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Balancing active and passive restoration

Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: the case of Brazil

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Abstract: Forest restoration requires strategies such as passive restoration to balance financial investments and ecological outcomes. However, its ecological outcomes are traditionally regarded as uncertain. We evaluated technical and legal strategies for balancing economic costs and ecological outcomes of passive versus active restoration in agricultural landscapes. We focused in the case of Brazil, where we assessed the factors driving the proportion of land allocated to passive and active restoration in 42 programs covering 698,398 hectares of farms in the Atlantic Forest, Atlantic Forest/Cerrado ecotone and Amazon; the ecological outcomes of passive and active restoration in 2,955 monitoring plots placed in three restoration programs; and the legal framework developed by some Brazilian states to balance the different restoration approaches and comply with legal commitments. Active restoration had the highest proportion of land allocated to it (78.4%), followed by passive (14.2%) and mixed restoration (7.4%). Passive restoration was higher in the Amazon, in silviculture, and when remaining forest cover was over 50%. Overall, both restoration approaches showed high levels of variation in the ecological outcomes; nevertheless, passively restored areas had a smaller percentage canopy cover, lower species density and less shrubs and trees (dbh > 5 cm). The studied legal frameworks considered land abandonment for up to four years before deciding on a restoration approach, in order to favor the use of passive restoration. A better understanding about the biophysical and socioeconomic features of areas targeted for restoration is needed in order to take a better advantage of their natural regeneration potential.

Key words: Amazon; Atlantic Forest; Forest Code; large-scale restoration; natural regeneration; restoration methods; restoration monitoring

Abstract in Portuguese:

A restauração florestal reque estratégias como a restauração passiva para balancear investimentos financeiros e retorno ecológico. Entretanto, o retorno ecológico da restauração passiva é tradicionalmente tido como incerto. Assim, nós avaliamos as estratégias técnicas e legais para balancear os custos econômicos e retorno ecológico da restauração passiva e ativa em paisagens agrícolas. Focamos nosso estudo no Brasil, onde avaliamos os fatores influentes na proporção de terras para a restauração ativa e passiva em 42 programas abrangendo 698,398 hectares de propriedades rurais na Mata Atlântica, ecótono Mata Atlântica/Cerrado e Amazônia; as respostas ecológicas do uso da restauração ativa e passiva em 2955 parcelas de monitoramento estabelecidas em três programas; e o esquema legal desenvolvido por alguns estados brasileiros para balancear o uso de diferentes estratégias de restauração para cumprir compromissos obrigatórios. A restauração ativa teve a mais alta proporção de indicação (78,4%), seguida da restauração passiva (14,2%) e mista (7,4%). A prescrição da restauração passiva foi maior na Amazônia, em usos do solo de silvicultura e quando a cobertura florestal foi superior a 50%. No geral, ambas estratégias mostraram altos níveis de variação de resultados ecológicos; entretanto, áreas em restauração passiva apresentaram menor porcentagem de cobertura de dossel, densidade de espécies e de indivíduos de arbustos e árvores (dbh > 5 cm). Os esquemas legais estudados consideraram o abandono da área por até quarto anos antes de decidir sobre uma abordagem de restauração, de forma a favorecer o uso da restauração passiva. Um melhor entendimento dos fatores biofísicos e socioeconômicos de áreas alocadas para a restauração é necessário para melhor aproveitar o potencial de regeneração natural.

RECENT INTERNATIONAL COMMITMENTS have paved the way for an unparalleled engagement of countries in forest and landscape restoration (hereafter FLR), including reforestation at the center of human strategies to face many facets of the global environmental crisis (Aronson & Alexander 2013, Suding *et al*. 2015, Chazdon *et al.* 2016). Such a wide scale functional improvement of degraded landscapes requires the adoption of cost-effective restoration approaches, which have been increasingly necessary to meet ambitious restoration targets while achieving desired ecological outcomes. Global financial investments in restoration programs are expected to reach U.S. $18 billion per year (Menz *et al*. 2013); however, many factors still limit the technical effectiveness of ecological restoration for conserving biodiversity and the supply of ecosystem services (Birch *et al.* 2010, Maron *et al.* 2012, Shoo *et al*. in press). One of the key strategies to balance financial investments and ecological outcomes in tropical forest restoration is to take advantage of natural regeneration processes when it is feasible, minimizing human inputs and making a better use of ecosystem resilience (Chazdon 2014).

There is already a robust set of evidence that second-growth tropical forests are capable of reaching remarkable levels of forest cover increase within a few decades in human-modified tropical landscapes (Aide *et al*. 2013, Ferraz *et al.* 2014, Sloan *et al.* 2015, Poorter *et al.* 2016). According to the forest transition theory, historical conversion of agricultural lands to forests has occurred as an indirect effect of socio-economic shifts, rather than human-intended interventions to support forest gain (Aide & Grau 2004). While it is clear that land abandonment may result in high-levels of forest regeneration at the landscape level, scientific evidence is yet limited to predict which specific portions of landscapes will regenerate (Holl & Aide 2011). Tropical forest regeneration is a complex process regulated by many biophysical and human factors that are, in many cases, stochastic and difficult to predict or manipulate (Norden *et al.* 2015). Factors like land use history, isolation from seed sources, and human-mediated disturbances are sometimes difficult to measure or estimate, and may determine if a native forest will regenerate in a given site, how long it may take, and how the forest will develop overtime (Norden *et al*. 2009, Arroyo-Rodriguez *et al.* In press, Jakovac *et al.* 2015). Thus, determining where, when, and how humans have to intervene to support tropical forest recovery is a major challenge for restoration practitioners (Holl & Aide 2011, Shoo *et al.* In press).

The high level of uncertainty for adopting passive or active restoration approaches is particularly challenging in mandatory restoration programs, such as those related to biodiversity off-setting policies (Maron *et al.* 2012), and specific national legislations (Soares-Filho *et al.* 2014, Palmer & Ruhl 2015). Although cheaper restoration approaches will also be preferred, failures in mandatory restoration can compromise certification, suspend licenses and payments for ecosystem services, and result in the application of fines and other judicial impediments. All these aspects may result in higher economic setbacks than spending more money planting trees (Aronson *et al.* 2011). Since planting seedlings or sowing seeds is expected to accelerate and increase the predictability of establishing an initial forest physiognomy of native trees in degraded sites – the end point of most mandatory restoration projects (Chaves *et al.* 2015) –, active restoration has been preferred in many restoration programs constrained by legal commitments. With the growing interface between legislation and restoration (Palmer & Ruhl 2015), deciding whether passive or active restoration approaches shall be adopted in each land portion, understanding the ecological trajectories established by these approaches, and supporting the development of more flexible and adaptive legal instruments to support the use of passive restoration, remain crucial.

Balancing passive and active restoration is also essential when the scale of restoration programs is limited by funding constrains, and not land availability. Depending on the resilience of lands targeted for restoration, a given amount of financial resources can be invested to establish restoration plantations in a smaller area or passive restoration in a larger area. Although larger scale would be preferable whenever possible, poor ecological outcomes resulting from insufficient spontaneous regeneration can be a serious limitation.

The goal of this work was to evaluate the technical and legal frameworks implemented to balance the economic costs and ecological outcomes of passive and active restoration in agricultural landscapes. More specifically, we aimed to investigate the following overreaching questions: (1) What are the social and biophysical factors driving the land allocated to passive and active restoration?; (2) what are the ecological outcomes of the use of passive and active restoration?; and (3) what legal framework may promote a balance in the use of passive and active restoration? Based in the case of Brazil, we assessed the factors driving the proportion of passive and active restoration in 42 programs covering 698,398 hectares of farms in the Atlantic Forest, Atlantic Forest/Cerrado ecotone, and Amazon; the ecological outcomes of the use of passive and active restoration evaluated in 2,955 monitoring plots distributed in three restoration programs; and the regulatory decisions associated with the selection of restoration approaches in the context of a legal framework developed by the states of Acre, Bahia, Pará, and Rondônia to balance the use of restoration approaches to comply with legal commitments

METHODS

PROPORTION OF PASSIVE AND ACTIVE RESTORATION EMPLOYED IN RESTORATION PROGRAMS – To assess the factors affecting the allocation of land to passive and active restoration, we evaluated 42 restoration programs in Brazil, including a total of 2021 landholdings and 698,398 hectares of farms, distributed among the tropical forest biomes of the Amazon, the Atlantic Forest and the ecotone between the Atlantic Forest and the Cerrado (savanna - Figure 1). Details on the restoration programs and reasons for their inclusion in this study were presented in Supplementary Material 1.

Most of the programs (87.8% of the restoration area) were planned to exclusively restore riparian forests along water springs and riparian buffers, following the requirements of the previous version of the Forest Code, modified in 2012 (*e.g.* a circular radius of 50 m around water springs and dual riparian corridors of 30 m each along streams; see details in Garcia *et al.* 2013). Based on these requirements and on aerial photographs (1:25,000–1:30,000) or high resolution satellite images, the boundaries and land use of Areas of Permanent Protection (APPs) – where restoration was mandatory – were determined using GIS imagery techniques. All land portions within APPs not covered by native vegetation were targeted for restoration, resulting in a restoration commitment of 36,154 hectares for the 42 programs assessed. In a few projects (*e.g.* NGOs' experimental restoration centers, "green" condominiums, farms investing in the sustainable production of native timber species), the whole farm area was targeted for restoration. Overall, the restoration commitment of these programs consisted of establishing an initial forest physiognomy of several native trees, which should be achieved within less than five yr.

The proportion of land allocated to each restoration approach was determined based on a diagnosis. The first step of this diagnosis consisted of determining where to restore. Once a land portion was targeted for restoration according to legislation or specific requirements of a restoration program, its actual land use (e.g. pasturelands, croplands, orchards, commercial tree plantations) was pre-determined through a site-by-site evaluation using photointerpretation of aerial photographs/satellite images. All of these sites were visited for field checking, in which they were classified according to three main diagnosis categories for further indication of a specific restoration approach: passive, active and mixed restoration (Table 1). More details about this restoration diagnosis framework are available in Rodrigues *et al.* (2011). The selection of restoration approaches were mostly based on field observations of the presence of spontaneously regenerating individuals of woody species in the sites targeted for restoration, without considering the regeneration capacity of these sites in the mid-run. Based on the application of this framework, we obtained the proportion of the total area to be restored allocated to each restoration approach within a specific program.

The explored factors were: biome type, agricultural land use, and native forest cover. Biome type was explored to contrast the influence of a more intense, historical landscape modification (Atlantic Forest and Cerrado) with a less intensive, recently modified biome (Amazon); agricultural land use because the level of intensification may influence ecosystem resilience and its potential of natural regeneration and seedling performance; and native forest cover because of the influence on seed dispersal and consequent potential of spontaneous woody species regeneration in agricultural lands. Restoration programs were then classified according to (1) biome were they were located – Amazon, Atlantic Forest, Atlantic – Cerrado ecotone, (2) main land uses – cattle ranching, agriculture (sugarcane, maize and soybean), silviculture (commercial Eucalyptus and pine tree plantations), and mixed (a mosaic of the previous land uses and commercial orchards), which represent the main land uses of the farms included in the program, and not necessarily the land cover at the sites targeted for restoration; (3)

percentage of native forest cover remaining in the landscape, according to the forest cover of each program obtained by photointerpretation of recent aerial photographs/high resolution satellite images or, when this information was not available, to official data of native forest cover of the municipality where the restoration program was located; and (4) proportion of land allocated to each restoration method (passive, active, or mixed, i.e., the combination of both in the same area) indicated.

We then tested, using chi-square tests, the influence of vegetation type (Amazon, Atlantic Forest, and Atlantic Forest/Cerrado ecotone), land use (agriculture, cattle ranching, silviculture or mixed), and remaining forest cover (less than 10%, 10-50%, 51-75%) on the percentage of land allocated to each restoration approach within each program. The null (random) hypothesis was that the proportion of land allocated to each restoration approach was independent of the proportion of farms in different biomes, in different land use types and with different percentages of remaining forest cover. Tests were performed in R (v. 3.1.1).

ECOLOGICAL OUTCOMES OF THE USE OF PASSIVE AND ACTIVE RESTORATION IN DIFFERENT FOREST TYPES – To assess the ecological outcomes of the use of passive and active restoration, a group of restoration programs, including five already included in the previous item and one new program, was monitored in the first five yr following implementation. We expected to determine if the adoption of each of the three restoration approaches previously described produces different, distinguishable patterns of ecological outcomes, and, if such distinction is confirmed, which approach has better results for the limited timeframe of five years. Details about implementation and maintenance protocols traditionally applied in restoration projects in these regions can be accessed in Rodrigues *et al.* (2009, 2011). We evaluated extensive restoration monitoring programs in the Atlantic Forest/Cerrado Ecotone – Seasonal Semideciduous Forest of São Paulo state, southeastern Brazil (three programs: active, passive and mixed restoration) –, and in the Atlantic Forest, at the Dense Ombrophilous Forest of Bahia, northeastern Brazil (two programs: active, passive and mixed restoration) and in the Mixed Ombrophilous Forest of Paraná state, southern Brazil (1 program: passive restoration), a sub-tropical forest. A total of 2955 monitoring plots of 100 or 120 m² were assessed, sampling a total of 31.7 hectares of restoration forests in this subset of programs selected from the 42 programs included in addressing the first question of proportion of land allocated to each restoration approach. Only the program from Paraná state was not included in question 1.

We randomly distributed a pre-determined number of 25 x 4 m or 30 x 4 m monitoring plots within each restoration project (i.e., a specific area where a given restoration approach was implemented), depending on project area. In each plot we assessed: (1) percent canopy cover, estimated by measuring the vertical projection of the tree canopies in a 25 or 30 m long line placed in the forest floor, depending on plot size; (2) percent invasive grasses ground cover, estimated by measuring the percentage of a 25 or 30 m long line placed in the forest floor covered by invasive grasses, depending on plot size (25 x 4 m or 30 x 4 m), especially the African fodder grasses *Urochloa decumbens* and *Panicum maximum*; (3) density of native and exotic species per plot in two size classes (height ≥ 50 cm and dbh ≤ 5 cm; and dbh > 5 cm, for evaluating the level of development of forest structure and further regeneration potential, respectively); and (4) density of individuals (stems of trees and shrubs) of native species per plot, according to the above mentioned size classes. We lacked information regarding the density of exotic individuals to include in this analysis.

We plotted canopy cover, woody species density, and density of individuals from woody species (dbh ≤ 5 cm), which are considered key ecological variables to measure restoration endpoints in the context of the studied projects (Chaves *et al*. 2015), as a function of restoration age to assess variability within and among restoration approaches for each forest type through time. We further divided the data into two age classes: from 0.2 to 3 yr of age and between 3.1 and 5 yr to evaluate the influences of forest type and restoration method on the response variables. Such age classes were adopted because different ecological outcomes are expected in these specific moments. In the first class, it is expected that a reasonable number of individuals from woody species are present to support the development of a closed canopy in the following years; the second class represents the period in which it is expected that the forest canopy is closed enough to suppress invasive grasses and to support regeneration of smaller individuals of woody species in the understory. In spite of the importance to include older sites to assess restoration success (Suganuma & Durigan 2015), our dataset was limited to young restoration sites.

Due to the binomial nature of percent data, we employed a logistic regression approach to assess the influence of forest type and restoration approach in the percent canopy cover and in the percent of invasive grasses found. We employed the package car for R (v. 3.1.1) to conduct the regressions. We further tested the influence of forest type and restoration approach on native species density, native individuals' density, and exotic individuals' density for individuals sampled in both size classes. We ran ANOVAS, followed by Tukey tests, to assess the influence of the variables of restoration approach and vegetation type on species and individuals density using the log + 1 of the density data to meet assumptions of normality and homocedasticity. The null (random) hypothesis was that the ecological outcomes measured were independent of the vegetation type or restoration approach used. We employed R (v. 3.1.1) to run the analyses.

LEGAL FRAMEWORKS TO BALANCE THE USE OF PASSIVE AND ACTIVE RESTORATION – To investigate how legal frameworks may promote a better balance in the use of passive and active restoration, we evaluated the framework established by Environmental Compliance Programs (PRA, acronym in Portuguese) designed to support the implementation of the new Forest Code, from 2012, in different states of Brazil. The official working groups to elaborate the PRA of the states of Pará, Acre, and Rondônia, in the Amazon, and of the state of Bahia, in the Atlantic Forest of northeast Brazil, were leaded by the Laboratory of Forest Ecology and Restoration, University of São Paulo (including many co-authors of this paper). More information about the contextualization of the PRA in the Forest Code is provided in Supplementary Material 1.

The development of PRA in Pará started in 2012 and included, since its beginning, the participation of managers and policy-makers representing different state governmental agencies (*e.g.* Agriculture, Environment, Legal affairs) and research institutes. In the states of Bahia, Acre, and Rondônia, the development of PRA started as a consultancy project lead by the same laboratory, and further included representatives of different state governmental agencies and research institutes to consolidate the proposed program. In these states, the development of PRA was based on three main issues: i) approaches for restoration implementation and parameters for its monitoring; ii) administrative mechanisms to support program management by state agencies; and iii) the construction of a legal instrument to regulate the program. In this study, we focused on the first issue: exploring the regulatory decisions associated with the selection of restoration approaches, i.e. the legal requirements, technical basis, and sequential steps for deciding whether passive, mixed, or active restoration will be adopted in each land portion where restoration is mandatory by law.

In this process, the first step was to develop a large survey on the main environmental situations of each state (vegetation types, land uses, degradation levels, soils, etc.), in order to obtain a list of the main situations where restoration is needed. Different stakeholders were invited to discuss this assessment in open meetings in order to recommend the most appropriate restoration approach for each environmental and socioeconomic (land tenure, landholding size, funding availability for restoration, integration to external markets) situation, as well as monitoring parameters to assess the effectiveness of each method. The main idea was that different decision-makers and stakeholders involved in the "restoration supply chain" at each state had to be part of the PRA elaboration process to foster the creation of an implementable policy, consistent with current restoration knowledge and practice. The recommendations of the participants were then synthetized in a framework that described the timeline in which decisions are to be made regarding restoration interventions, monitoring, and corrective actions within the 20 year period of a restoration program (the official deadline in which restoration commitments have to be met).

RESULTS

ALLOCATION OF RESTORATION APPROACHES – Active restoration had the highest proportion of land allocated to it (78.4 ± 21.8%), followed by passive (14.2 ± 21.1%) and mixed restoration (7.4 ± 12.1%) (F_{40} = 8.34, $p < 0.0001$). Percent area allocated to each restoration method was significantly different in each of the three biomes were programs were located (X^2_4 = 48.59, $p < 0.0001$), mainly due to a higher proportion of area, than expected by random, allocated to passive restoration in the Amazon and a lower than expected proportion of passively restored land in the Atlantic and in the Atlantic-Cerrado biomes (Figure 2A). The proportions of land allocated to each restoration approach were also related to the main land use at the program site (X^2_6 = 112.86, $p < 0.0001$) due to a higher proportion than expected by random of land under passive restoration for areas with silviculture and a higher than expected by random proportion of land under mixed restoration in areas with agriculture (Figure 2B). There was a higher proportion of land than expected by random under passive restoration for areas with over 50 percent remaining forest cover (Figure 2C). Most of those areas were located in the Amazon biome.

ECOLOGICAL OUTCOMES – The main ecological indicators employed to assess the outcomes of a restoration program showed a high variability for the three restoration approaches evaluated (Figure 3). Despite the variability within each approach and region, we observed a significant effect of the restoration approach employed on the probability of invasive grass presence both in Semideciduous and in Dense Ombrophilous Forests for the two restoration age ranges (Table 2). The probability of finding invasive grasses was higher in areas between 3.1 and 5 yr old but it varied within each method depending on the type of forest (Table 2). The probability of having a closed canopy was always lower in passively restored areas and the difference increased for older areas in both forest types (Table 2). No comparison could be done for Mixed Ombrophilous Forests as there was only one restoration method in this monitored area.

We observed significant effects of both restoration approach and forest type with regards to density of species and individuals (Table 3). Density of species and individuals of smaller sized plants (h ≥ 50 cm; dbh ≤ 5 cm) were significantly lower in passively restored areas located on Seasonal Semideciduous Forests, but not on Dense Ombrophilous Forests. For larger individuals (dbh > 5 cm), differences among approaches only became significant in the older age group, with less native species and individuals in the passively restored areas regardless of forest type. Passively restored areas had significantly less exotic individuals than either active or mixed restored areas (Table 3).

LEGAL FRAMEWORK – The first step of the legal regulatory framework is to protect areas registered to be restored in CAR against further human-mediated disturbances (Figure 4). Such protection includes removal of cattle, goats and other grazing domesticated animals from the site and fencing its boundaries, stopping soil cultivation for agricultural production, protecting against fires and erosion from neighboring sites. The landowner may decide about the restoration method only two or four yr after engaging to the PRA, in order to allow some level of expression of natural regeneration to increase the reliability of restoration methods prescription. During this period, the farmer has to protect the area from human-mediated disturbances and encourage natural regeneration. Then, passive or active restoration approaches can be adopted depending on the level of spontaneous regeneration of native woody species. If a passive restoration approach is adopted, farmers have to re-assess natural regeneration to confirm that the selected approach was appropriate; if natural regeneration is not sufficient to kickstart forest regeneration, the restoration approach has to be changed to active (arrow going from passive to active restoration boxes in the figure). Once a restoration method is implemented and confirmed, monitoring has to be done, at least, at the 7th, 13th, 19th and 20th yr following implementation and reports have to be presented to the state environmental agency. Monitoring will be carried out both by the farmer, to support decisions regarding corrective actions, and by environmental secretariat agents, to verify legal compliance. Corrective actions include planting seedlings or seeds in the entire area, in the cases where passive restoration was chosen but natural regeneration was not sufficient, as well as enrichment plantings (artificial enrichment), when ecosystems ongoing restoration have shown a limited successional development due to the lack of late-successional trees in the plant community (Figure 4).

DISCUSSION

Seedling plantation or direct seeding covering the entire area was the most indicated method in the restoration diagnosis programs, developed according to the previous version of the Forest Code, in the Brazilian Amazon and Atlantic Forest regions, while passive restoration was only relevant in the Amazon and mixed restoration had only a minor participation at the studied restoration programs. The prioritization of active restoration can be explained by two different perspectives. First, most of the restoration programs assessed are located in highly-modified agricultural landscapes, with a long and recent history of fire and intensive land use for crop production, cattle ranching and silviculture (Rodrigues *et al.* 2011; Melo *et al*. 2013; Solar *et al.* In press). In such conditions, soil seed banks of native woody species are progressively depleted and seed rain reduced due to limitations of seed sources and vertebrate dispersers (Holl & Aide 2011, Arroyo-Rodriguez *et al.* In press). Although the reduced forest cover in the Atlantic Forest restoration programs (9.2%) clearly indicates a limitation for natural regeneration, the same would not be expected for the Amazonian programs, for which average forest cover was much higher (56.3%). There is a higher forest regeneration potential in agricultural lands immersed in landscapes with a higher percentage of remaining forest cover due to a lower dispersal limitation (Chazdon 2014). This explains the fact that passive restoration was implemented in more cases in the Amazon biome compared to either the Atlantic or the Atlantic-Cerrado ecotone. Active restoration was recommended for 60 percent of the cases in the last two biomes, as already indicated by other work (Rodrigues *et al*. 2011). In addition, the predominance of restoration sites in riparian buffers – both in the Amazon and in the Atlantic Forest – may have contributed to this diagnosis of high proportion of active restoration, since these areas are well known for their flat terrain, fertile soils and importance for water supply to cattle, which may have contributed to the intensification of land use in these areas (now targeted for restoration) and may have hampered their natural regeneration. As expected, the proportion of passive restoration was higher for silviculture, where longer harvesting cycles and the creation of a shaded environment create favorable conditions for native species recruitment in the plantations' understory, in Brazil and in other tropical regions (Lamb 2014, Pryde *et al*. 2015). Based on these contexts, it could be assumed that the diagnosis was correct and active restoration was truly needed in most of these programs.

A second perspective, with a robust set of evidences in the literature, may consider that the proportion of active restoration was overestimated. Studies on historical regeneration dynamics both in the Atlantic Forest (Baptista *et al.* 2006, Lira *et al.* 2012, Ferraz *et al*. 2014, Rezende *et al.* 2015) and in the Amazon (Rosa *et al*. 2015) have shown considerable increases in native forest cover due to passive restoration. For instance, Ferraz *et al.* (2014), working in landscapes dominated by sugarcane and pasturelands in southeastern Brazil – the very similar situation of most Atlantic Forest programs included in our study – showed that native forest cover increased from 8 to 16 percent from 1962 to 2008 due to natural regeneration. Thus, even in landscapes with historically intense land use and very limited forest cover, passive restoration can be a viable approach, but may take longer to occur and require further enrichment plantings to recover tree diversity.

Remarkable increases in forest cover due to natural regeneration have been described in many tropical landscapes (Aide *et al.* 2013; Sloan *et al.* 2015), yet the knowledge to predict which sites are able to regenerate in the future is limited. The restoration diagnosis approach described in this work, and adopted by restoration programs in the context of the previous Forest Code, was essentially based on the most evident indicator of the forest regeneration potential of a site: the abundance of spontaneously regenerating individuals of native woody species. However, passive restoration potential may be highly influenced by a slow, but continuous, temporal accumulation of individuals and species in the sites after interruption of land use by agricultural activities, instead of by the pre-existence of regenerating individuals right after the protection of the area for restoration. Thus, the new regulatory framework established by the updated version of the Forest Code may enhance the adoption of passive restoration, since the longer period, four years, provided to decide upon the selection of restoration approaches may allow a better expression of the natural regeneration potential.

As a consequence of restoration efforts of Amazonian municipalities to get out of the beef and soy moratorium (Nepstad *et al.* 2014), or the need to obtain environmental certification to safeguard market fidelity in Eucalyptus and sugarcane industries (Rodrigues *et al*. 2011), and legal penalties obligating legal compliance, most restoration programs were planned to obtain faster and more predictable results in terms of forest recovery. Indeed, active and mixed restoration methods appeared to achieve a greater percent of canopy cover, lower percent of soil cover by invasive grasses, and higher species and individuals' density through time than passive restoration. But passive restoration leads to a lower presence of exotic species, which can be a risk for restoration success. One must consider, however, that the monitoring data showed great variability in the response variables even within active restoration, which highlights that outcomes of active restoration are not as predictable as expected.

Active restoration was shown to be as variable and unpredictable as passive restoration. Although it is intuitive to think that planting seedlings or sowing seeds of native species in an entire area will speed up restoration processes and increase the chances of reestablishing a forest structure with a reasonable number of species, there are many factors that may prevent a predictable, unidirectional ecosystem response to restoration. Problems with species selection, quality of seeds and seedlings, soil degradation, competition with invasive species, failures in maintenance, and natural and human-mediated disturbances make active restoration a risky activity. In addition, previous intensive land uses in some of the areas assessed, which reduced the presence of naturally regenerating individuals and lead to the diagnosis that active restoration was needed may also have led to high environmental heterogeneity and thus high variability in the outcomes of active restoration approaches, as consequence of both local (e.g. field area, type, duration, and severity of agriculture activities, soil properties) and landscape-scale factors (e.g. isolation/connectedness, percent of native vegetation cover, matrix disturbance regime) (Zermeño et al. 2015). Overall, human modifications of environment tend to increase its spatial heterogeneity.

Although chronosequences of restoration plantings carried out in the Atlantic Forest of southeastern Brazil have shown predictable trajectories in terms of vegetation structure and species richness (Suganuma & Durigan 2015), they were based in restoration sites that had already enough canopy cover to support successional process and understory re-initiation. Many younger restoration projects may not reach this stage, and be lost before the canopy is close enough to shade invasive grasses and support the recolonization of woody native species in the understory. The current assessment was based on young restoration sites (up to five years old). Monitoring of older sites may show less variability across active restoration sites within a biome. In addition, the reduced size of the plots used to assess vegetation structure and composition may have also contributed to inflate spatial variability, since the typical fine-scale heterogeneity of the variables assessed in restoration sites may require larger plots to minimize among-plots variation.

The above-mentioned scientific and technological challenges to prescribe a restoration method and monitoring its outcomes have key consequences for designing effective policies for restoration. Fortunately, the development of a legal framework for the Environmental Compliance Program of the new Forest Code in the states of Acre, Pará, Rondônia, and Bahia has been planned to include a period of two to four years to protect the areas and encourage natural regeneration before farmers decide to use active or passive restoration approaches, in order to favor passive restoration whenever it is possible. Another advantage of these legal frameworks is that they go beyond traditional legal perspectives of restoration as a short-term, punctual activity ending some few years after implementation, with reasonable chances of success, which is highly influenced by the view of restoration as a tree planting activity. The approach of these frameworks is closer to the reality of restoration, a mid- to long-term process, with higher chances of failures and a constant need for monitoring and corrective actions.

Differently than previous restoration legislations, in which environmental secretariats had a direct influence in restoration planning, determining which restoration approaches were accepted or not based on subjective decisions of law enforcement agents, requiring a lot of documents, time and, sometimes, bribes to authorize project implementation, the proposed PRAs are more pragmatic. The PRA is focused in the role of government as a provider of a transparent and simple legal environment for farmers and project managers to determine which restoration outcomes are expected, and to enable public agents and farmers to understand and apply the legislation. In this new regulatory framework, farmers' decisions upon restoration approaches have not to be authorized by public agents; they have only to be communicated in a web-based, self-declaratory system, based on the rationale proposed by the legal framework described in Figure 4.

The high proportion of active restoration indicated in the diagnoses and its equally high levels of uncertainty compared to passive restoration highlight the need to advance our understanding about the drivers of natural regeneration in human-modified tropical landscapes as well as increase our understanding of community assembly processes in planted versus naturally regenerating forests. Advancing these understandings will allow greater reliability in the prescriptions of restoration approaches, a reduction in financial inputs and the optimization of ecological restoration outcomes taking better advantage of the natural regeneration potential of areas targeted for restoration. A research approach such as this would support a shift in the investment rationale currently adopted in restoration projects, migrating from massive investments in seedling plantation to financial incentives for farmers and the use of natural regeneration when feasible. Incentives could include payments for ecosystem services and other economic mechanisms to support natural regeneration in marginal agricultural areas, a strategy with much higher socioeconomic appeal and chances to engage landowners in forest and landscape restoration rather than solely active restoration.

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LITERATURE CITED

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TABLES

TABLE 1. Restoration diagnosis and its related restoration approach applied in each of the 42 restoration programs reviewed in the present study.

Restoration diagnosis	*Restoration methods*
null or very limited potential for autogenic restoration: sites occupied by mechanized agriculture or pasturelands with none or very few spontaneously regenerating seedlings or native isolated trees species	*active restoration*: Plantations of seedlings (1666 seedlings/ha, 3m×2m spacing) or direct seeding of several native tree species (> 50 species) covering the entire area, equally divided into fast growing and wide canopy species, and slow growing and/or narrow canopy species
intermediate potential for autogenic restoration: abandoned sites or pasturelands with patchy distribution of sites covered and not covered by spontaneously regenerating seedlings or native isolated trees species	*mixed restoration*: Encouragement of regenerating individuals of native trees and shrubs by manual or chemical control of invasive grasses and active restoration of patches not covered by spontaneously regenerating seedlings or native isolated trees species
fair potential for autogenic restoration: spontaneously regenerating seedlings or native isolated trees species covering most of the site	*passive restoration*: Site isolation from human-mediated disturbances and, when necessary, encouragement of regenerating individuals of native trees and shrubs by manual or chemical control of invasive grasses. Enrichment plantings with late-successional tree species in low diversity regenerating forests were also included in this category

TABLE 2. Comparisons of the percentage of invasive grasses cover and canopy cover among different restoration approaches in younger and older restoration areas in three forest types (SSF - Seasonal Semideciduous Forest, DOF - Dense Ombrophilous Forest, and MOF - Mixed Ombrophilous Forest) of the Atlantic Forest of Brazil. The first two values represent the mean and standard error, and values in parenthesis represent the probabilities, based on logistic binomial regressions, of higher percentages of invasive grass and canopy cover following a given restoration approach within each forest type, with a significance value of $p < 0.05$ indicated by *. NA indicates cases in which analysis were not applied because the restoration method was not assessed in a given forest type and restoration age.

		Ground cover by invasive grasses (%)			canopy cover (%)		
Age	Approach	SSF	DOF	MOF	SSF	DOF	MOF
0.2-3.0 years	mixed	25.1 ± 3.9 (*prob.* = 0.25*)	18.6 ±1.5 (*prob.* = 0.18*)	NA	40. ± 3.2 (*prob.* = 0.38*)	22.9 ± 0.8 (*prob.* = 0.22*)	NA
	active	21.0 ± 1.51 (*prob.* = 0.20*)	33.4 ± 2.21 (*prob.* = 0.33*)	NA	29.0 ± 1.3 (*prob.* = 0.29*)	13.9 ± 1.03 (*prob.* = 0.14*)	NA
	passive	14.4 ± 6.4 (*prob.* = 0.14*)	31.5 ± 14.0 (*prob.* = 0.32)	52.6 ± 2.96	9.8 ± 2.3 (*prob.* = 0.09*)	20.4 ± 5.6 (*prob.* = 0.2*)	39.6 ± 2.30
3.1-5.0 years	mixed	51.5 ± 3.3 (*prob.* = 0.51*)	84.0 ± 4.5 (*prob.* = 0.84*)	NA	56.1 ± 3.07 (*prob.* = 0.56*)	56.7 ± 7.6 (*prob.* = 0.57*)	NA
	active	58.9 ±1.75 (*prob.* = 0.59*)	NA	NA	33.9 ± 1.43 (*prob.* = 0.34*)	NA	NA
	passive	98.0 ±1.11 (*prob.* = 0.98*)	68.9 ± 2.10 (*p* = 0.68*)	51.7 ± 2.06	10.1 ± 2.9 (*prob.* = 0.10*)	29.5 ± 1.9 (*prob.* = 0.29*)	35.8 ± 1.95

TABLE 3. Comparisons of ecological outcomes among different restoration approaches assessed in younger and older restoration areas in three forest types (SSF - Seasonal Semideciduous Forest, DOF - Dense Ombrophilous Forest, and MOF - Mixed Ombrophilous Forest) of the Atlantic Forest of Brazil. Values represent the mean and standard error, and letters indicate significant differences based on a post-hoc Tukey test ($p < 0.05$) across methods within a forest type (capital letters) and across forest types within a given approach (lower case letters). NA indicates cases in which analysis were not applied because the restoration approach was not assessed in a given forest type and restoration age.

			native species density (dbh < 5 cm)			
Approach		*0.2-3.0 years*			*3.1-5.0 years*	
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	7.8 ± 0.5Aa	4.7 ± 0.1Ab	NA	4.9 ± 0.2Aa	3.7 ± 0.4Aa	NA
Active	8.1 ± 0.2Aa	3.3 ± 0.1Bb	NA	4.9 ± 0.1A	NA	NA
Passive	2.3 ± 0.3Ba	4.0 ± 0.5Aac	7.6 ± 0.3 Bc	2.7 ± 0.4Ba	6.9 ± 0.2Bb	6.7 ± 0.3b
			native species density (dbh > 5 cm)			
		0.2-3.0 years			*3.1-5.0 years*	
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	1.5 ± 0.2Aa	0.2 ± 0.03Ab	NA	2.3 ± 0.2Aa	4.0 ± 0.5Ab	NA
Active	1.2 ± 0.1Aa	0.3 ± 0.04Ab	NA	1.9 ± 0.1A	NA	NA
Passive	0.7 ± 0.1Aa	0.5 ± 0.3Aa	1.4 ± 0.1a	0.3 ± 0.2Ba	2.0 ± 0.1Bb	1.5 ± 0.1b
			native individuals density (dbh< 5 cm)			
		0.2-3.0 years		*3.1-5.0 years*		
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	1225 ± 75Aa	1416 ± 54Aa	NA	780 ± 37Aa	392 ± 45Ab	NA
Active	1042 ± 19Aa	690 ± 29Bb	NA	678 ± 16AB	NA	NA
Passive	467 ± 83Ba	3083 ± 1023Abc	4270 ± 338c	435 ± 60Ba	771 ± 19Bb	3689 ± 333c
			native individuals density (dbh > 5 cm)			
		0.2-3.0 years			*3.1-5.0 years*	
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	192 ± 25Aa	30 ± 4Ab	NA	293 ± 22Aa	581 ± 76Aa	NA
Active	129 ± 8Aa	34 ± 6Ab	NA	230 ± 10A	NA	NA
Passive	114 ± 27Aa	67 ± 42Aa	264 ± 28a	32 ± 18Ba	298 ± 23Bb	302 ± 25b

	exotic individuals density (dbh< 5 cm)					
	0.2-3.0 years			*3.1-5.0 years*		
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	90 ± 10Aa	311 ± 13Ab	NA	144 ± 17Aa	58 ± 17Aa	NA
Active	100 ± 5Aa	276 ± 12Ab	NA	67 ± 4B	NA	NA
Passive	3.7 ± 3.7Ba	167 ± 67Ab	1186 (125) c	42 ± 17Ba	40 ± 4Aa	2436 ± 447b
	exotic individuals density (dbh > 5 cm)					
	0.2-3.0 years			*3.1-5.0 years*		
	SSF	DOF	MOF	SSF	DOF	MOF
Mixed	30 ± 7Aa	23 ± 4Aa	NA	51 ± 8Aa	100 ± 29Ab	NA
Active	23 ± 3Aa	26 ± 5Aa	NA	32 ± 3A	NA	NA
Passive	0 Aa	0Aa	0a	0 Ba	5 ± 1Ba	3 ± 2a

FIGURES

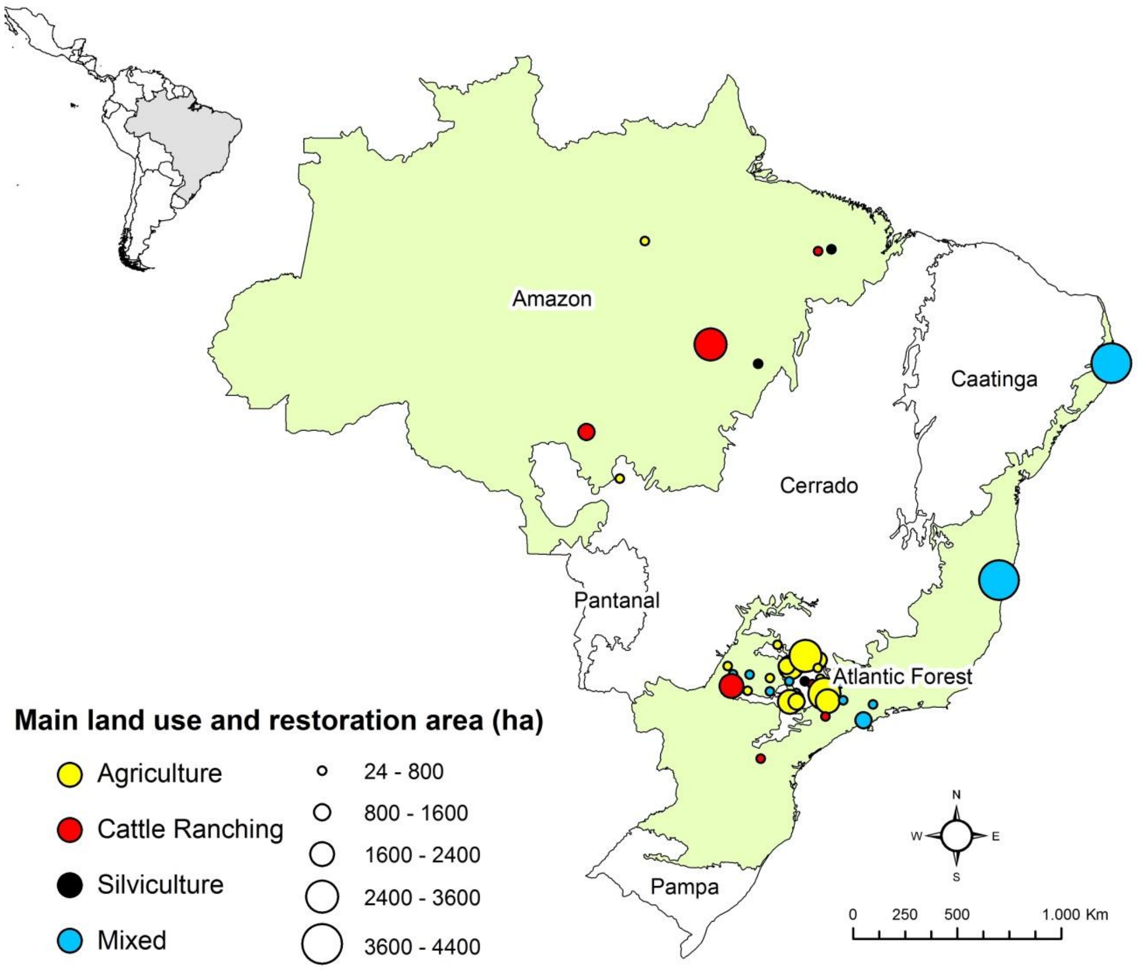

Figure 1. Location, main land uses, and restoration area of 42 programmes evaluated in Brazil.

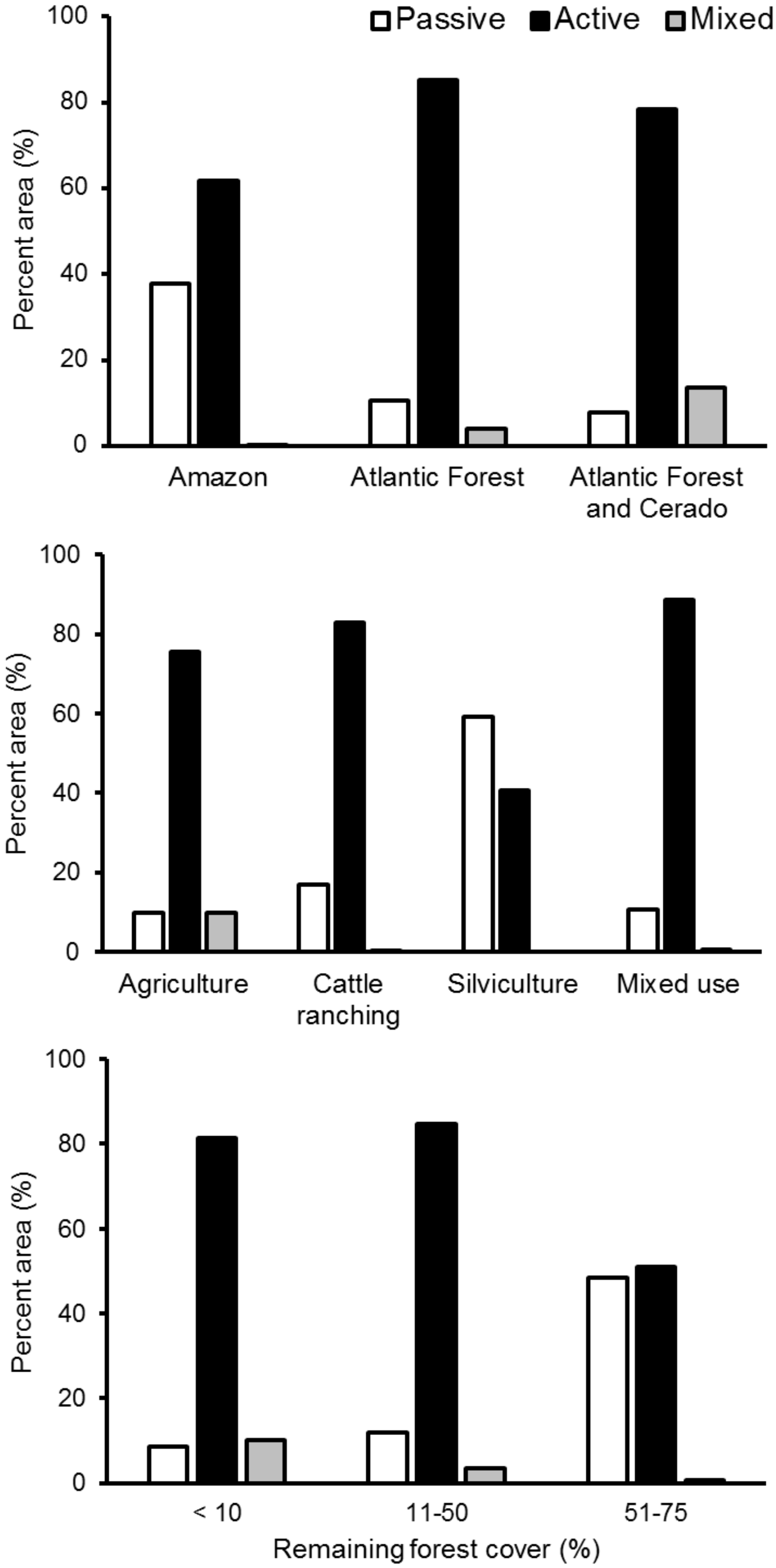

Figure 2. Percent area allocated to each restoration method by biome (A), land use (B), and percent remnant forest cover (C).

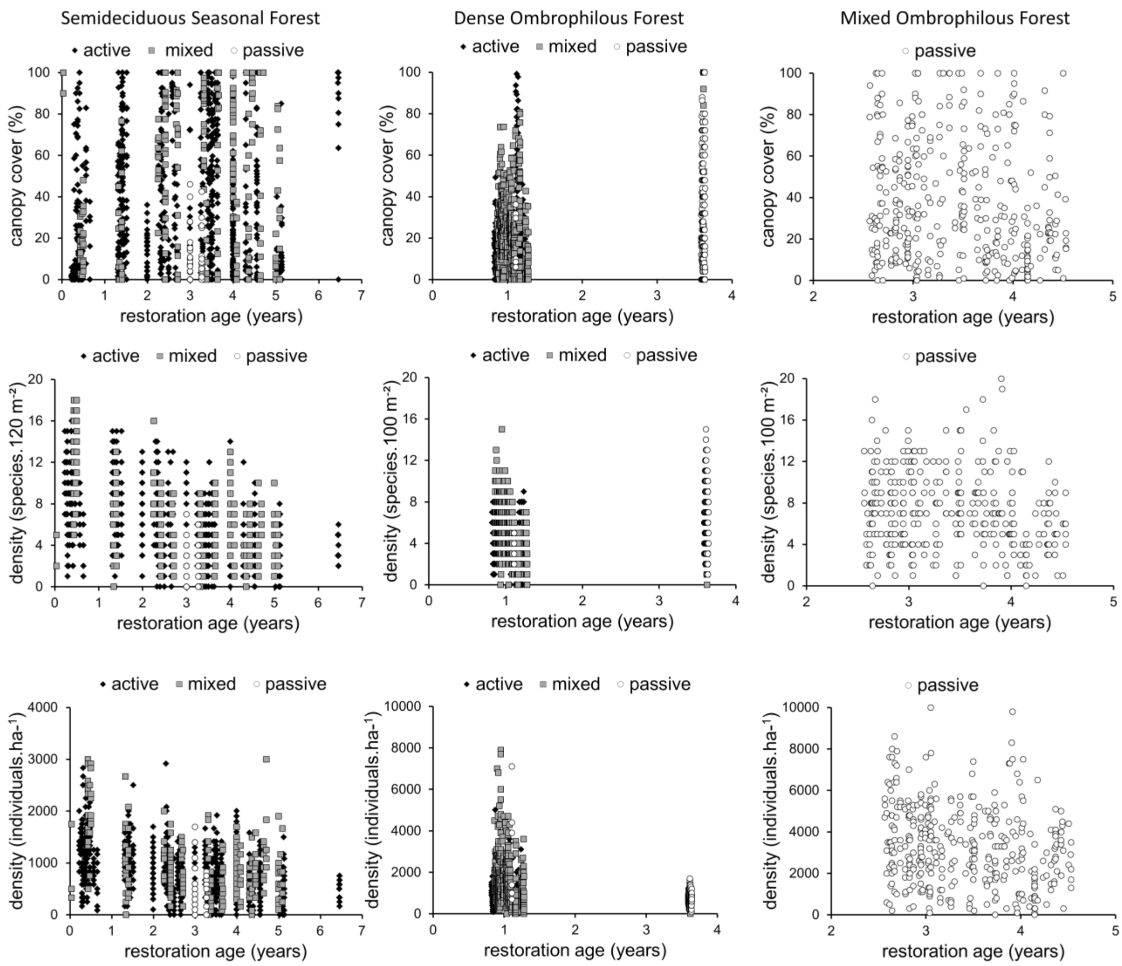

Figure 3. Data dispersion of monitoring plots (100 and 120 m²) established in restoration projects implemented through different methods in the Seasonal Semideciduous Forest in São Paulo state (active: n = 1,147; mixed: n = 271; passive: n = 45), Dense Ombrophilous Forest of Bahia state (active: n = 355; mixed: n = 510; passive: n = 236), and Mixed Ombrophilous Forest of Paraná state (passive: n = 392) in Brazil.

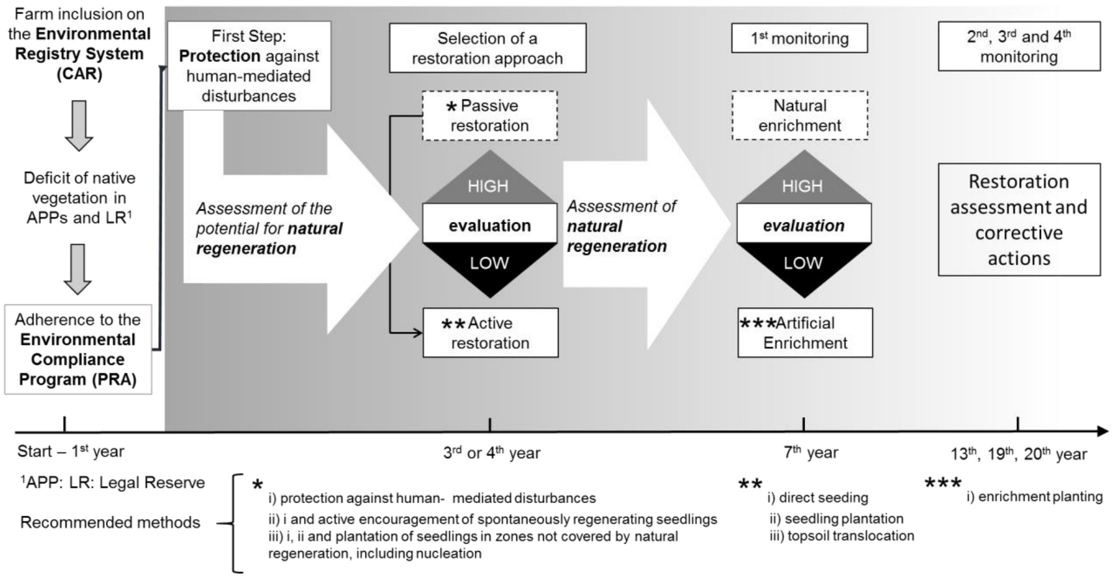

Figure 4. Conceptual framework for selecting restoration approaches according to the Environmental Compliance Program of the states of Acre, Bahia, Pará, and Rondônia in Brazil. "Active" and "passive restoration" boxes refer to approaches needed to reestablish an initial native vegetation cover in the site targeted for restoration. Monitoring can be done by the farmer, to support the adoption of corrective actions to favor restoration trajectory, and by law enforcement agents, to check legal compliance.