Received: 14 April 2021 | Accepted: 5 August 2021

DOI: 10.1111/1365-2664.14065

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Nature-based solutions for a changing world

Balancing natural forest regrowth and tree planting to ensure social fairness and compliance with environmental policies

Markus Gastauer[1] | Angela Silva Miazaki[2] | Renato Crouzeilles[3,4,5] | Paulo André Tavares[6] | Eric D. S. M. Lino[3] | Ricardo Ribeiro Rodrigues[7]

[1]Instituto Tecnológico Vale, Belém, Pará, Brazil
[2]Pós-Graduação em Ciências Ambientais, Universidade do Estado de Minas Gerais, Frutal, Brazil
[3]International Institute for Sustainability, Rio de Janeiro, Brazil
[4]International Institute for Sustainability Australia, Canberra, ACT, Australia
[5]Mestrado Profissional em Ciências do Meio Ambiente, Veiga de Almeida University, Rio de Janeiro, Brazil
[6]Department of Soil Science, College of Agriculture “Luiz de Queiroz”, University of São Paulo, Piracicaba, Brazil
[7]Department of Biological Science, College of Agriculture “Luiz de Queiroz”, University of São Paulo, Piracicaba, Brazil

Correspondence
Markus Gastauer
Email: markus.gastauer@itv.org

Funding information
Fundação de Amparo à Pesquisa do Estado de São Paulo, Grant/Award Number: 2013/50718-5 and 2016/17680-2

Handling Editor: Ainhoa Magrach

Abstract

1. The environmental benefits and lower implementation costs of (assisted) natural forest regrowth (NFR) compared to tree planting qualify it as a viable strategy to scale up forest restoration. However, NFR is not suitable in all places, because the potential for forest regeneration depends on the socio-environmental context and differs greatly over space and time. Therefore, it is critical to quantify the potential contribution of NFR for reaching forest restoration targets and complying with environmental policies.
2. Here, we quantify the socio-environmental consequences of NFR by considering four targets differing in restored area in the Atlantic Forest (6, 8, 15 and 22 Mha). We quantified the compliance with environmental policies, expected distribution of natural and restored vegetation within the biome and social fairness (distribution of restoration efforts and costs within small, medium and large-sized properties) of two hypothetical forest restoration scenarios.
3. We show that large-scale forest restoration prioritizing the areas with the highest potential for NFR (Scenario I) allows us to comply with one-third of the current environmental debt in the Atlantic Forest. Furthermore, this scenario disproportionately burdens specific types of land use, increases socioeconomic inequalities and concentrates restoration activities in regions in which the natural vegetation cover is already high.
4. By contrast, Scenario II—eradicating the environmental debt that results from environmental policies, then prioritizing areas with the lowest overall restoration costs until reaching the restoration targets—is socially fairer and maximizes compliance with environmental policies. Its outcomes are more homogeneously distributed among counties and small, medium and large-sized properties from the Brazilian Atlantic Forest. Despite doubling the implementation costs, the lower overall restoration costs in Scenario II result from significantly lower opportunity costs than in Scenario I.

5. *Synthesis and application*. The environmental, social and economic outputs of large-scale forest restoration in the Atlantic Forest can be maximized when NFR and tree planting are balanced (Scenario II). To achieve compliance with forest restoration commitments, we thus advocate for the site-specific selection of the best forest restoration strategy to guarantee social fairness and compliance with environmental policies at minimum overall restoration costs.

KEYWORDS

areas of permanent preservation, environmental debt, implementation costs, land tenure, legal reserves, opportunity costs, smallholders

1 | INTRODUCTION

Tropical forest restoration is considered a promising strategy to reduce existing social inequalities (Ota et al., 2020), mitigate climate change (Besseau et al., 2018) and protect biodiversity more effectively (Brancalion, Meli, et al., 2019; Molin et al., 2018). To achieve these multiple benefits, ambitious restoration targets were set for Brazil (MMA, 2018; WRI, 2019). However, the high costs associated with tree planting are major hurdles for large-scale forest restoration (Gastauer et al., 2020; Nunes, Gastauer, et al., 2020; Saraiva et al., 2020). A cheaper alternative is natural forest regrowth (NFR), that is, the growth of trees that develop from seeds that fall and germinate in situ following the removal of the degrading agents (Brancalion et al., 2020; Nunes et al., 2017), which can achieve similar or even better results than active restoration regarding carbon sequestration and biodiversity benefits (Crouzeilles et al., 2017; Meli et al., 2017). Assistance from nucleation techniques or enrichment plantings may further facilitate and enhance shrub and tree establishment in areas under restoration and accelerate NFR (Boanares & Azevedo, 2014). Therefore, (assisted) NFR has increasingly been considered a more viable restoration strategy to upscale forest restoration (Crouzeilles et al., 2020; Strassburg et al., 2019).

The success of (assisted) NFR, however, depends on the environmental, social, economic and political context (hereafter socio-environmental context; Chazdon, 2014; Crouzeilles et al., 2020). The environmental context affects the spontaneous arrival of plant propagules and their successful establishment and may favour, delay or even impair the recovery of biodiversity and the vegetation structure (de Lima et al., 2020; Freitas et al., 2019; Holl et al., 2017). The socioeconomic context determines where NFR is allowed to occur and persist (Chazdon & Guariguata, 2016; Reid et al., 2019). Lastly, the least studied topic is related to the political context, which can either stimulate or prevent NFR (Chazdon et al., 2020). NFR is thus not equally suitable at all sites, and the potential of forests to regenerate differs greatly over space and time.

The Brazilian Law on the Protection of Native Vegetation (LPVN in Portuguese acronym; N^{o} 12.651/2012) aims to protect ecologically sensitive areas (areas of permanent preservation; APP in Portuguese), such as buffer zones around water bodies, steep slopes and mountaintops. The law also aims to allocate a specific area within private properties (legal reserves; RL in Portuguese) to conserve biodiversity and provide ecosystem services (Alves et al., 2020; Oliveira et al., 2017). APPs or RLs not covered by natural vegetation constitute an environmental debt and require restoration or offsets, and the environmental surplus, that is, the area covered by natural or restored ecosystems exceeding the legal thresholds, may be legally deforested or used for offsets (Azevedo et al., 2017). Concerns have arisen that despite its lower implementation costs, NFR may not be suitable for reducing current environmental debt, because the socio-environmental context in counties or regions with elevated environmental debt may delay or impair NFR.

A recent study developed a spatially explicit predictive model and found *c*. 22 Mha of degraded lands with potential for NFR in the Brazilian Atlantic Forest hotspot (Crouzeilles et al., 2020). According to this study, the potential for NFR depends principally on the distance to the closest forest remnant. This finding increases concerns regarding the restoration of the current environmental debt in the biome because degraded APPs and RLs from regions with reduced forest cover may not regrow naturally. Furthermore, counties with a lower remaining forest cover, for example, that of the corn, soy or sugarcane heartlands (Rezende et al., 2018), are expected to have a lower potential for NFR than regions with a higher remnant forest cover, which are dominated by less productive types of land use. Consequently, a large-scale forest restoration focusing solely on NFR may disproportionally transfer the costs associated with forest restoration to specific types of land uses (Salvini et al., 2018) that are less targeted by the powerful Agribusiness Parliamentary Front in the Brazilian congress (Fearnside, 2016). Lastly, if smaller rural properties have a higher potential for NFR, smallholders may be disproportionally burdened in such a scenario.

The aim of this article is to examine the socio-environmental consequences of NFR in the Brazilian Atlantic Forest. To this end, we quantified the potential for NFR within (a) the current legal environmental debt according to the LPVN; (b) distinct types of agricultural land use (considered as areas available for restoration) and (c) different land tenure classes (public lands, small, medium and large-sized properties). Then, we defined two distinct scenarios for scaling up forest restoration activities, considering four targets differing across restored area in the Atlantic Forest (see Methods for details). Scenario I aimed to prioritize only the areas with the highest potential for NFR for reaching the restoration targets. Scenario II aimed to eradicate environmental debts by balancing NFR with tree planting, starting with the environmental debts of lowest overall restoration costs (implementation and opportunity costs). For restoration targets exceeding the current environmental debt in the Atlantic Forest, further areas were selected according to the lowest overall restoration costs. To compare both scenarios, we quantified (d) environmental performance as compliance with the LPNV, (e) the expected distribution of natural or restored vegetation cover throughout the biome as well as (f) social fairness (distribution of restoration efforts and costs among small, medium and large-sized properties) of both restoration scenarios across restoration targets.

2 | MATERIALS AND METHODS

2.1 | Study site and forest restoration targets

The Brazilian Atlantic Forest is a global conservation and restoration hotspot (Brancalion, Niamir, et al., 2019). It covers the Brazilian coast from the state of Rio Grande do Norte in the northeast to the state of Rio Grande do Sul in the south (Law N° 11.428/2006). A long history of land-use changes due to urbanization and agricultural development has resulted in widespread deforestation and fragmentation, leading to a dramatic reduction in forest cover (Ribeiro et al., 2009). According to a recent estimate, 28% of the original forest cover remains, but the percentage of natural vegetation differs among regions (Lira et al., 2012; Rezende et al., 2018). The largest remnants of natural vegetation are found in the coastal mountain ridges from Southeast, including Bahia state, as well as in the northern inland area. Sugarcane and soy prevail among the agricultural activities in the western parts of Rio Grande do Sul, Paraná, São Paulo and Minas states, while pastures dominate land use in the northern part of the Atlantic Forest (Figure 1).

Although the cover from natural (forest) vegetation has tended to increase in recent decades (Costa et al., 2017; Hansen et al., 2013; Rosa et al., 2021), ambitious restoration targets for the coming decades have been formulated for the Brazilian Atlantic Forest. A recent but rough estimate identified 6 Mha of environmental debts within the Atlantic Forest (Soares-Filho et al., 2014). With our current database, which is more robust and accounts for more specificity within the LPVN, we detected a slightly higher environmental debt in the Atlantic Forest (*c*. 8 Mha; see below). The Atlantic Forest Restoration Pact, a bottom-up, non-governmental movement involving more than 300 organizations and private corporations, aims to restore 15 Mha of degraded and deforested lands by 2050 within the biome (www.pactomataatlantica.org.br). Crouzeilles et al. (2020) developed further forest restoration targets based on the potential for NFR and opportunity costs. In a 'maximum potential' scenario, they assumed that all areas with potential for NFR could be restored (*c*. 22 Mha), independent of the associated opportunity costs.

2.2 | Data sources and processing

For our analysis, we used freely available data sources about current land use and land cover ('MapBiomas', www.mapbiomas.org; Souza et al., 2020) and land tenure information (Freitas et al., 2018; Sparovek et al., 2019, see Appendix S1 for details). To build an APP raster, we separately mapped (a) the buffer zones of hydrological components such as rivers, springs and lakes; (b) areas with slopes larger than 45°; (c) areas above 1,800 m a.s.l.; and (d) mountaintops (Appendix S2).

The potential for NFR as well as the forest restoration opportunity costs was derived from Crouzeilles et al. (2020). They developed a probabilistic, spatially explicit model with a 30 m resolution, which accounted for the NFR that occurred between 1996 and 2015, and they used socioeconomic and environmental variables to predict the potential for NFR over the next 20 years (the model accuracy is *c*. 80%). We considered (assisted) NFR as a feasible restoration strategy for all agricultural land types with a potential for NFR > 50%.

Restoration costs were estimated for each pixel from current land use (annual opportunity costs) and the potential for NFR (implementation costs; Crouzeilles et al., 2020). Transaction costs were not addressed. Based on county-wide gross values for cattle breeding and the primary agricultural crops divided by the area of specific land-use type within the county, the annual opportunity costs were computed separately for pasture and agricultural areas (Appendix S3).

Forest restoration implementation costs were estimated as (100 − potential for NFR in %) × US$ 5,482, where US$ 5,482 represents the cost of tree planting per hectare in the Atlantic Forest (Benini & Adeodato, 2017) and does not include further transaction costs. If an area has 100% potential for NFR, the implementation cost is 0. By contrast, if an area has 0% potential for NFR, the implementation cost is equal to the cost of tree planting. Because the aim is to engage in forest restoration activities within the next two decades, we divided the absolute implementation costs (for each pixel) by 20 to achieve an annual value that can be summed with the annual opportunity costs to obtain the overall restoration costs.

To quantify the potential for NFR within distinct types of land use, the environmental debt (APPs and RLs) and different land tenure classes, we performed a pixel-wise analysis (30 m resolution). For that purpose, all the shapes were converted to rasters. To outline the environmental debt and eventual environmental surpluses, we used the APP raster and related it to the current land cover for all land tenure classes except medium-sized and large rural properties; the latter were analysed separately to check the amount of environmental debt in RLs within each property (20% of the total area of medium-sized and large properties according to LPNV). To optimize the outcomes, we selected areas for RL restoration with the lowest overall restoration costs but ignored the legal possibilities to offset RLs.

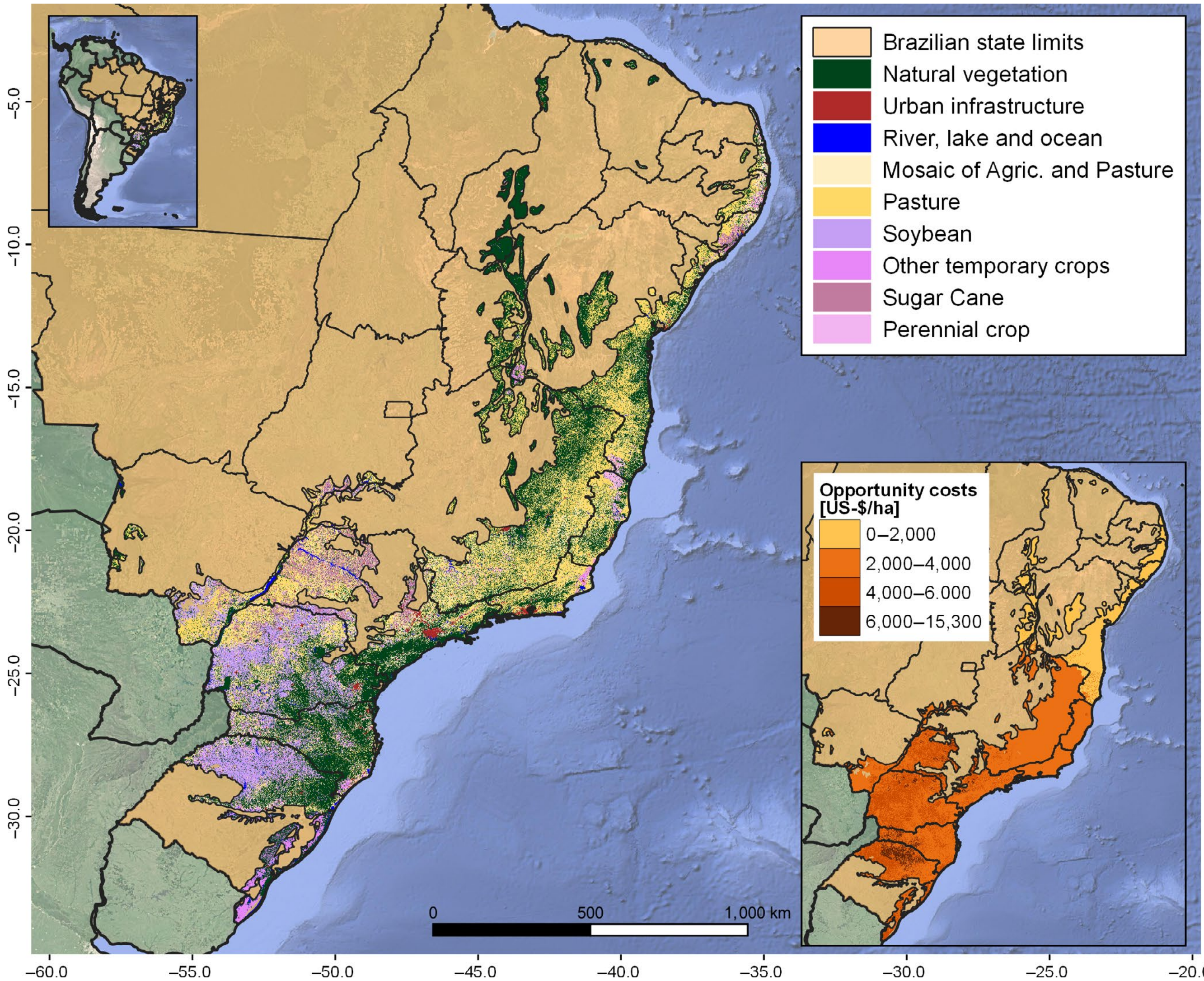

FIGURE 1 Current land use and average forest restoration opportunity costs in the Brazilian Atlantic Forest. The data regarding current land use are from the MapBiomas project, and the opportunity costs were retrieved from Crouzeilles et al. (2020, see method section)

To connect information available from distinct rasters, we used Raster Calculator from QGIS to build synthetic rasters. From that product, we built frequency tables using the 'freq' function from the RASTER package in R Environment v. 4.0.2 (R Development Core Team, 2018).

2.3 | Restoration scenarios

We compared two distinct large-scale forest restoration scenarios at the same pixel level. For Scenario I, we presupposed that restoration starts in areas with only the highest potential for NFR for reaching each specific forest restoration target. That is, the maximum forest restoration target (22 Mha) hypothetically restores all the areas with high potential for NFR (>50%; Crouzeilles et al., 2020). For Scenario II, we assumed that the decrease of the environmental debt (APPs and RLs) is prioritized, starting with the restoration of areas with the lowest overall restoration costs (implementation and opportunity costs) inside the APPs, followed by RLs, until reaching specific forest restoration targets. For restoration targets exceeding the environmental debt in the Atlantic Forest (8 Mha), further areas were selected according to the lowest overall restoration costs.

We computed the compliance with the LPNV, county-wide percentage of natural and restored vegetation cover and social fairness for each target in both scenarios. Compliance with LPNV is defined as the percentage of restored environmental debts (APP and RL). Regarding the county-level vegetation cover, a 30% threshold value is considered necessary for the persistence of different taxonomic groups in the biome (Banks-Leite et al., 2014; Lima & Mariano-Neto, 2014). We quantified the number of counties with <10%, 20%, 30% or 50% natural or restored vegetation cover for all outcomes (four targets from both scenarios). Social fairness is measured as the proportional distribution of restoration activities (in percent of property size) and opportunity costs (in US$ per land unit remaining for agricultural purposes).

3 | RESULTS

3.1 | Distribution of NFR potential in the Atlantic Forest

We mapped 15.63 Mha of APPs in the Brazilian Atlantic Forest (11.27% of the entire study area). Of that area, 6.97 Mha are not covered by natural vegetation. Medium-sized and large rural properties cover 49.36 Mha; the RLs in these medium and large rural properties add up to 5.28 Mha, with 1.33 Mha representing environmental debts according to the LPVN. Together with the APPs from all the land tenure classes, the absolute environmental debt in the Atlantic Forest is thus estimated to be 8.31 Mha, which is not uniformly distributed within the study area (Figure 2). In total, 37.92% of the current environmental debt in APPs and RLs (3.10 Mha) has an NFR potential of higher than 50% (Figure 3a).

The relative environmental debt is higher in private rural properties than in public lands, and small rural properties and areas without land tenure information show higher environmental debts compared to other land tenure categories (Table 1). The environmental surplus surpasses the environmental debt in all classes and is proportionally higher in public areas and areas without land tenure information than in large, medium-sized or small rural properties (Table 1).

The potential for NFR is not proportionally distributed among the different land-use classes. Sugarcane shows the lowest proportional potential for NFR, and the potential for NFR is highest in the land-use categories of Mosaic of Agriculture and Pasture, Other Temporary Crops and Pasture (Figure 3b). The current land use differs among land tenure classes (Appendix S4), and the percentage of areas available for restoration is lowest for public lands and highest for small properties. Areas without land tenure information and large rural properties are in intermediate positions, and the potential for NFR is highest for small rural properties (Figure 3c).

3.2 | Comparison of different restoration scenarios

Exclusive NFR to scale up forest restoration in the Brazilian Atlantic Forest (Scenario I) will disproportionately burden extensive types of land use and small rural properties, independent of the forest restoration target (Figure 4a), and it will result in higher annual opportunity costs per future unit of arable land for small rural properties than for medium-sized or large properties (Figure 4b). The environmental debts in APPs and RLs will be solved only partially by NFR (Figure 4c,d) and remain unrestored in some regions from the Atlantic Forest, while vegetation cover in areas with a high percentage of remnant forests will increase further (Figure 5). More than 15% of all counties will not reach a natural or restored vegetation cover of 20% in this scenario (Figure 5, embedded box). Annual opportunity costs for the restoration of all areas with NFR potentials larger than 50% are estimated to be US$76,677 Bi/year, and annual implementation costs are estimated to be US$ 2,375 Bi (Figure 6).

By contrast, Scenario II will distribute restoration efforts more fairly between different land tenure classes. Although the relative restoration efforts are still greater for small rural properties than for medium or large ones (Figure 4e), the opportunity and implementation costs per future unit of arable land are more homogeneously distributed among small, medium and large-sized properties (Figure 4f). Degraded APPs and RLs from all counties will be restored (Figure 4g,h), distributing future natural or restored vegetation cover more homogeneously among counties, reducing the number of counties with low (<20%) and very low (<10%) natural or restored vegetation cover compared to Scenario I (Figure 5). As expected, the annual implementation costs are higher for Scenario II than for Scenario I (Figure 6), but the contribution of NFR is still significant in Scenario II, because up to 6.68 Mha (in the 22 Mha restoration target) may regrow naturally. Contrary to the implementation costs, the opportunity costs are significantly lower in Scenario II than in Scenario I, resulting in overall lower restoration costs for Scenario II (Figure 6).

4 | DISCUSSION

4.1 | NFR potential is concentrated in marginal types of land use and small properties and does not target complete environmental debts

Our analysis confirmed that the potential for NFR is not homogeneously distributed among different types of land use and different land tenure classes in the Atlantic Forest. Thus, the exclusive restoration of areas with a high potential for NFR to achieve forest restoration targets for the Atlantic Forest disproportionally burdens some types of land uses and small rural properties, reducing the environmental responsibility of medium-sized and large rural properties. Only one-third of the current environmental debts have a NFR potential greater than 50%, so (assisted) NFR may be unable to restore large parts of the current environmental debt in the Brazilian Atlantic Forest.

Our data show that the NFR potential is highest for the land-use types Mosaic of Agriculture and Pasture and Other Temporary Crops, while soy or sugarcane show the lowest values. Within the Mosaic of Agriculture and Pasture and the Other Temporary Crops land use category, the pixels for different types of land uses without specific spectral signatures are pooled (Souza et al., 2020). Both categories are frequently associated with marginal areas comprising little mechanized household agriculture for subsistence and extensive cattle ranching on less fertile, steeper slopes that reduce the possibility for mechanization (Almeida et al., 2016; Neves et al., 2020). The higher potential for NFR on this type of land use thus confirms our expectations that the NFR potential is higher in areas that are less targeted by the agribusiness lobby.

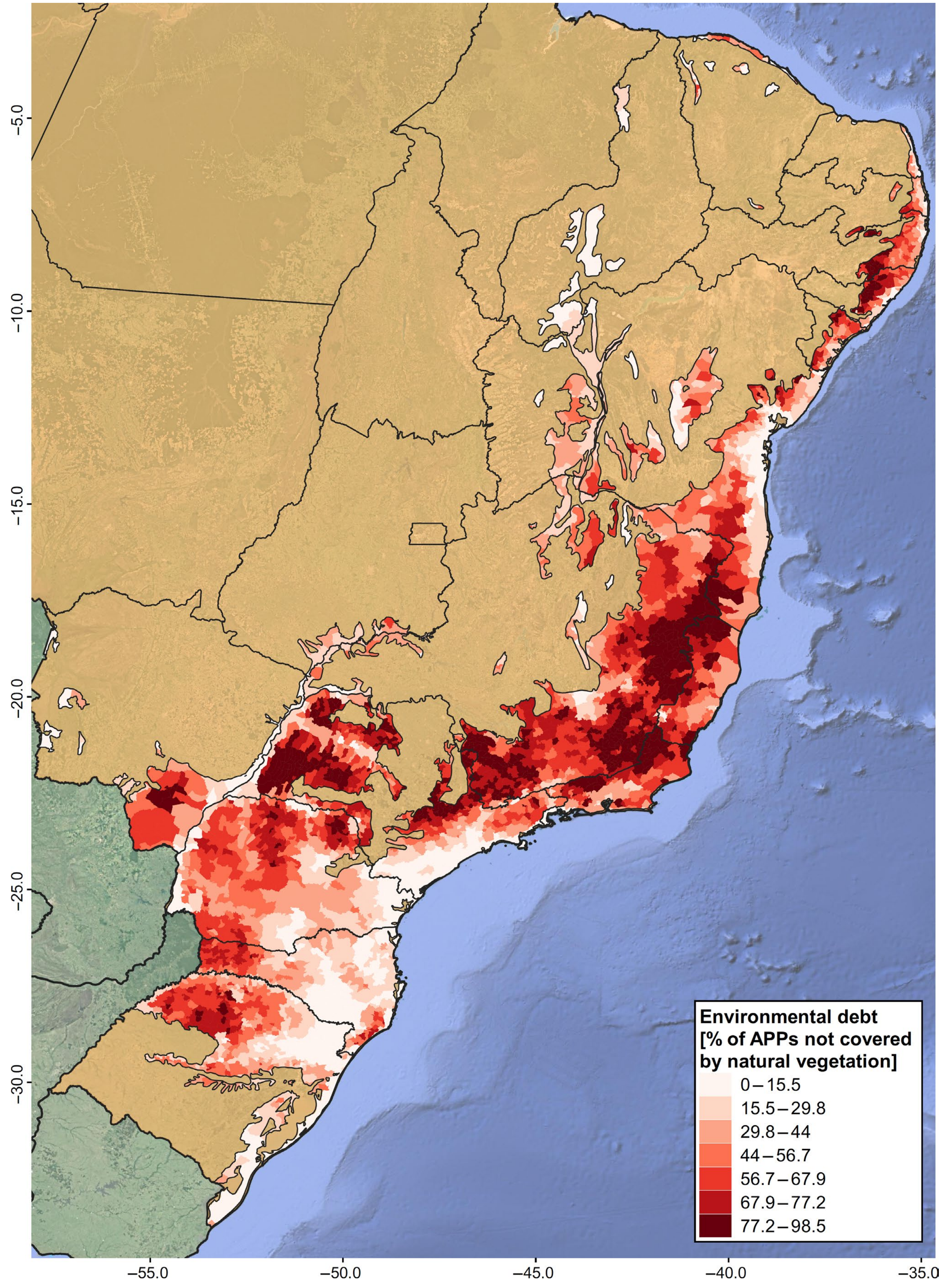

FIGURE 2 Per county relative environmental debt in areas of permanent preservation (APPs) in the Brazilian Atlantic Forest

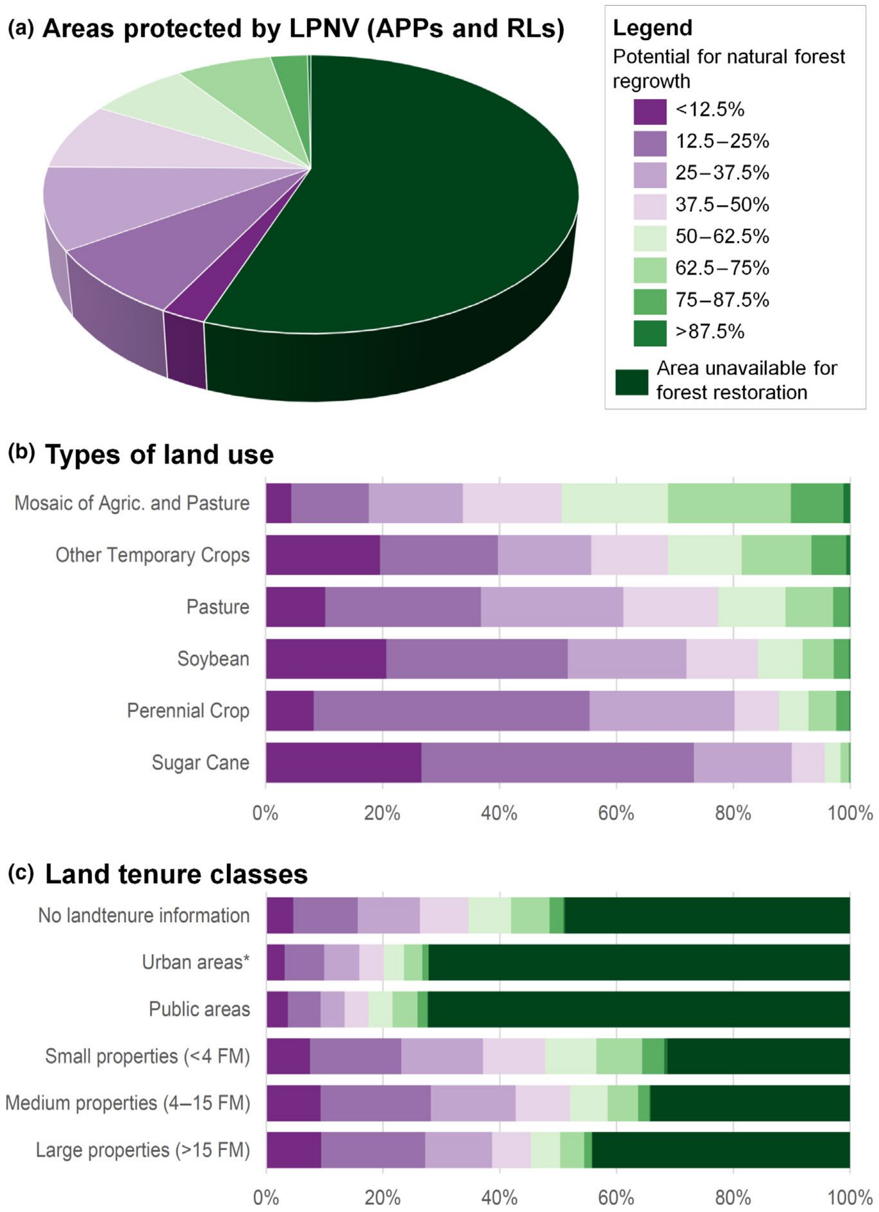

FIGURE 3 Relative potential for natural forest regrowth of different types of land use (a), environmental deficits (APPs and RLs, b) and different land tenure classes (c) in the Brazilian Atlantic Forest. APP, areas of permanent preservation. *Includes transportation network and water bodies, as defined by Freitas et al. (2018) and Sparovek et al. (2019)

Compared to overall property size, small rural properties possess a higher potential for NFR compared to medium-sized and large rural properties. Interestingly, the relative amount of area restorable by (assisted) NFR is not correlated to the relative cover of native vegetation within different land tenure categories, because large rural properties have a proportionally higher cover of remnant native vegetation, confirming previous studies (Stefanes et al., 2018). Instead, a higher potential for NFR results from a lower percentage of sugarcane (the maintenance of sugarcane mills requires large rural properties to guarantee the constant supply of raw material) and a proportionally higher amount of Mosaic of Agriculture and Pasture. Consequently, restoration efforts focusing exclusively on NFR demand proportionally larger areas to be restored on smaller properties, including household agriculture systems, indicating that large agribusiness companies may not be the primary drivers of compliance with forest restoration commitments in this forest restoration scenario.

Furthermore, we mapped an overall environmental debt of 6.97 Mha in APPs and an additional 1.30 Mha in RLs consistent with previous estimates (Rezende et al., 2018), which accumulates in the less mountainous, more productive areas of Brazil's interior. Assuming that pixels with an NFR potential of greater than 50% can regrow by (assisted) NFR, one-third of the current environmental debt can be solved by NFR, while this restoration strategy may not be suitable for two-thirds of the environmental debt. Selecting further areas for forest restoration activities based on the NFR potential may thus not target areas that are legally protected by environmental policies (LPNV) and increase environmental surpluses (at least in some rural properties) in the Brazilian Atlantic Forest. Because environmental surpluses from private rural properties are not protected by the LPNV, carbon stocks and the associated co-benefits for biodiversity and ecosystem services therein are at risk of legal deforestation and require further incentives to protect regrowing

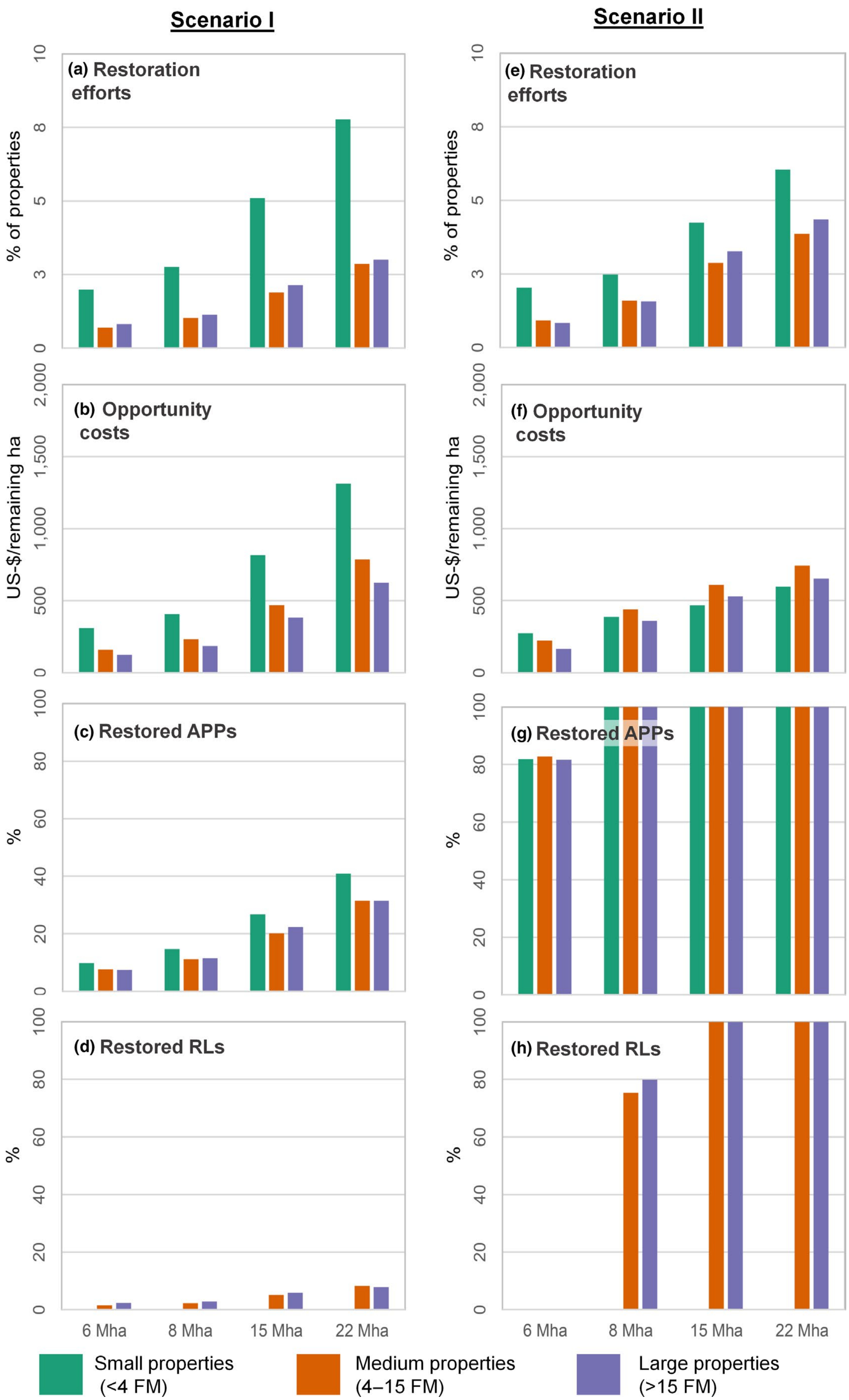
Scenario I
Scenario II
(a) Restoration efforts
(b) Opportunity costs
(c) Restored APPs
(d) Restored RLs
(e) Restoration efforts
(f) Opportunity costs
(g) Restored APPs
(h) Restored RLs
% of properties
US-$/remaining ha
%
0
3
5
8
10
500
1,000
1,500
2,000
20
40
60
80
100
6 Mha
8 Mha
15 Mha
22 Mha
Small properties (<4 FM)
Medium properties (4–15 FM)
Large properties (>15 FM)

FIGURE 4 Social and environmental consequences of two different scenarios to upscale forest restoration activities in the Brazilian Atlantic Forest, considering four targets differing in the restored area in the Atlantic Forest (6, 8, 15 Mha and 22 Mha). For the differences among the restoration scenarios, please refer to the text. FM is fiscal model used to separate private rural properties in small, medium and large-sized properties (Supplementary Material 1). Restoration efforts (a), cumulated opportunity costs (b), percentage of restored areas of permanent preservation (APPs, c) and legal reserves (RLs, as defined by the Brazilian Law on the Protection of Native Vegetation (No 12.651/2012, d) for Scenario I; restoration efforts (e), cumulated opportunity costs (f), percentage of restored APPs (g) and RLs (h) for Scenario II

TABLE 1 Total area, current environmental debt and surplus in different land tenure classes from the Brazilian Atlantic Forest

	Total area [Mha]	Area protected by LPNV[a] [Mha]	Current environmental debt [Mha] (% of protected area)	Current environmental surplus [Mha] (% of total area)
No land tenure information available	40.25	4.59	2.04 (44.32%)	17.11 (42.50%)
Public areas	6.31	0.81	0.13 (16.67%)	3.92 (61.63%)
Small rural properties (<4 FM)	37.15	4.45	2.48 (55.68%)	9.64 (25.96%)
Medium-sized rural properties (4–15 FM)	20.65	4.35 2.25[b]	1.79 (41.11%) 1.11 (49.49%)[b]	4.11 (19.92%)
Large rural properties (>15 FM)	28.71	6.03 2.85[b]	1.74 (28.82%) 1.01 (35.49%)[b]	8.11 (28.25%)
Total[c]	133.08	20.24 14.95[b]	8.18 (40.40%) 6.97 (46.62%)[b]	42.87

[a]Areas of permanent preservation (APP) only for areas without land tenure information, public areas and small rural properties; APP and legal reserves (RL) for medium and large rural properties.

[b]Areas of permanent preservations only.

[c]Lacking from this table are 5.59 Mha in urban areas, transportation networks and water bodies.

forests in the Atlantic Forest (Chazdon et al., 2020; Freitas, Englund, et al., 2018).

4.2 | Tree planting plus NFR increases environmental compliance and social fairness by reducing overall restoration costs

To comply with forest restoration commitments, the NFR strategy (Scenario I) burdens disproportionately small rural properties. Proportionally larger restoration efforts on small properties result in higher opportunity costs per remaining unit of agricultural land, disproportionally burdening smallholders in this NFR strategy. Scenario I furthermore does not target the entire environmental debt and concentrates restoration activities in counties with an already elevated forest cover. Scenario II, however, which balances NFR and tree planting as restoration strategies to comply with environmental debts and reach forest restoration targets while minimizing overall restoration costs, is socially fairer, because the restoration efforts are proportionally distributed among small, medium and large-sized properties. The environmental outcomes of Scenario II outperform those from Scenario I, and although nearly doubling implementation costs in comparison to Scenario I, the overall costs for forest restoration in Scenario II are lower when restoration targets from the Atlantic Forest Restoration Pact or beyond become accomplished.

In both scenarios, the relative restoration obligation (in % of property size) is higher in small than in medium-sized or large properties, but only in Scenario I are the opportunity costs per remaining unit of agricultural lands higher in small than in medium-sized or large rural properties. Here, we estimated the restoration opportunity costs on a countywide basis, and we did not consider the differences in soil properties, crop or management systems within or between properties that influence productivity and real opportunity costs. Evidence is given that productivity decreases with property size (WRI, 2020) so that actual restoration opportunity costs in small rural properties may be even higher than estimated here. Furthermore, the transaction costs not evaluated in this study are expected to decrease with the property size, additionally burdening small rural properties compared to medium-sized or large properties. Higher restoration costs in small rural areas indicate that large agribusiness companies contribute proportionally less than smallholders to forest restoration commitments when (assisted) NFR is prioritized (Scenario I), although they hold the largest environmental debts (Mello et al., 2021). By contrast, Scenario II distributes restoration opportunity costs more fairly

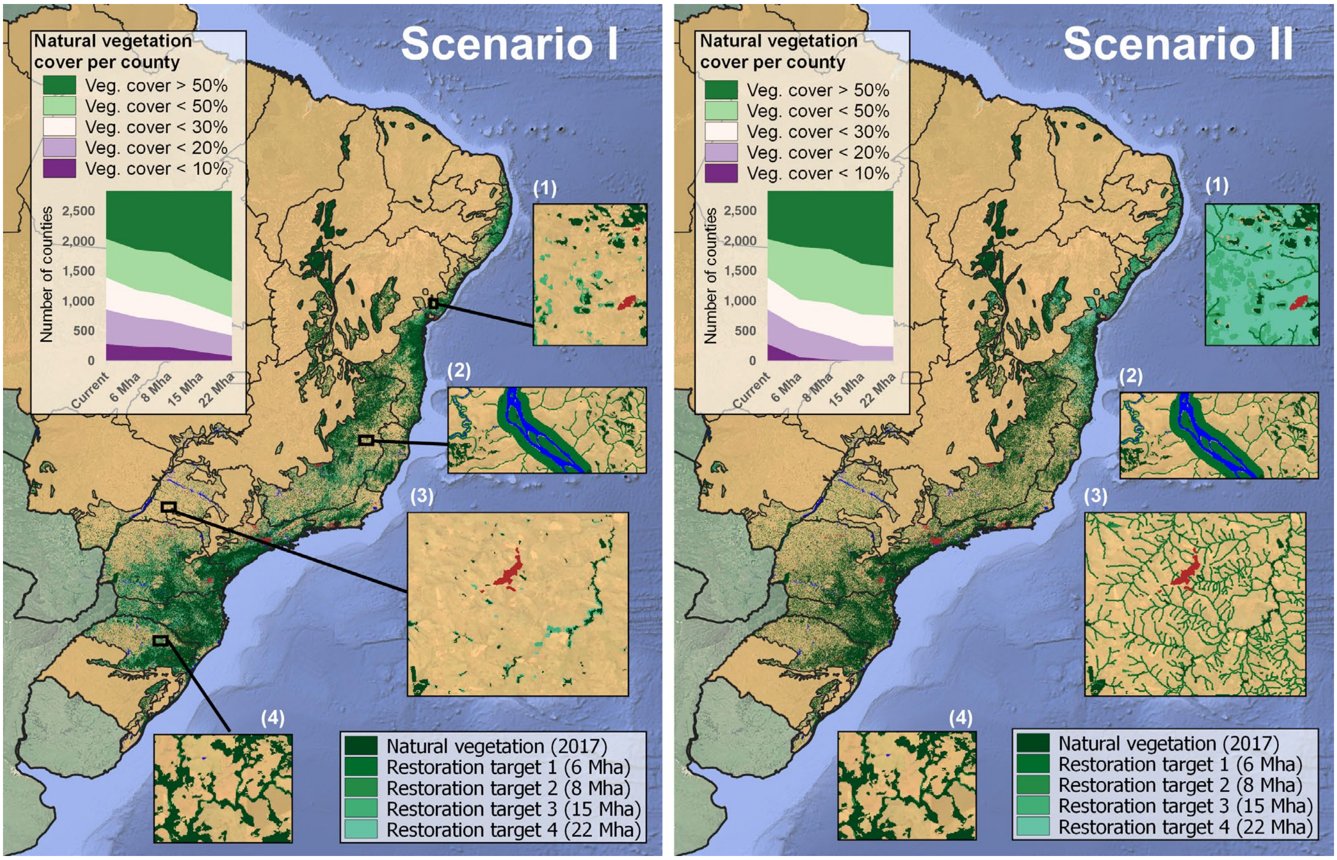

FIGURE 5 Spatial outcomes of two forest restoration scenarios (see methods for details) for the Brazilian Atlantic Forest considering four targets that differ in the amount of restored area (6, 8, 15 Mha and 22 Mha). The embedded maps show the differences in restoration outcomes between restoration scenarios in northern Bahia state (1), the Rio Doce basin (2), the São Paulo inland (3) and the Gaucho Highlands (4). The embedded boxes illustrate the percentage of native vegetation per county after reaching different restoration targets

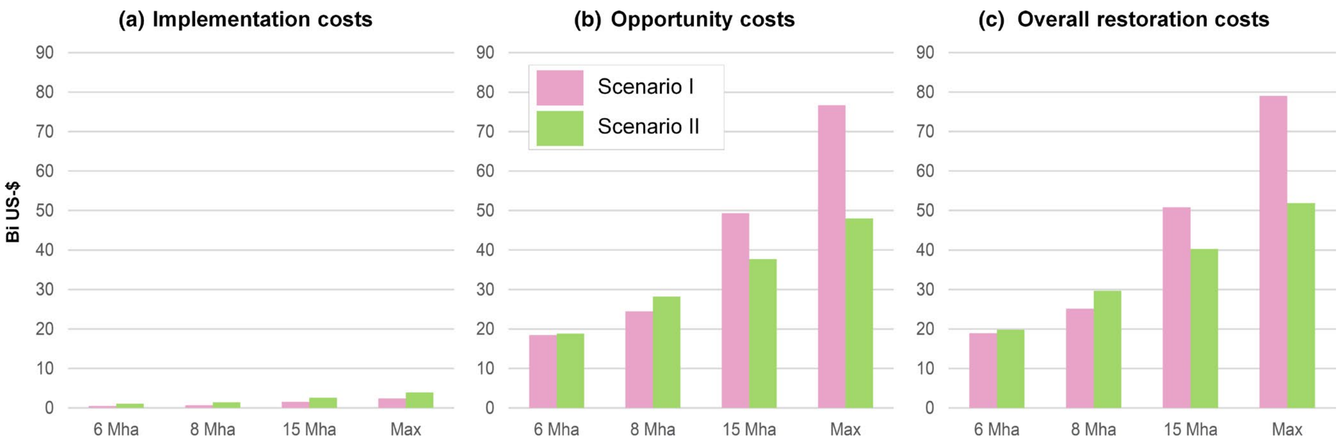

FIGURE 6 Annual implementation (a), opportunity (b) and overall restoration costs (c, implementation + opportunity costs) of different forest restoration targets (6, 8, 15 and 22 Mha) in two restoration scenarios for the Brazilian Atlantic Forest

among different land tenure categories by balancing NFR with seedling planting.

Scenario II prioritizes the eradication of the entire environmental debt of the Atlantic Forest (estimated to be 8.18 Mha), which generates three important benefits compared to Scenario I. First, this strategy guarantees full compliance of rural properties with LPNV, which is important to obtain access to the technical assistance, production technology and markets necessary to compensate for the restoration opportunity costs (Stabile et al., 2020). Second, restored APPs and RLs receive integral protection against iterated degradation or deforestation (Nunes et al., 2020), guaranteeing their persistence, while restoration activities in private lands outside APPs or RLs (the so-called vegetation surplus in the LPNV terminology) may be legally deforested. Third, the restoration of degraded APPs and RLs in Scenario II targets regions and counties with low or very low remaining vegetation cover, thus distributing remaining and restored ecosystem services such as pollination, the protection of water resources and carbon sequestration better throughout the biome than in Scenario I.

Apart from a better socio-environmental performance, the large-scale forest restoration in Scenario II is associated with lower overall restoration costs, and up to 30% of restoration costs may be saved compared to Scenario I, in which more than 8 Mha would be restored. These savings arise because the annual opportunity costs are greater than the implementation costs, so the prioritization to restore less productive stands is the economically more rational scenario, even when tree planting is required. Here, we used a coarse spatial resolution for estimating restoration opportunity costs (county-level) so that restoration efforts from targets larger than 8 Mha in the current Scenario II are concentrated in north-eastern states in the Brazilian Atlantic Forest, where restoration opportunity costs are lower than those in the southern agricultural heartlands. More detailed analysis, for example, considering differences in soil fertility and productivity within rural properties, may identify degraded areas with low associated restoration opportunity costs from regions other than the Northeast. The biome-wide restoration of APPs and RLs to achieve the 6 or 8 Mha target is furthermore expected to enhance the NFR potential throughout the biome. Thus, the revision of the NFR, in addition to the inclusion of further criteria to set restoration priorities, for example, the pricing of the carbon sequestration potential differing among regions, may thus distribute the restoration activities and associated environmental benefits in the more ambitious targets (15 or 22 Mha) more evenly among regions and counties from the Brazilian Atlantic Forest in the future.

5 | CONCLUSIONS

Lower environmental performance, non-compliance with LPNV, higher burdens for small properties that may increase socioeconomic inequalities between land tenure classes and higher overall restoration costs in Scenario I underline the need for site-specific selection of the best forest restoration strategy to upscale forest restoration activities in the Brazilian Atlantic Forest, as balancing NFR with seedling planting maximizes environmental, social and economic outputs of restoration commitments. The analysis of the environmental, social and economic benefits may outcompete pure NFR strategies in other biomes where NFR is currently considered the most promising strategy to achieve restoration commitments. Thus, we highlight the importance of considering all socio-environmental consequences to set global, national, biome-wide and regional restoration priorities, not only implementation costs, to optimize the outputs of restoration efforts.

ACKNOWLEDGEMENTS

We are grateful to the Research Foundation of São Paulo (FAPESP, grants 2013/50718-5 and 2016/17680-2).

CONFLICT OF INTEREST

Authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

R.R.R. and M.G. designed the study; A.S.M. and M.G. analysed the data provided by R.C., P.A.T. and E.D.S.M.L.; and M.G. wrote the first draft of this manuscript. All the authors contributed to further versions and approved the final version of the manuscript to be published.

DATA AVAILABILITY STATEMENT

All data used in this study are from publicly accessible repositories (see Section 2 for details). Two raster files containing areas protected by LPNV created for this study and the potential of natural forest regrowth are available via figshare https://doi.org/10.6084/m9.figshare.16546185 (Gastauer, 2021) and https://doi.org/10.6084/m9.figshare.16814863 (Crouzeilles, 2021).

ORCID

Markus Gastauer https://orcid.org/0000-0002-9599-0902
Eric D. S. M. Lino https://orcid.org/0000-0002-9320-1148

REFERENCES

Alves, G. H. Z., Tófoli, R. M., Rodrigues-Filho, J. L., Sacramento, P. A., Cionek, V. M., Figueiredo, B. R. S., & do Couto, E. V. (2020). Brazil's vegetation ravage may be encouraged by law. *Biodiversity and Conservation*, *29*, 1105–1107. https://doi.org/10.1007/s10531-020-01933-7

Azevedo, A. A., Rajão, R., Costa, M. A., Stabile, M. C. C., Macedo, M. N., Dos Reis, T. N. P., Alencar, A., Soares-Filho, B. S., & Pacheco, R. (2017). Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 7653–7658. https://doi.org/10.1073/pnas.1604768114

Banks-Leite, C., Pardini, R., & Tambosi, L. R. (2014). *Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot*. Retrieved from https://science.sciencemag.org/content/345/6200/1041.abstract

Besseau, P., Graham, S., & Christophersen, T. (2018). *Restoring Forests and Landscapes: The Key to a Sustainable Future*. Global Partnership on Forest and Landscape Restoration.

Boanares, D., & de Azevedo, C. S. (2014). The use of nucleation techniques to restore the environment: A bibliometric analysis. *Natureza & Conservação*, *12*, 93–98. https://doi.org/10.1016/j.ncon.2014.09.002

Brancalion, P. H. S., Amazonas, N. T., Chazdon, R. L., Melis, J., Rodrigues, R. R., Silva, C. C., Sorrini, T. B., & Holl, K. D. (2020). Exotic eucalypts: From demonized trees to allies of tropical forest restoration? *The Journal of Applied Ecology*, *57*, 55–66. https://doi.org/10.1111/1365-2664.13513

Brancalion, P. H. S., Meli, P., Tymus, J. R. C., Lenti, F. E. B., M. Benini, R., Silva, A. P. M., Isernhagen, I., & Holl, K. D. (2019). What makes ecosystem restoration expensive? A systematic cost assessment of projects in Brazil. *Biological Conservation*, *240*. https://doi.org/10.1016/j.biocon.2019.108274

Brancalion, P. H. S., Niamir, A., Broadbent, E., Crouzeilles, R., Barros, F. S. M., Almeyda Zambrano, A. M., Baccini, A., Aronson, J., Goetz, S., Reid, J. L., Strassburg, B. B. N., Wilson, S., & Chazdon, R. L. (2019). Global restoration opportunities in tropical rainforest landscapes. *Science Advances*, *5*, eaav3223. https://doi.org/10.1126/sciadv.aav3223

Chazdon, R. L. (2014). *Second growth: The promise of tropical forest regeneration in an age of deforestation* (Vol. 53, p. 440). University of Chicago Press.

Chazdon, R. L., & Guariguata, M. R. (2016). Natural regeneration as a tool for large-scale forest restoration in the tropics: Prospects and challenges. *Biotropica*, *48*, 716–730. https://doi.org/10.1111/btp.12381

Chazdon, R. L., Lindenmayer, D., Guariguata, M. R., Crouzeilles, R., Benayas, J. M. R., & Chavero, E. L. (2020). Fostering natural forest regeneration on former agricultural land through economic and policy interventions. *Environmental Research Letters*, *15*. https://doi.org/10.1088/1748-9326/ab79e6

Costa, R. L., Prevedello, J. A., de Souza, B. G., & Cabral, D. C. (2017). Forest transitions in tropical landscapes: A test in the Atlantic Forest biodiversity hotspot. *Applied Geography*, *82*, 93–100. https://doi.org/10.1016/j.apgeog.2017.03.006

Crouzeilles, R. (2021). Potential for natural forest regrowth in the Atlantic Forest. *figshare*. Media. https://doi.org/10.6084/m9.figshare.16814863.v1

Crouzeilles, R., Beyer, H. L., Monteiro, L. M., Feltran-Barbieri, R., Pessôa, A. C. M., Barros, F. S. M., Lindenmayer, D. B., Lino, E. D. S. M., Grelle, C. E. V., Chazdon, R. L., Matsumoto, M., Rosa, M., Latawiec, A. E., & Strassburg, B. B. N. (2020). Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. *Conservation Letters*, *13*, e12709. https://doi.org/10.1111/conl.12709

Crouzeilles, R., Ferreira, M. S., Chazdon, R. L., Lindenmayer, D. B., Sansevero, J. B. B., Monteiro, L., Iribarrem, A., Latawiec, A. E., & Strassburg, B. B. N. (2017). Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science Advances*, *3*, e1701345. https://doi.org/10.1126/sciadv.1701345

de Almeida, C. A., Coutinho, A. C., Esquerdo, J. C. D. M., Adami, M., Venturieri, A., Diniz, C. G., Dessay, N., Durieux, L., & Gomes, A. R. (2016). High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data. *Acta Amazonica*, *46*, 291–302. https://doi.org/10.1590/1809-4392201505504

de Benini, R. D. M., & Adeodato, S. (2017). *Forest restoration economy*. The Nature Conservancy.

de Lima, R. A. F., Oliveira, A. A., Pitta, G. R., de Gasper, A. L., Vibrans, A. C., Chave, J., Ter Steege, H., & Prado, P. I. (2020). The erosion of biodiversity and biomass in the Atlantic Forest biodiversity hotspot. *Nature Communications*, *11*, 6347. https://doi.org/10.1038/s41467-020-20217-w

Fearnside, P. M. (2016). Brazilian politics threaten environmental policies. *Science*, *353*, 746–748. https://doi.org/10.1126/science.aag0254

Freitas, F. L. M., Englund, O., Sparovek, G., Berndes, G., Guidotti, V., Pinto, L. F. G., & Mörtberg, U. (2018). Who owns the Brazilian carbon? *Global Change Biology*, *24*, 2129–2142. https://doi.org/10.1111/gcb.14011

Freitas, F. L. M., Guidotti, V., Sparovek, G., & Hamamura, C. (2018). NOTA TÉCNICA: MALHA FUNDIÁRIA DO BRASIL. Retrieved from https://www.imaflora.org/public/media/biblioteca/1594237486-imaflora_atlasagropecuario_documentacao_malhafundiaria_v1812.pdf

Freitas, M. G., Rodrigues, S. B., Campos-Filho, E. M., do Carmo, G. H. P., da Veiga, J. M., Junqueira, R. G. P., & Vieira, D. L. M. (2019). Evaluating the success of direct seeding for tropical forest restoration over ten years. *Forest Ecology and Management*, *438*, 224–232. https://doi.org/10.1016/j.foreco.2019.02.024

Gastauer, M. (2021). Areas protected by law in the Brazilian Atlantic Forest. *figshare*. Media. https://doi.org/10.6084/m9.figshare.16546185.v1

Gastauer, M., Cavalcante, R. B. L., Caldeira, C. F., & Nunes, S. S. (2020). Structural hurdles to large-scale forest restoration in the Brazilian Amazon. *Frontiers in Ecology and Evolution*, *8*, 342. https://doi.org/10.3389/fevo.2020.593557

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, *342*, 850–853. https://doi.org/10.1126/science.1244693

Holl, K. D., Reid, J. L., Chaves-Fallas, J. M., Oviedo-Brenes, F., & Zahawi, R. A. (2017). Local tropical forest restoration strategies affect tree recruitment more strongly than does landscape forest cover. *The Journal of Applied Ecology*, *54*, 1091–1099. https://doi.org/10.1111/1365-2664.12814

Lima, M. M., & Mariano-Neto, E. (2014). Extinction thresholds for Sapotaceae due to forest cover in Atlantic Forest landscapes. *Forest Ecology and Management*, *312*, 260–270.

Lira, P. K., Tambosi, L. R., Ewers, R. M., & Metzger, J. P. (2012). Land-use and land-cover change in Atlantic Forest landscapes. *Forest Ecology and Management*, *278*, 80–89. https://doi.org/10.1016/j.foreco.2012.05.008

Meli, P., Holl, K. D., Rey Benayas, J. M., Jones, H. P., Jones, P. C., Montoya, D., & Moreno Mateos, D. (2017). A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. *PLoS ONE*, *12*, e0171368.

Mello, K., Fendrich, A. F., Sparovek, G., Simmonds, J. S., Maron, M., Tavares, P. A., Brites, A. D., Rodrigues, R. R., Joy, C. A., & Metzger, J. P. (2021). Achieving private conservation targets in Brazil through restoration and compensation schemes without impairing productive lands. *Environmental Science & Policy*, *120*, 1–10. https://doi.org/10.1016/j.envsci.2021.02.014

MMA. (2018). *Política Nacional de Recuperação da Vegetação Nativa*. Retrieved from http://www.mma.gov.br/florestas/política-nacional-de-recuperação-da-vegetação-nativa

Molin, P. G., Chazdon, R., de Barros, F., Ferraz, S., & Brancalion, P. H. S. (2018). A landscape approach for cost-effective large-scale forest restoration. *The Journal of Applied Ecology*, *55*, 2767–2778. https://doi.org/10.1111/1365-2664.13263

Neves, A. K., Körting, T. S., Fonseca, L. M. G., & Escada, M. I. S. (2020). Assessment of TerraClass and MapBiomas data on legend and map agreement for the Brazilian Amazon biome. *Acta Amazonica*, *50*, 170–182. https://doi.org/10.1590/1809-4392201900981

Nunes, F. S. M., Soares-Filho, B. S., Rajão, R., & Merry, F. (2017). Enabling large-scale forest restoration in Minas Gerais state, Brazil. *Environmental Research Letters*, *12*. https://doi.org/10.1088/1748-9326/aa6658

Nunes, S., Gastauer, M., Cavalcante, R. B. L., Ramos, S. J., Caldeira, C. F., Silva, D., Rodrigues, R. R., Salomão, R., Oliveira, M., Souza-Filho, P. W. M., & Siqueira, J. O. (2020). Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species. *Forest Ecology and Management*, *466*. https://doi.org/10.1016/j.foreco.2020.118120

Nunes, S., Oliveira, L., Siqueira, J., Morton, D. C., & Souza, C. M. (2020). Unmasking secondary vegetation dynamics in the Brazilian Amazon. *Environmental Research Letters*, *15*. https://doi.org/10.1088/1748-9326/ab76db

Oliveira, U., Soares-Filho, B. S., Paglia, A. P., Brescovit, A. D., de Carvalho, C. J. B., Silva, D. P., Rezende, D. T., Leite, F. S. F., Batista, J. A. N., Barbosa, J. P. P. P., Stehmann, J. R., Ascher, J. S., de Vasconcelos, M. F., De Marco, P., Löwenberg-Neto, P., Ferro, V. G., & Santos, A. J. (2017). Biodiversity conservation gaps in the Brazilian protected areas. *Scientific Reports*, *7*, 9141. https://doi.org/10.1038/s41598-017-08707-2

Ota, L., Herbohn, J., Gregorio, N., & Harrison, S. (2020). Reforestation and smallholder livelihoods in the humid tropics. *Land Use Policy*, *92*, 104455. https://doi.org/10.1016/j.landusepol.2019.104455

R Development Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Reid, J. L., Fagan, M. E., Lucas, J., Slaughter, J., & Zahawi, R. A. (2019). The ephemerality of secondary forests in southern Costa Rica. *Conservation Letters*, *12*, e12607. https://doi.org/10.1111/conl.12607

Rezende, C. L., Scarano, F. R., Assad, E. D., Joly, C. A., Metzger, J. P., Strassburg, B. B. N., Tabarelli, M., Fonseca, G. A., & Mittermeier, R. A. (2018). From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. *Perspectives in Ecology and Conservation*, *16*, 208–214. https://doi.org/10.1016/j.pecon.2018.10.002

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F. J., & Hirota, M. M. (2009). The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. *Biological Conservation*, *142*, 1141–1153. https://doi.org/10.1016/j.biocon.2009.02.021

Rosa, M. R., Brancalion, P. H. S., Crouzeilles, R., Tambosi, L. R., Piffer, P. R., Lenti, F. E. B., Hirota, M., Santiami, E., & Metzger, J. P. (2021). Hidden destruction of older forests threatens Brazil's Atlantic Forest and challenges restoration programs. *Science Advances*, *7*. https://doi.org/10.1126/sciadv.abc4547

Salvini, G., Dentoni, D., Ligtenberg, A., Herold, M., & Bregt, A. K. (2018). Roles and drivers of agribusiness shaping Climate-Smart Landscapes: A review. *Sustainable Development*, *26*, 533–543. https://doi.org/10.1002/sd.1897

Saraiva, M., Ferreira, M. D. P., da Cunha, D. A., Daniel, L. P., Homma, A. K. O., & Pires, G. F. (2020). Forest regeneration in the Brazilian Amazon: Public policies and economic conditions. *Journal of Cleaner Production*, *269*, 122424. https://doi.org/10.1016/j.jclepro.2020.122424

Soares-Filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., & Alencar, A. (2014). Land use. Cracking Brazil's forest code. *Science*, *344*, 363–364. https://doi.org/10.1126/science.1246663

Souza, C. M., Z. Shimbo, J., Rosa, M. R., Parente, L. L., A. Alencar, A., Rudorff, B. F. T., Hasenack, H., Matsumoto, M., G. Ferreira, L., Souza-Filho, P. W. M., de Oliveira, S. W., Rocha, W. F., Fonseca, A. V., Marques, C. B., Diniz, C. G., Costa, D., Monteiro, D., Rosa, E. R., Vélez-Martin, E., … Azevedo, T. (2020). Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat archive and earth engine. *Remote Sensing*, *12*, 2735. https://doi.org/10.3390/rs12172735

Sparovek, G., Reydon, B. P., Guedes Pinto, L. F., Faria, V., de Freitas, F. L. M., Azevedo-Ramos, C., Gardner, T., Hamamura, C., Rajão, R., Cerignoni, F., Siqueira, G. P., Carvalho, T., Alencar, A., & Ribeiro, V. (2019). Who owns Brazilian lands? *Land Use Policy*, *87*, 104062. https://doi.org/10.1016/j.landusepol.2019.104062

Stabile, M. C. C., Guimarães, A. L., Silva, D. S., Ribeiro, V., Macedo, M. N., Coe, M. T., Pinto, E., Moutinho, P., & Alencar, A. (2020). Solving Brazil's land use puzzle: Increasing production and slowing Amazon deforestation. *Land Use Policy*, *91*, 104362. https://doi.org/10.1016/j.landusepol.2019.104362

Stefanes, M., Roque, F. D. O., Lourival, R., Melo, I., Renaud, P. C., & Quintero, J. M. O. (2018). Property size drives differences in forest code compliance in the Brazilian Cerrado. *Land Use Policy*, *75*, 43–49. https://doi.org/10.1016/j.landusepol.2018.03.022

Strassburg, B. B. N., Beyer, H. L., Crouzeilles, R., Iribarrem, A., Barros, F., de Siqueira, M. F., Sánchez-Tapia, A., Balmford, A., Sansevero, J. B. B., Brancalion, P. H. S., Broadbent, E. N., Chazdon, R. L., Filho, A. O., Gardner, T. A., Gordon, A., Latawiec, A., Loyola, R., Metzger, J. P., Mills, M., … Uriarte, M. (2019). Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nature Ecology & Evolution*, *3*, 62–70. https://doi.org/10.1038/s41559-018-0743-8

WRI. (2019). *ONU declara a Década sobre Restauração de Ecossistemas*. Retrieved from https://wribrasil.org.br/pt/blog/2019/03/onu-declara-dacada-sobre-restauracao-de-ecossistemas

WRI. (2020). The new climate economy – The global commission on the economy and climate. *WRI*.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Gastauer, M., Miazaki, A. S., Crouzeilles, R., Tavares, P. A., Lino, E. D. S. M., & Rodrigues, R. R. (2021). Balancing natural forest regrowth and tree planting to ensure social fairness and compliance with environmental policies. *Journal of Applied Ecology*, 58, 2371–2383. https://doi.org/10.1111/1365-2664.14065