value include the importance of a given forest patch for landscape connectivity, a metric already used by São Paulo in environmental licensing (Joly et al., 2010).

Since our focus is to highlight the shortcomings of CONAMA and present alternatives, we did not develop this second part further. Still, we vehemently suggest a more inclusive evaluation of successional stages considering the multiple interactions among forests, landscapes and society (see Poorter et al., 2023). Including this two-tier assessment may complicate the process for the decision-makers at first moment, but once governments have developed supportive instruments (e.g., ecosystem services maps), it can help by making it simple for landowners while bringing reliability to the entire system.

General recommendations

Following the recommended specific changes and the additional inclusive framework, we developed ideas on adjustments that could improve the overall classification process, resulting in significant benefits. While forest protection based on the ecological succession concept may be adequate for understanding forest complexity (Chang et al., 2019), combining it with the ecological integrity and conservation value (Rosenfield et al., 2023; Areendran et al., 2020) by considering ecosystem services and landscape value, would improve its conservation potential.

The AFPL legal framework is not protective regarding initial and pioneer forests in general and even intermediate and advanced stages forests in urban areas. Thus, reviewing the legal framework should also enhance the protection of initial stages by evaluating their biodiversity, social and landscape values. At the same time, the closer proximity of large human populations to urban forests, which increases the potential of realised ecosystem services (Brauman et al., 2020), justifies higher protection. The negligence of the legislation regarding the protection of forests in the initial stage can compromise the forest transition process observed in the Atlantic Forest in general and in São Paulo, particularly in recent years (Molin et al., 2018; Calaboni et al., 2018; Piffer et al., 2021). This recommendation is fundamental if we consider that the increase in forests has been occurring mainly with young forests (Piffer et al., 2022; Rosa et al., 2021), which are more vulnerable to chronic forest removal. Moreover, allowing further fragmentation will lead to the deterioration of the few conserved remaining forest fragments in the Atlantic Forest (Pütz et al., 2011).

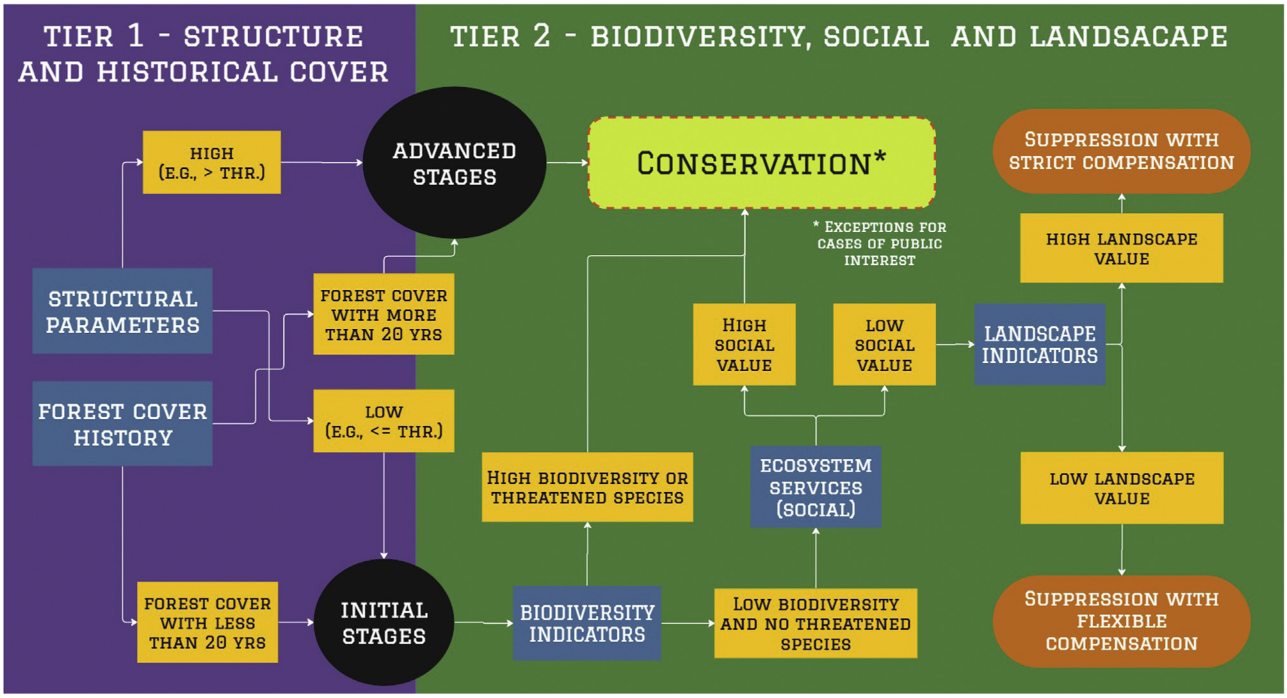

Fig. 3. Proposed framework for assessing successional stages based on two tiers: 1) Structural parameters (threshold (thr.) values must be defined by parameter and by forest type; e.g., Londe et al., 2020) and forest cover history and 2) Biodiversity indicators, ecosystem services and landscape indicators.

Furthermore, one must consider the possibilities of different forest successional pathways, such as the common cases of slow invasion of exotic species, abandoned monocultures, frequent disturbances, or the absence of critical natural disturbances, which may lead to an arrested succession. However, the AFPL states that in case of fire, unauthorised deforestation or other intervention, native vegetation does not lose its stage classification for regularisation. So, the law considers some significant anthropic interferences, but in a way that further complicates the definition of the successional stage. For example, when a fragment is burned or illegally deforested before the permitting request for forest removal, an official protocol on how to estimate the previous state of that fragment by going through unburned surrounding areas or investigating satellite imagery that may not give the exact prior conditions.

Final considerations

We perceive the current successional stages classification system as an obstacle to protecting the Atlantic Forest from further deforestation. Among the many possible causes, we suggest the high pressure for land occupation due to the opportunity cost for agriculture and urban growth, combined with a lack of oversight by environmental agencies due to governments' low incentives for environmental causes. We agree with Issii et al. (2020) that although there is a synergistic potential in applying the Atlantic Forest Law and the Native Vegetation Protection Law to promote less fragmented landscapes, this potential is impaired by the absence of consolidated government structures of command and control. Multiple factors can motivate governments to review the existing legislation for classifying successional stages within the Atlantic Forest. These factors encompass advancements in scientific knowledge, civil society demands, and international environmental agreements. Such movements are imperative for conservation and restoration efforts and for promoting law improvements. The AFPL was a great victory for Brazilian society, and its content is justified by the historical and scientific context in which this law and associated legal instruments were created. However, a new technical framework to strengthen it is needed and viable almost two decades after the law's enactment and more than three decades after the São Paulo state resolution publication. The Atlantic Forest ecology, conservation, and governance knowledge has dramatically increased in recent years and is now readily available for developing more effective, science-based regulations. The timing is perfect for scientists, policymakers, and other stakeholders to co-produce a revised AFPL implementation framework.

Declaration of interests

PHSB and RRR are partners at Re.green, a forest restoration company. Additionally, the authors declare no known competing personal or financial interests that could influence this work.

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Appendix A. Supplementary data

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