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Research Paper

Using land inequality to inform restoration strategies for the Brazilian dry forest

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HIGHLIGHTS

- Distribution of land and restoration opportunities is highly unequal.
- Large landowners retain nearly half of the vegetation deficit.
- Numerous smallholders lack restoration incentives.
- Restoration planning must account for land inequality.

ABSTRACT

Forest and landscape restoration aims not only to restore ecosystems but to improve people's livelihoods. However, mapping of restoration often neglects key socioeconomic aspects such as land-access inequalities. In this article, we quantify and describe the distribution of vegetation deficits (areas that demand mandatory restoration) across small and large rural properties across 1,204 municipalities of the Brazilian Caatinga biome. We mapped 313,537 ha of vegetation deficit, i.e. areas previously cleared that will need to be restored for legal compliance. This vegetation deficit is almost equally shared between 141,144 smallholders and only 2,986 in large properties. Around half of this vegetation deficit is spatially clumped mainly in the East and along the main river basin of the region dominated by rich large-holders. On the other hand, spatially scattered and poor small landowners hold around another half of the vegetation deficit across several municipalities. Because of such an unequal distribution of native vegetation deficit, we propose three different restoration strategies to account for land-access inequalities and socioeconomic differences at the municipality level. This is one of the first studies to clearly address land inequality and socioeconomic profile of landowners to inform adapted restoration strategies. Restoration planning that ignores land concentration and socioeconomic contexts may reproduce inequalities known to be one of the main causes of ecosystem degradation across Global South countries.

1. Introduction

Restoration of degraded landscapes is actually one of the main strategies to mitigate climate change and pursue the Sustainable Development Goals – SDGs (Zhang et al., 2021). Restoration, however, has to do with landscape planning and the synergies and tradeoffs affecting biological, economic and social dimensions of social-ecological landscapes must be addressed to make restoration a transformative movement (Chazdon and Brancalion, 2019; Chazdon, Gutierrez, et al., 2020). Because land concentration is a big problem for many Global South countries, this landscape feature cannot be neglected by restoration planning (Reydon et al., 2015). When a careful land distribution analysis is missing, opportunities and incentives for restoration might reproduce land inequality and its undesirable socio-environmental consequences (Lovelock and Brown, 2019). On the other hand, understanding land distribution among social actors can add both social and environmental accountability to decisions, better informing where and how to restore.

In Brazil, protection and restoration of native vegetation in rural private properties are regulated by the Protection of Native Vegetation Law – PNVL (Brasil, 2012), also known as Brazilian Forest Code. According to this legal framework, every rural private property must account for a minimum percentage of its area covered with native vegetation. This legal mandatory vegetation cover - that varies from 20

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to 80% depending on property size and biome where farms are located - has been, by far, the largest driving force of restoration initiatives in Brazil (Soares-Filho et al., 2014). Brazilian restoration movements rely on this legal enforcement to promote forest and landscape restoration (Melo et al., 2013; Pinto et al., 2014). Lack of environmental legal adequacy implies that landowners lose access to public funds and/or credits for production. However, restoration programs rarely make a clear distinction between large and small landowners when it comes to mapping and quantifying restoration opportunities at large scales. Ignoring land inequalities may lead to unequal/unfair spending of economic resources and political efforts, privileging few large rural properties and leaving millions of small farms behind restoration incentives (Andersson and Agrawal, 2011). For example, Strassburg et al (2022) proposed a comprehensive prioritization exercise for the restoration worldwide that, despite its high quality, was criticized because it ignored socioeconomic aspects of the landscapes. Such an unadvertised consequence has been intensively debated in the scientific literature with an increasing recognition of the need to include social accountability on restoration programs (Fleischman et al., 2022).

Although the majority of private rural properties (83.3%) in Brazil belong to small landowners they occupy only 11% of the registered farms, while 31% of the Brazilian private lands belong to only 12% of landowners (Sparovek et al., 2019). Yet, patterns and causes of land-use changes differ largely between large and smallholders mostly due to economic constraints (Rajão et al., 2020). Large landowners are able to clear proportionally more land which may be more intensively used (Rajão et al., 2020). On the other hand, small landowners have limited capacity for land clearing and intensification, relying on traditional methods of small-scale peasant agriculture (Peluso and Lund, 2011). Regardless of the category of landowner (large or small), land clearing can lead to vegetation deficits (i.e. beyond permitted by law) creating a compulsory obligation to restore vegetation. Also, actors as different as large and smallholders are likely to have different views on restoration barriers and opportunities (Crouzeilles et al., 2020). A successful restoration planning would therefore inform how restoration opportunities are distributed not only in space but principally within socioeconomic actors. Quantifying the amount and spatial distribution of the vegetation deficit as well as its share between categories of landowners is crucial to balance efforts and promote egalitarian access to resources, opportunities, and incentives for restoration (Eisinger, 2022).

Here we provide a novel analysis on how legal vegetation deficit is distributed in space and between large and smallholders in the Brazilian Caatinga. This is a densely populated (∼26 million inhabitants) seasonally dry tropical forest (Silva et al., 2017) that is among the poorest regions of Brazil and suffers from severe social and economic inequalities that must be also reflected in the access to land. This region does not count with large restoration initiatives such as other parts of Brazil [e.g. the Brazilian Atlantic Forest Restoration Pact that already produced in-depth analyses on many aspects of the restoration opportunities for this region; (Melo et al., 2013). The recent maps of restoration opportunities produced for the Caatinga are based mostly on biological and physical aspects of the landscapes and, though useful, lack crucial information on how restoration opportunities are distributed among socioeconomic actors (Antongiovanni et al., 2022).

We were guided by the following questions: 1) How is the legal vegetation deficit distributed across property sizes and municipalities of the Brazilian dry forest? and; 2) How can we use land concentration and socioeconomic indicators to subsidize the proposition of adapted restoration strategies? To answer these questions, we used a comprehensive assessment of the native vegetation cover and socioeconomic indicators for 1,204 municipalities in the Brazilian dry forest. We aimed to understand how restoration opportunities are spatially distributed according to the socioeconomic actors - i.e. private small and large holders. Such land inequality information could make restoration socially accountable for decision makers and restoration practitioners. Finally, in order to avoid the unintended reproduction of environmental and social inequalities, we discuss our results highlighting the importance of considering land-access when designing large-scale restoration prioritizations..

2. Methods

2.1. Study area and socioeconomic conditions

Our study area is the Caatinga biome that covers around 11% of Brazil, with an area of 912,529 km^2 (Silva et al., 2017). The Caatinga is a seasonally dry tropical forest with annual rainfall ranging from 240 to 1200 mm, where less than 100 mm of rain occurs during the dry season, causing a severe annual water deficit (Pennington et al., 2000). Historically, the Caatinga municipalities are among the poorest in Brazil and the ca. ∼ 26 million people living in this region are largely dependent on forest goods and services as well as on small-scale slash-and-burn agriculture and free-range livestock (Albuquerque and de Araújo, 2017). This is a historically neglected biological realm in Brazil that, despite its importance for biodiversity and human livelihoods, counts with only a small proportion of its area declared protected area (Silva et al., 2017). To date, 46% of the native vegetation was lost, mostly by pasturelands while irrigated agriculture is growing in recent years. Degraded landscapes are formed mostly by abandoned pastures and former small-scale agriculture sites. Chronic anthropogenic disturbance is also an issue for this region because small-scales subsistence extractivism and traditional pastoralism are among the most important livelihoods.

In order to characterize the municipalities of the Caatinga, we also compiled data from the last official Brazilian census grouped by municipalities (IBGE, 2011). We used data on the three subdimensions of the Human Development Index - HDI, HDI-Education, HDI-Longevity and HDI-Income. We were also interested in economic inequalities and also annotated values of the Gini index for each municipality and percentage of the population living in extreme poverty. All data are from 2010, the last census available for Brazil and may reflect socioeconomic reality with accuracy.

2.2. Land use in the Caatinga forest

We used the land cover map of 2019 with 30 m spatial resolution from Collection 5.0 of the Mapbiomas (MapBiomas., 2021); Fig. S1. At this resolution, very small changes in vegetation cover, may be either undetectable or overestimated and this may affect mostly smallholders. However, the Mapbiomas database has been extensively used for research and to inform public policy with no significant claims of inaccuracy on the outcomes derived from their estimations of land cover. We then assessed the Brazilian land tenure database from the Forest and Agricultural Management and Certification Institute – Imaflora (Imaflora., 2018). This is the best compilation of different official databases for Brazil with all available *shapefiles* of more than 4.5 million polygons of both public lands and private properties across Brazilian territory. For this study, we clipped the Caatinga biome limits as defined in the Brazilian Institute of Geography and Statistics (IBGE, 2019) and retained more than 1.6 million polygons. We assigned each private rural land into two mutually excluding categories of size: (a) small properties (those properties smaller than 4 *Fiscal Modules* – FM) and (b) large properties (greater than 4 FM). *Fiscal Module* is a weight factor that changes across Brazilian municipalities ranging from 5 to 110 ha that is used for many purposes such as differential taxation and application of the PNVL. This cutoff is officially used by public policies to separate large and small landowners. After excluding unregistered polygons, our final database of the Caatinga land tenure resulted in 996,182 properties summing up to 33.2 Mha of lands distributed across 1,204 municipalities, covering 40.6% of the Caatinga territory. This constitutes a rather representative sample of the land-tenure schemes of the region.

2.3. Native vegetation balance

Brazilian environmental legislation (PNVL) recognizes the value of natural vegetation for the society as a whole and all private properties must accomplish both social and environmental function (Soares-Filho et al., 2014). The legislation recognizes two categories of protected areas within private lands: 1) Legal Reserves (LR) and; 2) Areas of Permanent Protection (APP). The "legal reserves'' are intended to protect natural resources for future generations and are computed as a percentage of the areas of farms that must be covered with natural vegetation. This amount varies from 20 to 80% of the farms depending on the biome where it is located. For the Caatinga, legislation demands 20%, while in Amazonia this rises up to 80% of farm area. The second category that sums up to the LR is the APP and comprises ecologically important areas such as river margins, steep slopes and watersprings. These must also be covered with vegetation to protect both soil and water resources. The amount of vegetation on river margins also varies depending on width of the river and these amounts are established by the legislation (Table 1). Any deviation below these rules can be considered as vegetation deficit and must be calculated separately for LR and APP. For this category, we used the dataset of surface water bodies of 2016 from the National Water Agency (ANA, 2016) to create the vector files (polygons) of the APP buffer areas using the width according to their classes in the PNVL (Table 1). For the hilltop preservation areas we used the Digital Elevation Model from the Shuttle Radar Topography Mission (SRTM) dataset available at the National Institute for Spatial Research - INPE (https://www.dsr.inpe.br/topodata/). We used the software Quantum Gis v3.3 for the APP estimation.

For this study, every farm larger than 4 FM with less than 20% of vegetation cover or with less riverine forest than established by legislation was considered as having a vegetation deficit. The amount of the deficit is therefore the area needed to be restored to reach the 20% threshold of LR and/or the amount of vegetation required to compose the forest strips along rivers. This is always applied for large properties (i.e. greater than 4 fiscal modules), but in some cases, small landowners can legally keep less than 20% because the law established an amnesty for deforestation below the 20% threshold if it occurred before July 22nd of 2008 (Art. 67° of the PNVL). Therefore, for smallholders, any percentage of native vegetation below 20% would be considered as legal reserve as of July 22nd 2008. Any further deforestation that causes a reduction in vegetation cover below the value accounted for in 2008 is considered as a vegetation deficit for small properties. Therefore, for smallholders, any percentage of native vegetation below 20% would be considered as legal reserve as of July 22nd 2008. To estimate the native vegetation balance (*NVB*) in each property, we first estimated the area of remaining native vegetation in hectares inside each rural private property. This estimation was done using the land-use maps from 2019 and 2008.

The *NVB* for each large property (NVB_L) was calculated using the formula below:

$$NVB_L = V_{2019} - (0.2 \times A)$$

where A is the area of the property and V_{2019} is the area of native vegetation inside the property in the year 2019, both in hectares. For small landowners (NVB_S), we kept the formula of NVB_L only when the conversion to values below 20% of native vegetation occur after 2008, but when it occurred before 2008 ("consolidated areas"), we adjusted the NVB calculation using the value existing in 2008, as detailed in the following formula:

$$NVB_S = V_{2019} - V_{2008}$$

In all situations, negative values of *NVB* indicate a vegetation deficit and, in such cases, when the rural property had APP with natural vegetation cover, we applied a "discount" in the total deficit by summing the area of vegetation cover inside APP as a surplus (Art. 15th of the PNVL). All these adjustments for small-holders are in accordance with Brazilian legislation. According to this law, the vegetation deficit can be optionally "compensated" for example, in third party properties with a vegetation surplus in the same biome. This means that any large landowners with more than 20% of its areas still covered with native vegetation and any recovered area after 2008 for smallholders can lease their areas to compensate others'deficits in the same biome.

This scheme does not affect the deficit calculation but can affect the computation of the final restoration opportunities because not all degraded areas would forcefully undergo restoration. However, we reinforced that our computations of deficit did not considered compensation schemes as we aim to calculate legal opportunities for restoration in the biome.

Table 1
A summary of information on the factors influencing the calculation of minimum size of the Areas of Permanent Protection (APP), within types of landscape components and the categories derived from each situation according to the Protection of Native Vegetation Law – PNVL.

Landscape component that demands protection o thee vegetation	Categories depending on the context	Vegetation cover for legal compliance
Rivers and streams	<10 m width	30 m
	10–50 m width	50 m
	50–200 m width	100 m
	200–600 m width	200 m
	> 600 m width	500 m
Natural lakes and lagoons	> 20 ha (rural area)	100 m
	> 20 ha (urban area)	30 m
	< 20 ha	50 m
Artificial reservoirs	rural area	> 30 m
	urban area	> 15 m
Hills	> 45° of slope	total area
	> 1,800 m of altitude	total area

2.4. Statistical analyses

We first used descriptive statistics to answer the following questions: (1) How much native vegetation remains in private properties in the Caatinga? (2) How is it distributed among classes of rural properties size (small vs. large)? (3) What is the total deficit of native vegetation according to the PNVL? and (4) How is this deficit distributed across rural properties of different sizes and municipalities? To test whether the amount of vegetation deficit in LR and APP increases proportionally with the area of private properties and whether this relationship is mediated by category of property size (small or large) we used an analysis of covariance (Ancova) with the category of property size as a co-variable. We tested whether total vegetation deficit per municipality is correlated with proportional deficit in large properties through Spearman's correlation test. Our restoration prioritization approach was based on the amount of deficit shared between large and small properties per municipality unit. We divided municipalities in terciles based on the proportion of vegetation deficit shared between large and small landowners. Municipalities with more than 66% of the deficit concentrated in large properties were assigned to a category of restoration focused on large landowners. On the other side, those municipalities with less than 33% of the deficit in large properties were assigned to a category of restoration focused on small landowners. In between these categories, we created an intermediate class called hybrid, a strategy designed to mix strategies for both large and smallholders that comprised all municipalities whose vegetation deficits were shared among small and large landowners in proportions not smaller than one third (33%) for each category, thus less biased towards either small or large landowners. between large and small landowners. To understand how the socioeconomic features and the native vegetation cover are related to each strategy of restoration we did an ANOVA followed by a post-hoc Tukey test aiming to capture differences that may be of interest for the design of restoration strategies. All analyses, both descriptive and spatial were made using R language (R Development Core Team, 2016).

3. Results

3.1. Distribution of native vegetation

Officially established private properties hold nearly 20 million hectares of native vegetation of Caatinga forest. Most of these rural private properties – 975,078 (97.8%) – belongs to small landowners and cover 17.9 Mha (millions of hectares) of lands whereas only 21,104 large properties (2.2% of the total) occupy an area of 15.2 Mha, thus evidencing the strong inequality of land distribution in the region. The remaining native vegetation within properties obeys the same pattern and nearly half of the natural vegetation (ca. ~ 10.5 Mha) belongs to large landowners while the other half (~9.2 Mha) is shared by nearly a million small farms (Table 1). In total, 69% of the area belonging to large properties is covered by natural vegetation while in small properties this proportion drops to 51%.

3.2. Distribution of vegetation deficit

Regarding the native vegetation deficit, 21% of the large landowners (N = 4,631) and 15% of the small ones (N = 150,144) have some vegetation deficit (APP and/or LR) in their properties, all distributed in 1,133 municipalities. The native vegetation deficit reproduces land concentration and only 2,986 large landowners retain nearly half (139,644 ha) of the native vegetation deficit whereas 141,144 small landowners share the other half of the deficit (143,501 ha) (Table 1). Areas of permanent protection (APP) accounted for a smaller amount of the vegetation deficit, summing a little more than thirty thousand hectares distributed over 12.5 thousand small-sized properties that accumulate 60% of the deficit in APPs – i.e. non-vegetated around water bodies (Table 2). The remaining deficit for APPs is distributed among ca ~ 1.8 thousand large-sized properties where the average deficit per property is 4.3 times higher than that of small ones (Table 2). Altogether, these results suggest that the distribution of native vegetation deficit is as concentrated as land tenure for the Caatinga region.

The amount of vegetation deficit per municipality is predicted by how much land belongs to private owners (Fig. 1). However, there are nuances when this relationship is split between large and smallholders and between types of protection (LR or APP). For LR (the minimum percentage of farms that needs to be covered by natural vegetation), there is a weaker relationship for smallholders as compared to large ones (less steeper regression line), suggesting constraints for deforestation within smallholders (Fig. 1(a)). Conversely, the relationship is inverted for APPs (e.g. sensitive areas near rivers and steep slopes), being stronger for smallholders than for large ones, suggesting that these areas have greater importance for small-scale agriculture than for large landowners (Fig. 1(b)).

Municipalities with larger amounts of vegetation deficits are located in the East of the Caatinga, closer to the shoreline (Fig. 2a) but also along with the main permanent river in the region. Likewise, large landowners respond for the majority of the deficit in Eastern municipalities while smallholders are responsible for a greater proportion of the legal vegetation deficit over the Central-North and Central-South regions (Fig. 2b). Altogether, these maps evidence a moderate but significant correlation between the amount of deficit per municipality and the share of vegetation deficit within large properties (Spearman's rho = 0.47; p less than 0.0001). This suggests that at the regional scale, municipalities with a greater proportion of deficit in large properties also tend to concentrate larger absolute amounts of vegetation deficit.

3.3. Accounting to land access to plan restoration

Finally, we draw three main strategies of restoration based on the results presented above. The first strategy focuses on small landowners and must be located in municipalities where more than 66% of the vegetation deficit belongs to small properties. In this case, the average deficit is around 1,0 ha spread across many thousands of farms mostly in vegetated areas of the midwest Caatinga (Fig. 3). On the opposite side, the second strategy is focused on large landowners and might be preferred for municipalities with larger percentages (>66%) of vegetation deficit within large properties, mostly in the Northeast and in the South of the Caatinga (Fig. 3(a)). A third, hybrid strategy, must be designed to attend those municipalities where the share of vegetation deficit is not too biased towards small or large properties.

The opportunities for restoration based on legal requirements are so spread across the Caatinga that 64% (N = 735) of the 1,149 municipalities with legal vegetation deficit fell within the category of "restoration for small landowners". These municipalities have an average vegetation deficit of 146 ± 258 ha (mean ± standard deviation) and sum up a little more than one-third of the total deficit computed for the Caatinga (107,544 ha; Fig. 3(b)). In the hybrid strategy, there are 227 municipalities where vegetation deficit is more or less equally shared among large and small landowners, holding 95,917 ha of the deficit with an average of 423 ± 556 ha per municipality. Finally, 110,066 ha of deficit (roughly another third) belongs to only 187 municipalities with an average area of 589 ± 877 ha per municipality (Fig. 3(b)). In all categories, restoration efforts varied strongly, from less than 1,0 ha to more than 5,000 ha of vegetation deficit but the mean deficit per municipality tends to be larger as long as large properties respond to a greater proportion of total deficit.

The restoration strategies for each of the three scenarios differ in both scale and type of action (Table 3). Smallholder-focused restoration programs will have to deal with many thousands of landowners with small amounts of legal vegetation deficit that can be recovered with forest-friendly agricultural practices. This strategy is based on stimulating nature-based methods of restoration and promoting local farmer's organization that is likely to improve resilience of social-ecological productive landscapes dominated by smallholders. On the other hand, large holder-focused restoration demands the use of more active methods that stimulate the development and/or strengthening of the restoration supply chain and may help farmers to access markets with strong environmental compliance. In between these poles, there are

Table 2
Summary of the natural vegetation cover across 996,182 private properties within the Caatinga domains in Brazil.

Type of legally protected vegetation	Category of rural property	Area occupied (ha)	Area of native vegetation (ha)	Number of landowners with deficit	Vegetation deficit (ha)*
Legal reserves - LR	Large	15,242,439	10,573,307	2,986	**139,644**
	Small	17,964,103	9,250,151	141,144	**143,501**
	Total	33,206,542	19,823,458	144,130	**283,145**
Areas of permanent protection - APP	Large	28,050	16,091	1,872	**11,959**
	Small	30,004	11,571	12,529	**18,433**
	Total	58,055	27,662	14,401	**30,392**

* These values refer to the sum of deficits of all properties with less than 20% of vegetation cover for LR and/or any amount of vegetation cover below 100% for the APP.

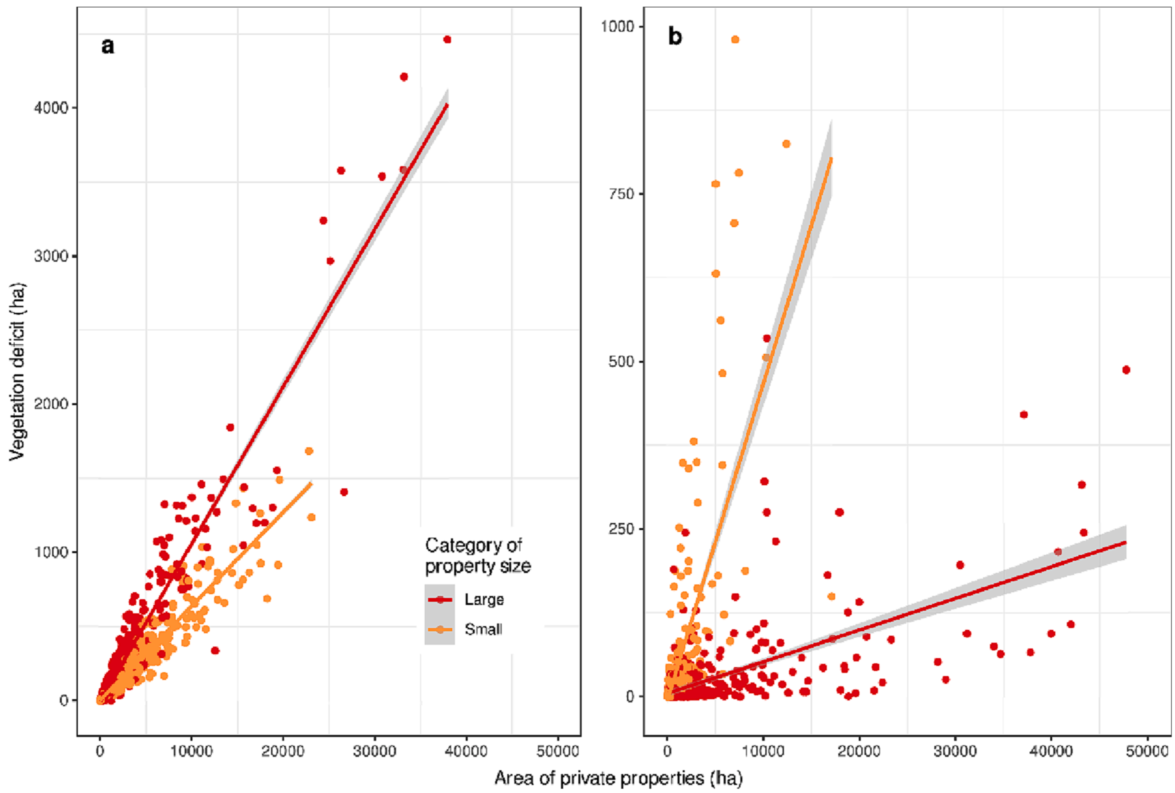

Fig. 1. Relationship between the area of private properties and the amount of vegetation deficit per municipality separated by category of property size (small and large) for areas of legal reserves – LR (a) and areas of permanent protection – APP (b).

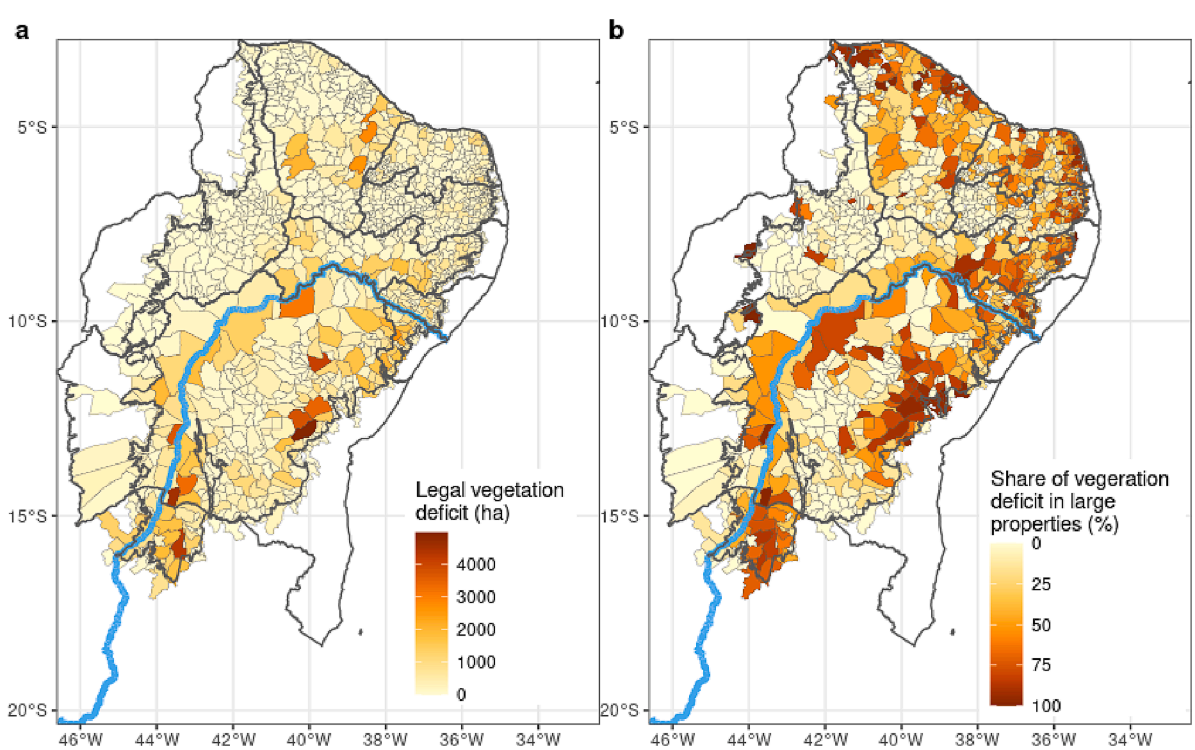

Fig. 2. Maps of the Caatinga domains with political frontiers of states (dark lines) and 1,204 municipalities (softer lines) showing: (a) the amount of vegetation deficit per municipality in hectares, and (b) the share of deficit between large and small properties for each municipality. Darker colors denote larger vegetation deficits (a) or higher percentage of vegetation deficit in large properties. The blue line represents the São Francisco river, the main watershed of the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

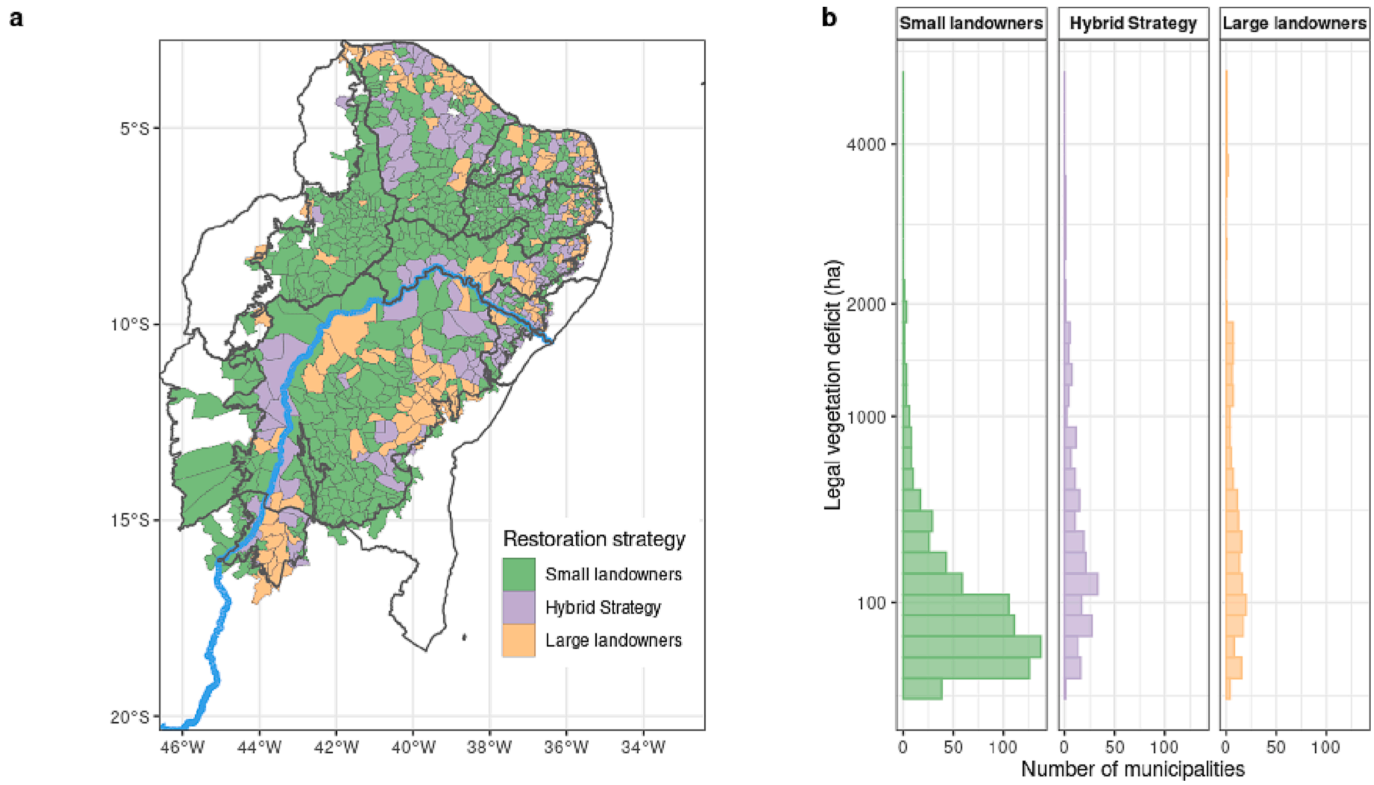

Fig. 3. The map of the Caatinga boundaries (a) showing the 1,149 municipalities with any native vegetation deficits colored according to three restoration strategies: 'Small landowners '(green) is planned for municipalities where more than 66% of the vegetation deficit belongs to smallholders. 'Large landowners' (yellow) must be preferred when 66% of the vegetation deficit is within large properties. The 'hybrid strategy' (purple) refers to municipalities with less biased vegetation deficits between categories of property. The horizontal bar-plot (b) shows the distribution of the amount of legal vegetation deficit per municipalities grouped by the main restoration strategy (color palette follows the same of the panel 'a'). The blue line represents the São Francisco river, the main watershed of the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
List of potential restoration methods and schemes of social organization needed to stimulate and attend to challenges and demands of small and large landowners restoration strategies, the expected outputs and illustrative references in line with the recommendations. This is not intended to be a comprehensive description of methods and outputs but represents the main concepts and actions behind each strategy. The list of references is not exhaustive but brings important support for the strategies.

Focus of restoration strategy	Specific restoration methods	Social engagement	Expected outputs	References for further details on strategies
Small landowners	Natural regeneration; Agroforestry; Favoring useful species for daily needs such as fuelwood, medicinal and forage for livestock	Capacity building; Cooperativism; Payment for ecosystem services; Biocultural restoration	Improved resilience of social-ecological systems; Enhanced household monetary and non-monetary income; increase synergies among water, energy and food securities	(Abbas et al., 2017; Fleischman et al., 2022; Hanspach et al., 2020; Rolo et al., 2021; van Noordwijk et al., 2018)
Large landowners	Planting; Direct seed sowing; Natural regeneration; Energetic forests	Product certification; Special taxing schemes; Access to credit specific lines	Legal compliance; Access to certified markets; Strengthening of restoration supply chain	(Melo et al., 2021; Pavel and Leaman, 2016; Soares-Filho et al., 2014)
Hybrid strategy	A balanced combination of strategies that maximize benefits for both sectors	Sharing of technologies among landowners; Social entrepreneurs for restoration	Increased dialogue among landowner's categories; collective decisions on priorities of restoration efforts	(Brancalion et al., 2018; Chazdon, Herbohn, et al., 2020; Meli, Herrera, et al., 2017; (Strassburg et al., 2020)

municipalities with a more equalized share of vegetation deficits between categories of property size that must adopt a hybrid approach to meet both the legal compliance of large landowners and the forest-friendly agricultural production of small-holders.

When we analyze the socioeconomic conditions of the municipalities grouped by restoration strategies, they present both similarities and discrepancies (Fig. 4). They are undistinguishable in terms of human development indexes (HDI for: education, longevity and income) and economic inequality (Gini Index). However, there is a slight but significant difference regarding the percentage of population living in extreme poverty. Municipalities categorized for restoration focused on smallholders have more people living in extreme poverty than other categories (Fig. 4). Finally, the restoration strategy focused on smallholders will attend municipalities with much more remaining forest than the other categories.

4. Discussion

Our work suggests that due to land inequality, large-scale restoration of the Caatinga must ideally consider different strategies for small and large landowners. Restoration based on legal vegetation deficit represents a limited (~313 thousand hectares of vegetation deficit) but an

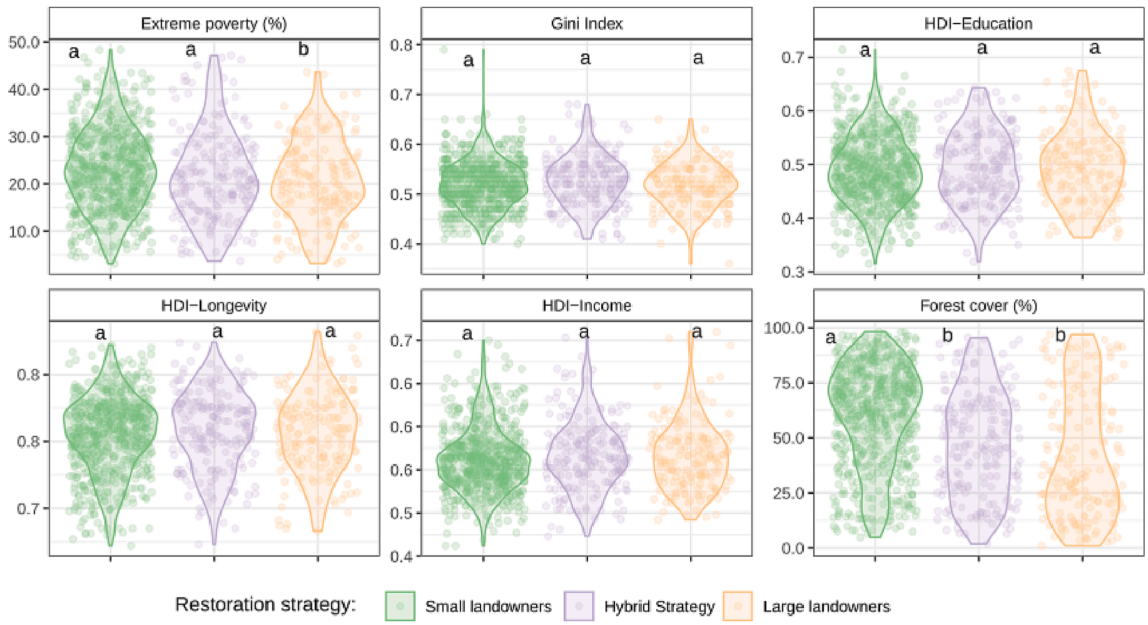

Fig. 4. Differences in terms of socioeconomic indicators (Human Development Indexes - HDI) and percentage forest cover of among municipalities of the Brazilian Caatinga assigned to each of the three restoration strategies. Different letters above violin-jitters indicate significant differences on pairwise comparison using Tukey's test.

important restoration window at the scale of municipalities. However, these opportunities for restoration are both socio-economically and spatially biased, thus requiring the understanding of barriers faced by different social actors such as large and small landowners. On one side - restoration for small landowners - there are poor people living in mostly forested municipalities with very small average vegetation deficits. On the other side - restoration for large landowners - municipalities with a smaller proportion of the population under extreme poverty conditions but with less forest cover and larger average vegetation deficits concentrated within large landowners. In some municipalities, both strategies must take place to attend to a more diverse scenario.

Our analyses showed that small and large landowners seem to experience different kinds of constraints to convert forest into agricultural fields, depending on the type of land to be protected, whether APP or LR (Rasmussen et al., 2016). First, the proportion of vegetation deficit in legal reserves (LR) tends to increase at a slower pace with the size of property of smallholders when compared to large landowners. Deforestation demands economic resources such as machinery or massive manpower labor contracts that might not be affordable for the majority of smallholders (Carrero and Fearnside, 2020). Such a constraint is not experienced by large landowners who tend to deforest relatively greater amounts of their farms if compared with smallholders (Rajão et al., 2020; Wren-Lewis et al., 2020). Smallholders were benefited by the amnesty given to deforestation beyond the 20% threshold before 22nd July 2008, so this reduces the calculation of the deficit thus making the relationship weaker. Such amnesty caused a reduction of around 58% in Brazil's "environmental debt" when compared to the former environmental law (Soares-Filho et al., 2014). However, the scenario is different when accounting only for APPs (e.g. riverine areas) that are proportionately more used by small landowners than by large ones. Lands nearby water sources are the most important for small-scale agriculture (Probst et al., 2020)and this may explain why vegetation deficits of small-holders for this type of area presents a stronger relationship with property area when compared to large-holders. However, average deficits of around one hectare at the property level for smallholders are more likely to recover spontaneously through natural regeneration while deficits of dozens to hundreds of hectares in large properties must demand more intensive and expensive restoration methods (Brancalion et al., 2019; Miccolis et al., 2019).

This can bebeattributed to the fact that beyond but refers to deforested areas after the amnesty period and below the minimum percentage required by lawrelatively Accounting for such discrepancies in the legal vegetation deficits between categories of landowners require adaptations in the restoration approaches (Meli, Holl, et al., 2017; Pinto et al., 2014). Our results show that these strategies fit municipalities with important differences in terms of vegetation cover and poverty levels. This is one of the first exercises of restoration prioritization that propose restoration strategies based on socioeconomic indicators and land inequality. Such information is likely to help design adapted strategies for restoration of very contrasting scenarios in terms of economic and social development (van Noordwijk, 2019). There is an ongoing debate on whether normative values related to restoration such as carbon, biodiversity and cost effectiveness can account for environmental justice in restoration initiatives (Strassburg et al., 2020). These top-down approaches contrast with the need for restoration planning to be otherwise informed by local marginalized people (Fleischman et al., 2022). Our work adds to this important debate by accounting for land inequality and therefore, overcoming the "one size fits all" approaches to restoration that fail to provide guidelines adapted to different social groups. We quantified and mapped the amount of restoration opportunities distributed across both socially vulnerable groups of small farmers and large landowners. Then, we highlight some of thesome most up to date restoration methods, aims and goals that might compose broad adaptive restoration strategies for diverse social groups. For example, stimulating forest-friendly agricultural practices for smallholders such as agroforestry and/or agrosilvopastoral systems can attend to legal requirements, restoration goals and rural livelihood goals ((Chazdon and Brancalion, 2019; Galabuzi et al., 2014). Though simple and seen as a cost-effective alternative to intensive restoration, agroforestry demands training of people and the creation of markets to improve the competitiveness of biodiversity-friendly products (Abbas et al., 2017; Rolo et al., 2021). Dealing with such a huge amount of smallholders is challenging and restoration programs that aim to attend to diverse actors must implement effective governance schemes with strong capillarity and must count with help of local organizations and cooperatives of rural workers (Meli, Herrera, et al., 2017; Melo et al., 2013, Melo et al., 2021). But mostly, restoration should be coupled with education for more sustainable practices and capacity building to at least, detain further ecosystem degradation and deforestation. A source of confusion is the definition of small and large holders according to fiscal modules that varied from 5 to 110 ha in the Caatinga, grouping together landowners with farms from 20 to 440 ha as smallholders. This tends to create a discrepancy within landowner's categories that may demand further compensatory mechanisms for resource distribution.

On the other hand, the restoration of large properties should be more focused on the urgency of compliance with environmental laws (Mello et al., 2021). Municipalities with legal vegetation deficits concentrated within large properties have to deal with a few but usually wealthier and politically powerful actors (Sparovek et al., 2019). This creates different challenges for restoration programs. For example, in the Brazilian Atlantic Forest, the strategy adopted for most restoration programs is to target the benefits of legal compliance for large landowners such as access credits and certified markets (Gastauer et al., 2020; Soares-Filho et al., 2014). Large restoration efforts must also demand more intensive interventions such as nurseries and capacity-building programs for rural workers across different stages of the restoration supply-chain (Brancalion et al., 2012). Restoration of large properties have the potential to trigger the creation of jobs as they are expected to afford hiring more manpower per farm (Strassburg et al., 2019). Finally, a sort of hybrid strategy that combines the main guidelines described above would demand a balanced dual approach for diverse actors and co-production of broad consensus must be pursued in order to make restoration strategies effective (Chambers et al., 2022).

5. Conclusions

We demonstrate that it is possible to design socially accountable restoration strategies based on land inequality and promote justice in resource allocation for restoration. This can improve the social impact of restoration and prevent prioritization exercises from neglecting social vulnerable groups (van Noordwijk et al., 2018). Unfortunately, land inequality is a widespread problem of Global South countries that leads to both poverty and environmental degradation (Peluso and Vandergeest, 2011). Restoration programs cannot reproduce social and economic inequalities if they aim to serve as a transformative tool for fighting climate change and promoting environmental justice (van Noordwijk, 2019). The native vegetation in the Caatinga is the most important factor to maintain the ecosystem multifunctionality, or multiple ecosystem functions (Manhães et al., 2022). The restoration programs must be aware that when recovering vegetation in this fragile ecosystem they are contributing to local sustainable development and human well-being for the most poorest Brazilian region (Costa et al., 2021).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104844.

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