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# Ecological restoration in Brazilian biomes: Identifying advances and gaps

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A R T I C L E I N F O

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A B S T R A C T

The Bonn challenge aims at the restoration of 350 million hectares of degraded ladscapes by 2030. In Brazil, the restoration goal for 2030 is 12 million hectares. Despite the great demand for ecological restoration across the whole of Brazil, there have been no analyses of the studies carried out in different biomes. In addition, conservation efforts must cover all biomes, so that different regions can take advantage of the many benefits of restoration. Our aim was to identify advances and gaps in current restoration knowledge in order to guide future efforts in Brazil. Our bibliometric survey in the Web of Science using 23 keywords related to restoration generated a total of 530 papers, of which 291 were included in the analysis. The papers were published in 121 scientific journals between 1988 and 2018, with the largest number of papers in 2016. The Atlantic Forest was the biome with the highest number of studies, as it is one of the most threatened tropical forest regions in the world and maintains the largest number of research institutions and receives the highest level of funding support in the country. Regarding the types of studies, temporal monitoring was more frequent in the Amazon, Cerrado, Caatinga, and Pampa, while the monitoring at one point in time was more frequent in the Atlantic Forest. From the studies examined, 31% used a reference area for comparing restoration success. The most studied organisms were plants (81%), and among them, trees were the most frequent, followed by fungi, birds, invertebrates, mammals, and reptiles. The pre-restoration degradation differed among biomes, with deforestation for logging the most cited in the Amazon, agriculture, and livestock in the Atlantic Forest and Cerrado, logging and cattle ranching in Caatinga, and livestock in the Pampa and Pantanal. In general, active/assisted natural succession was the most frequent restoration process: planting seedlings more readily occurred in the Amazon, Atlantic Forest, and Caatinga, whereas natural regeneration in the Cerrado and Pantanal and sowing in Pampa. The studies varied among the age of restoration (> 1 to 67 years for active restoration and > 1 to 120 years for passive/unassisted natural succession), and the number of species planted (1 to 121 species). We identified an important regional knowledge gap for the Pantanal, Caatinga, and Pampa, as well as the need to include reference areas, evaluate different restoration techniques (besides planting seedlings), and the inclusion of other taxa and life forms in biodiversity studies apart from trees. We also identified the need to expand research to assess landscape metrics, prioritization, legislation, and public policies.

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## 1. Introduction

Despite the long history of environmental degradation in Brazil and elsewhere in the world, only recently research lines have been developed to understand the dynamics of these processes and to attempt to revert them. Restoration ecology is a sub-discipline of Ecology, which includes practical activities of restoration, based on ecological theory and on cultural and socioeconomic questions/factors (Higgs, 2005; Aronson et al., 2011). Ecological restoration is defined by the Society for Ecological Restoration, 2004 as: "[…] a deliberate activity that initiates or accelerates the recovery of an ecosystem regarding its health, integrity and sustainability, which requires restoration because it has been degraded, damaged, transformed or totally destroyed as a direct or indirect result of human activities […]."

Restoration ecology, together with related activities, has grown worldwide in the last three decades. It is considered a key element for the conservation of natural resources through the intervention in degraded ecosystem and has gained attention in the management of public policies (Hobbs et al., 2011). In the nineties, there was a significant increase in the number of research papers owing to the gradual expansion of this science as an area of knowledge and research (Oliveira and Engel, 2011; Wortley et al., 2013). In addition, the consolidation of the global debate on the environment has created a demand for large-scale restoration projects (Soares-Filho et al., 2014). Globally, the Paris Agreement, the Initiative 20 × 20, and the Bonn Challenge have identified restoration targets of up to 350 million hectares by 2030 as possible avenues to sequester atmospheric carbon dioxide and slow climate change. In Brazil, a national restoration goal of 12 million hectares by 2030 has been established by the National Plan for the Recovery of Native Vegetation (MMA, 2017Brazil, 2017a). With respect to research, one of the goals of this national plan is to prepare a list of priority themes by region to fund research to address knowledge gaps (see Table 13 in MMA, 2017Brazil, 2017a). A key outcome of this plan is that restoration actions should be based on the best available science and these should be put into practice according to questions of greater relevance to the real world (Hobbs and Harris, 2001) and science can help better public policies for restoration (Garcia et al., 2019).

Faced with this immense challenge of large-scale restoration in Brazil, there is an urgent demand for information that will assist decision-makers in undertaking restoration projects in the coming years. The country already has an active network of researchers and practitioners which allows information to be exchanged through different communication platforms (Isernhagen et al., 2017). From this network, one of the main demands was a systematic review of published research in order to support public policy, legislation, improved implementation practices, and scaling up programs. Here, we fill this gap and present an overview on trends in ecological restoration across Brazilian biomes, based on a literature review.

## 2. Methods

### 2.1. Tool and database

To identify trends in ecological restoration studies in Brazil, we conducted a search for publications from 1945 until July 2018. We used the advanced search of the Web of Science platform with the following keywords: "ecological restoration"; "ecological engineering"; "rehabilitation"; "reclamation"; "bioremediation"; "reforestation"; "revegetation"; "tree planting"; "passive restoration"; seedling transplanting; "direct seeding"; "direct sowing"; "transposition of soil" OR "soil transposition"; "seed bank transposition" OR "seed bank translocation"; "seed rain translocation"; "bird perches" OR "artificial perches"; "nucleation"; "brushwood transposition", and "artificial shelters for animals". We combined all these keywords with each of the names of the six Brazilian biomes: Cerrado OR Savanna, OR Amazon, OR Atlantic forest, OR Caatinga, OR Pantanal, OR Pampa, AND Brazil.

### 2.2. Indicators

After generating the list with the papers, we used the following restoration indicators: (1) biome (and vegetation type), (2) restoration technique, including active/assisted natural succession (planting of seedlings, sowing, nucleation with perches, transposition of litter, seed rain and soil, transplantation and rescue of seedlings, bioremediation, translocation of fauna), and passive/unassisted natural succession (natural regeneration), (3) presence or absence of soil features/conditions (e.g., soil quality), (4) presence or absence of reference areas (positive, i.e., native remnant, or negative, i.e. degraded area), (5) we classified the studies based on monitoring at one point in time and temporal monitoring (i.e., single instance versus repeated studies over time), landscape metrics and modelling of restoration needs (which covered some aspect of landscape ecology, scenarios, and planning on spatial, economic, and species scale), types of public policy (legislation, governance, and management), and type of experimental implementation for restoration; (6) type of pre-restoration degradation (deforestation for logging, livestock, agriculture, dams, mining, fire, frost, and invasion of exotic species), for the studies of reviews, landscape metrics/ modelling restoration needs, public policy, legislation/management, and governance could not identify the types of pre restoration degradation, and therefore were not accounted for (7) taxa studied (plants, animals, and microorganisms), (8) number of species planted per area in active restoration (by direct seeding and seedling plantations), and (9) age of the evaluated area.

We categorized the studies found according to the biome classification by IBGE (Atlantic Forest, Amazon, Pantanal, Caatinga, Cerrado, and Pampa). Additionally, we assigned the study to the global biome types as suggested by Olson et al. (2001), namely Flooded Grasslands and Savanas, Mangroves, Tropical and Subtropical Dry Broadleaf Forests, Tropical and Subtropical Grasslands, Savannas and Shrublands; Tropical and Subtropical Moist Broadleaf Forests. We used this information to generate a map with the locations of each study. The locations of the review studies, landscape metrics/modelling of restoration needs, public policy, legislation/management, and governance did not show the study site coordinates, so they were not included in the map.

## 3. Results

Our keyword search identified 530 papers. After closer analysis, 291 were considered to be within the scope of this study (see Appendix A). A pioneering ecological restoration paper about the Amazon was published in 1988 (Uhl et al., 1988) and has 569 citations (Fig. 1). The peak in the number of publications on ecological restoration was in 2016, with 48 papers (Fig. 1). On average, each paper has received 11 citations so far. From the papers analysed, 18 had more than 50 citations and only five had more than 100 citations (Table A1, in Appendix A). Among these eighteen, seven were published in Forest Ecology and Management. The papers were published in 121 scientific journals. The journal with the largest number of publications was Restoration Ecology, with 27 papers, followed by Forest Ecology and Management, with 24 (Table A2, in Appendix A).

The Brazilian biome with the highest number of studies was the Atlantic Forest, with 56% of the studies analysed, followed by the Amazon (22%), Cerrado (16%), Caatinga (4%), Pampa (1%), and lastly, the only one especific study conducted on Pantanal (Fig. 2). The state with the highest number of studies was São Paulo (74 studies, ~25%). Direct seeding was the most common technique placed on non-forest areas while seedling transplantation was only used in forest areas (Fig. 3a). All studies were performed in forested areas in the Amazon and the Atlantic Forest, while in Caatinga and Pantanal all were performed in non-forested areas (Fig. 3b). About 25% of the studies conducted in forest areas in the Cerrado and Pampa (Fig. 3b).

From the keyword searched, no study on "ecological engineering"

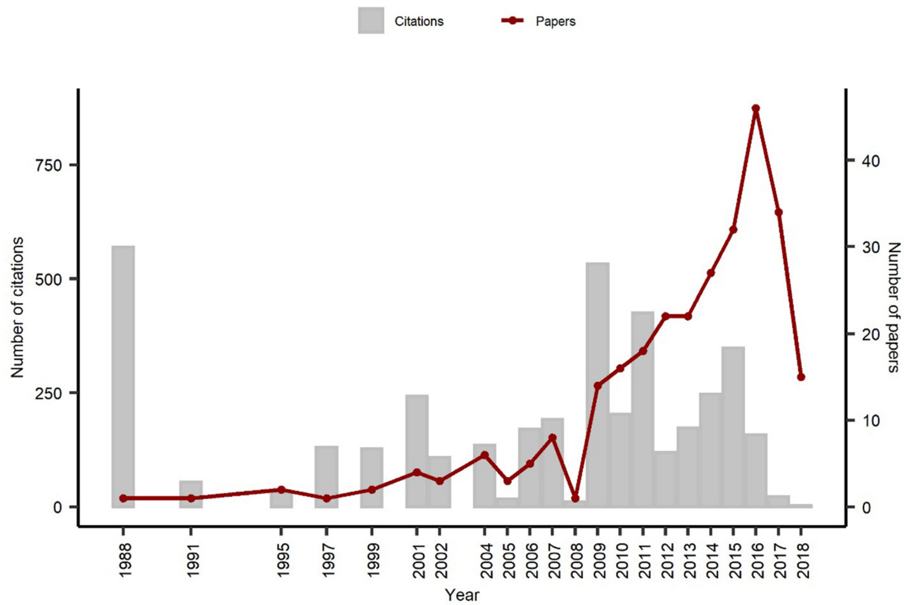


**Fig. 1.** Increase in the number of publications (line) and citations (grey bar) per year on restoration in the Brazilian biomes.

was found. In all biomes, there was a great diversification on the types of studies (Fig. 4a). The most frequent type of study was monitoring of restoration success over time, in which the most frequent was in the Amazon, Cerrado, Caatinga, and Pampa. In the Atlantic Forest, the most common study was monitoring at one point in time. From the studies performed, 31% used a reference area, among these, 55% used a positive reference area, 24% a negative reference area, 21% used negative and positive reference areas. Only 23% of the studies used or commented on soil features/conditions.

Regarding the pre-restoration situation, several types of degradation threats were cited for the analyzed areas in the studies (Fig. 4b). In the Amazon, the most observed degradation was logging/deforestation. In the Atlantic Forest and Cerrado, agriculture and livestock were the major causes of degradation. In Caatinga, logging and cattle ranching were most frequently mentioned, and in Pampa and Pantanal, livestock.

Regarding the restoration techniques, 70% were active/assisted natural succession and 30% passive/unassisted natural succession (Fig. 5). Seedling planting was the most used restoration technique in the Amazon (55% of studies), Atlantic Forest (46%), and Caatinga (50%); natural regeneration was more frequent in the Cerrado (33%) and Pantanal (100%); direct seeding was more frequent in the Pampa (60%). Natural regeneration was also well represented in the Amazon

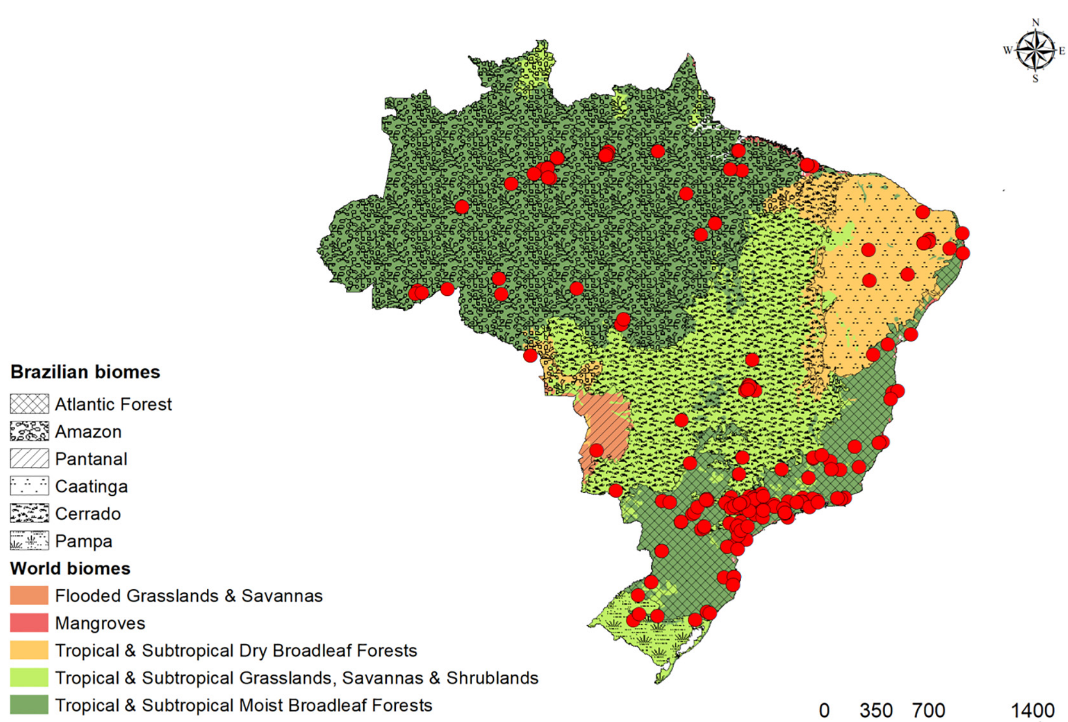


**Fig. 2.** Distribution of 291 study sites (according to the literature review) on the Brazilian biomes (and correspondent terrestrial ecoregions of the world classification of Olson et al., 2001).

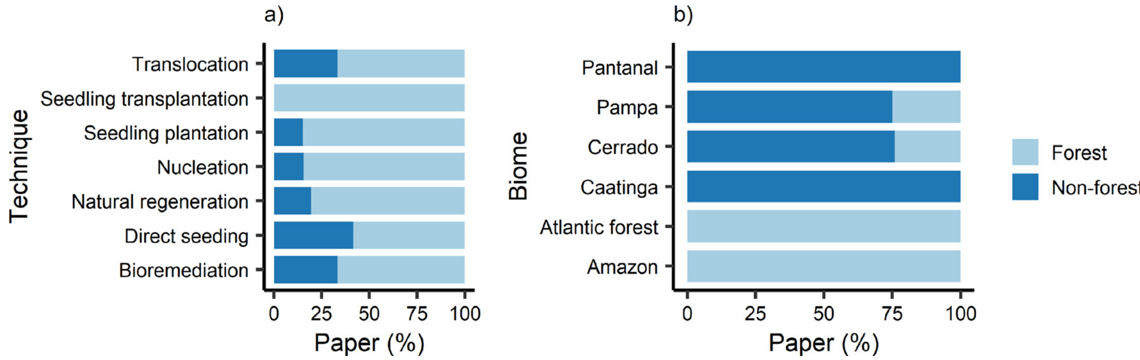


**Fig. 3.** Distribution of studies according to the restoration technique used (a) and ecosystem types of Brazilian biomes (b) through this literature review.

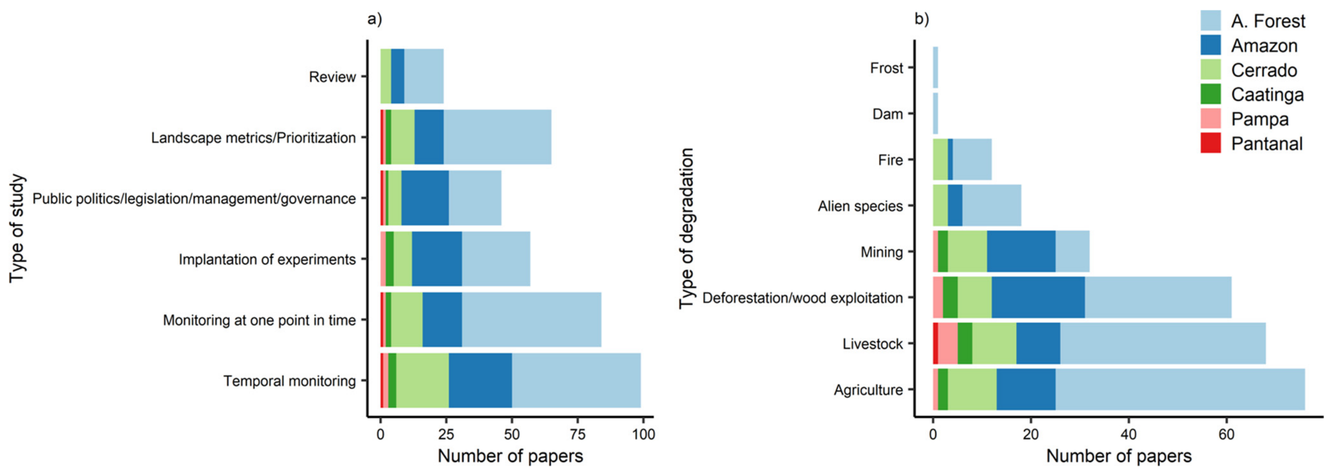


**Fig. 4.** Types of studies (a) and types of degradation (b) identified through this review on the restoration of Brazilian biomes.

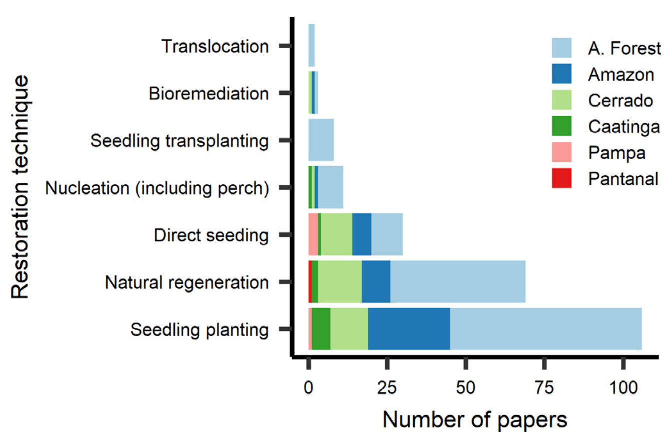


**Fig. 5.** Restoration techniques identified in the publications on the restoration of Brazilian biomes.

(19%) and Atlantic Forest (32%). For all restoration techniques covered by the studies, most were conducted in forest environments (overall mean: 78%). Direct seeding was the most common technique at non-forest sites (Fig. 3a).

The indicators of monitoring success were plants (81%, of which 79% were trees), and fungi (6%), birds (5%), invertebrates (4%), mammals (3%), and reptiles (0.4%) in restoration areas. The Atlantic Forest biome presented studies with all groups of organisms considered. The Cerrado appears with 83% of the groups, followed by the Amazon (75%), Caatinga (17%), and Pampa (8%) (Fig. 6).

The areas with active/assisted natural succession found in the studies were aged from less than one year to 67 years of restoration, while the areas of passive restoration passive/unassisted natural succession were aged from less than one year to 120 years (Fig. 7a). More than half of the reported areas (53%) had experienced less than 10 years of restoration, and the greater the age, the fewer the studies in restored areas. The number of species planted in areas with active/assisted natural succession ranged from 1 to 121 species per area, and most areas (36%) had less than 10 planted species (Fig. 7b).

## 4. Discussion

Our bibliometric study of published research addressing ecological restoration in Brazil over the last 30 years revealed solid and growing scientific production over the period. Although scientific production has increased substantially, we identified a large bias in the distribution of studies in relation to the restored biome, with a predominance of studies in the Atlantic Forest, Amazonia, and Cerrado and a small number in Pampa, Pantanal, and Caatinga, indicating relevant knowledge gaps. We also found asymmetries regarding the types of studies and techniques, and the organisms studied, which suggests a multiplicity of knowledge, but perhaps a limitation on the efficiency of restoration. As Brazil is a country of continental dimensions, with a great diversity of species and ecosystems and with ambitious goals to be achieved in international challenges (MMA, 2017; Brazil, 2017a), our study sheds light on the need for major financial and organizational efforts to increase knowledge about restoration in the country.

The strength of Brazilian scientific production on restoration ecology begins with the seminal publication of Uhl et al. (1988) addressing the natural recovery of the Amazon forest since pasture abandonment. The year of this publication coincided with the promulgation of the Brazilian Federal Constitution, which outlined that an ecologically balanced environment must be considered a fundamental

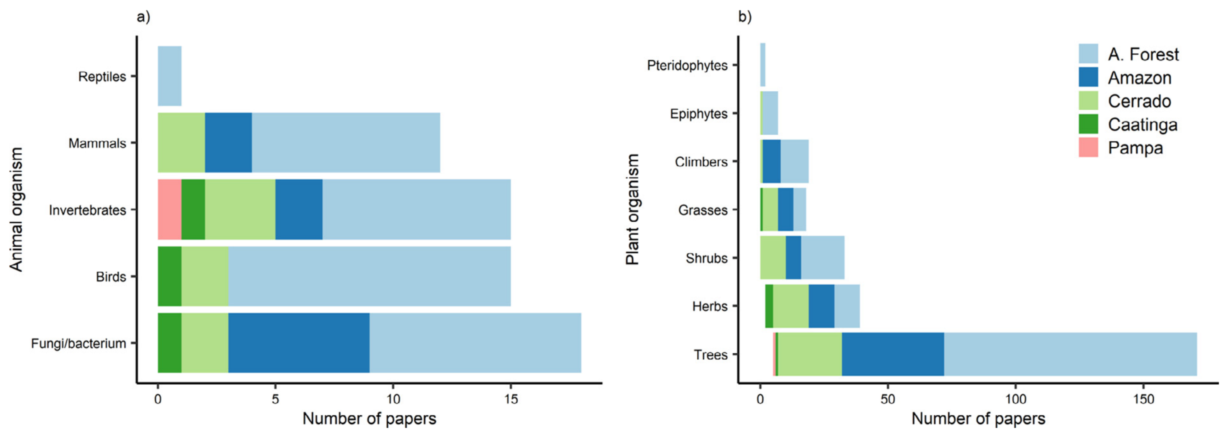


**Fig. 6.** Organisms studied on research about the restoration of Brazilian biomes. Pantanal biome did not have enough studies to enter the percentage of the graphs. In addition, groups such as amphibians and fish were not found in the studies.

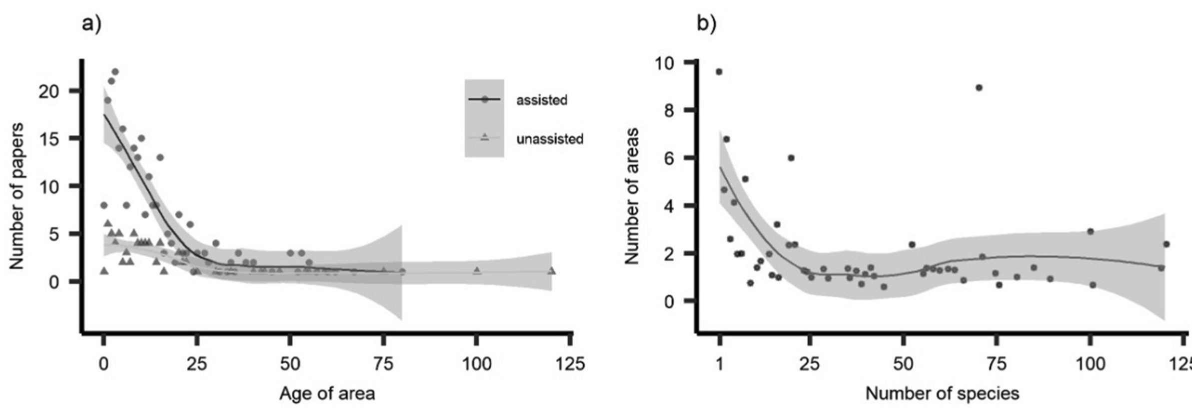


**Fig. 7.** Age of the areas analyzed in the publications on active/assisted and passive/unassisted natural succession techniques (a) and number of species planted in active/assisted natural succession (by direct seeding and seedling plantations) in the area (b) on the restoration of Brazilian biomes.

constitutional right, and the public power will be entrusted with the restoration of ecological processes (art 225, §1, I, Brazil, 1988). The enhancing of scientific production in 2004 (Guan et al., 2018) coincides with the implementation of several legal requirements (for instance, many CONAMA resolutions that defined parameters for restoration; Brazil, 2005) and the increased public investment in science (Massarani, 2013). This pattern coincides with the increasing growth of restoration efforts in other countries and ecosystems (Zhang et al., 2010; Oliveira and Engel, 2011; Wortley et al., 2013). However, a peak in 2016 coincides with number of publications in ecology and biodiversity in Brazil, despite the drastic decline in funding that could also impact biodiversity conservation (Fernandes et al., 2017; Overbeck et al., 2018).

Our study confirmed that the Atlantic Forest, with 56% of the total, has been the main focus of ecological restoration studies in Brazil (Oliveira and Engel, 2017). This biome is one of the most biologically diverse forests on Earth and one of the most degraded, with 28% of the natural vegetation remaining (Rezende, 2018) and ~70% of the population living within its borders (Ribeiro et al., 2009). Much of this large representation of the Atlantic Forest in all the studies is owing to the region, where the largest number of research centers and universities, including the state of São Paulo, have been established, which have boosted the training of researchers and scientific production in ecological restoration (Isernhagen et al., 2017; Sansevero et al., 2017). In addition, the São Paulo state was a pioneer in creating a state resolution for ecological restoration, which possibly spurred many studies (Brancalion et al., 2010). In the Amazon (22% of studies), the second more studied Brazilian biome, studies have been conducted by some important research centers, many of which collaborate with foreign teams. As it is an important center of biodiversity and ecosystem services globally, a significant contribution of research resources has been received in recent years (Strand et al., 2018). In the Cerrado, (16%) the number of studies on ecological restoration contrasts with its large dimension, as it is the second-largest Brazilian biome. We observed a very large gap in the remaining biomes, Caatinga (4%), Pampa (1%), and Pantanal (< 1%) which shows the need for additional research efforts. Specifically in the Pantanal, the number of studies is congruent with its extension (2% of Brazilian territory) and conservation status (> 80% of natural vegetation left; Roque et al., 2016), and thus, only 1.1% of Brazil's restoration liabilities in this biome (Brazil, 2017a; MMA, 2017; Garcia et al., In Press). However, considering its high potential of increasing natural and anthropic threats and low potential for natural regeneration (Pott et al., 2018; Lourival et al., 2019; Garcia et al., In Press; Guerra et al., 2020), research of alternative restoration practices should be encouraged (Tomas et al., 2019). In general, we also observed that few studies were conducted in non-forest environments, mainly in the Caatinga and Pantanal, but also in the Cerrado and Pampa. Despite some global large scale restoration initiatives, such as the Bonn Challenge, focusing on trees and forests, there is increasing scientific encouragement for restoration of non-forest ecosystems, which are important reservoirs of biodiversity and ecosystem services (Overbeck et al., 2015; Kollmann et al., 2016; Temperton et al., 2019).

Studies on ecological restoration in Brazil are mainly characterized by the monitoring of the restoration area for the advanced regeneration, which is usually effective for reducing costs of future interventions (Viani et al., 2017). Less than a third of the studies analyzed used a reference area and, among them, fewer used negative and positive references. However, reference ecosystems are useful models for planning, monitoring, and conducting restoration areas (SER, 2002). These models, mostly positive, are commonly used to assess the success of the restoration (Wortley et al., 2013).

The types of degradation that occurred before the restoration were related to the economic activities in each region, as seen by our results. In the Amazon, logging has been cited for years as a threat to forest composition and structure (Veríssimo et al., 1992; Johns et al., 1996; Holdsworth and Uhl, 1997; Cochrane and Schulze, 1999; Cochrane et al., 1999; Gerwing and Farias, 2000). In Caatinga, logging has caused more damage to woody vegetation than migratory agriculture itself (CAR, 1985). Agriculture and cattle raising represent about 20% of the Brazilian GDP (CEPEA, 2015) and are known as one of the main causes of conversion of natural vegetation (Castro, 2005), seen in the Atlantic Forest and Cerrado.

The initial conditions for restoration can vary from areas with high regeneration potential to severely degraded areas, with no conditions to initiate adequate autogenic processes (Aide et al., 2000). Hence, choosing the correct intervention technique is a determinant for the success of the restoration (SER, 2002). Our data indicate that most of the techniques used are actively assisted succession and this may be associated with the the lower-cost (Crouzeilles et al., 2017), since predominant low regeneration potential found in the Atlantic Forest (59% of areas that requires future restoration interventions; Brazil, 2017b). Sowing and planting of seedlings is the most active/assisted natural succession technique (Wortley et al., 2013; Palma and Laurance, 2015) and predominates in biomes with among half of areas as low regeneration potential such as the Amazon and Caatinga. In addition, biomes are submitted mainly to a natural regeneration contrast with their regeneration potential: low for most anthopogenic areas in Cerrado and in Pantanal (90% and 54% respectively) (Brazil, 2017b). Similar to this, sowing may be associated with the Pampa biome owing to the nature of its vegetal component, which is mostly herbaceous vegetation and comes from a large seed bank, but still poses as a challenge with most grassland species for seedling production (Overbeck et al., 2013).

Our study revealed that studies were focused mainly on the restoration of the arboreal component of the ecosystem (81%) and few studies focus on other life forms and organisms. Despite this tendency being observed worldwide (Young, 2000; Garcia et al., 2016; Mayfield, 2016) and the evaluation of the vegetation structure being one of the most accessible and efficient ways to indicate restoration success (Wortley et al., 2013), the use of multiple indicators may be much more appropriate to understand the ecological complexity in the restoration process (Barton and Moir, 2015). Furthermore, some taxonomic groups not included in the studies (for instance, amphibians and aquatic organisms such as fish, algae, benthos, phytoplankton, and zooplankton) should be much more sensitive to capture the functionality of the restored ecosystem (Baldigo et al., 2008; Parmar et al., 2016; Klimaszewski et al., 2016). Finally, less than one-third of studies are mentioned or used soil features/conditions, but we highlight that the restoration of soil quality should be incentivized since Brazil was identified as a second soil erosion hotspot (Borrelli et al., 2017).

The studies were also characterized by study areas less than 10 years of age, which is in accordance with the increased restoration initiatives in the last 30 years (Rodrigues et al., 2009). Our results show that almost a quarter of the studies use fewer than ten planted species, which can be considered a low initial species richness, depending on the restoration objectives as discussed by Durigan et al., 2010; Brancalion et al., 2010, Aronson et al., 2011. The diversity of species in the restoration process can be a key factor to obtain the ecological complexity (Rey-Benayas et al., 2009) and should be considered for the restoration of Brazilian biomes.

## 5. Conclusion

Brazil has been considered a key country for achieving global restoration goals as it concentrates some of the largest centers of biodiversity and ecosystem services in the world. Owing to these characteristics, it has become a pioneer country in the legal regulation of restoration activities, which has resulted in a significant increase in studies over the past 15 years. Although this trend has been significant, knowledge gaps in some biomes and limitations in using some techniques show the need for a breakthrough in knowledge towards the 12-million-hectare target to be met. Currently, when the financial crisis in Brazilian science and dramatic advance in the destruction of ecosystems take on unimaginable dimensions, we anticipate that there are no guarantees in filling gaps and meeting restoration goals.

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## Declaration of Competing Interests

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

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.117802.

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