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REVIEW ARTICLE

Historical trajectory of restoration practice and science across the Brazilian Atlantic Forest

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Restoration is fundamentally a hopeful intervention that can meaningfully improve the condition of human-degraded and destroyed ecosystems. Both restoration science and practice have gained special attention given the recently declared UN Decade of Ecosystem Restoration. Here, we present an overview of the historical development of forest restoration on the Brazilian Atlantic Forest with an emphasis in methodological and technical assumptions. We gathered information from primary and secondary studies to show how forest restoration concepts and strategies evolved over the years. Given the importance of reviews for informing management and policy as well as research, our study provides a summarized information on forest restoration approaches or practices that can help practitioners and non-initiated to understand how this field evolved in Brazil and how lessons learned can be useful for forest restoration in other countries.

Key words: conceptual synthesis, ecological restoration, restoration phases, restoration synthesis, trends, tropical forest, tropical region, UN Decade of Ecosystem Restoration (2021–2030)

Implications for Practice

- Lessons learned in the Brazilian Atlantic Forest can be useful for more effective decisions across different ecosystems and socioeconomic and ecological contexts around the world.
- Functional traits and evolutionary relationships among co-occurring species provide means of ensuring restoration efforts in terms of delivering target ecosystem services and overcoming environmental filters.

Introduction

Restoration practice—the process of assisting the recovery of a certain ecosystem that has been degraded, damaged or destroyed (SER 2004)—has ramped worldwide (Pape 2020). The United Nations General Assembly's declaration of 2021–2030, also called "UN Decade on Ecosystem Restoration" represented a turning point for global movement (Dhyani et al. 2020; Romanelli et al. 2020). The decade is a call for the protection and recovery of ecosystems for the benefit of people and nature, aiming to counteract land degradation, and achieve global sustainable goals. There are optimists' and even skeptics' points of view regarding how meaningful such a declaration will be on global pledges (Cooke et al. 2019; Young & Schwartz 2019; Dudley et al. 2020). Nevertheless, ecosystem restoration is expected to support global conservation efforts for local development and economic sustainability (Aronson & Alexander 2013; Aronson et al. 2020; UNEP & FAO 2020), and awareness of the importance of functional ecosystems for human well-being (UNEP & FAO 2020; Aronson et al. 2020); in accordance with the sustainable development goals, addressing issues related to water security, climate crisis, food, biodiversity loss, good health, and well-being.

Although the decade is aimed at all kinds of ecosystem restoration (UNEP & FAO 2020), much of the emphasis of publicity surrounding the declaration has been on degraded or converted forests (Dudley et al. 2020; Holl & Brancalion 2020). Forests occupy a center stage in global debates mainly because of aspects related to carbon removal and biodiversity conservation (Erbaugh et al. 2020) and also due to the wide range of human-induced disturbances they suffer (Nunez-Mir et al. 2015). Consequently, many forest ecosystems display reduced functionality and productivity and species loss, besides reduced delivery of ecosystem services (ES; Wenhua 2004; Nunez-Mir et al. 2015).

An ambitious forest restoration agenda has been set globally (Holl et al. 2020) and motivated by varied goals (Suding

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et al. 2015; Chazdon et al. 2016). As a mechanism of land and resource management, the "forest landscape restoration" (FLR) has been proposed as a management practice to promote restoration and human well-being (Erbaugh et al. 2020). However, competing definitions of FLR exist (Mansourian 2018), and debates rely on the lack of conceptual clarity as to how this approach can achieve such objectives (Stanturf et al. 2019).

The majority of current restoration targets come from developing countries in the global South (Fagan et al. 2020). In Latin America, for example, a total of 170 Mha of FLR were pledged as part of the Bonn Challenge, including commitments from 13 neotropical countries (Brancalion et al. 2019; Chagas et al. 2020). Brazil in particular made an ambitious pledge of 12 Mha of native vegetation recovery as a contribution to the Bonn Challenge global target (www.bonnchallenge.org). This restoration commitment is also part of Brazil's pledge to the Paris Climate Agreement and its National Policy for Native Vegetation Recovery. Moreover, the Atlantic Forest Restoration Pact (AFRP), created in 2009 as a movement to restore 15 Mha of degraded/deforested lands by 2050, pledged 1 Mha toward the 2020 Bonn Challenge (Crouzeilles et al. 2019). The increasing forest cover already reached in the Brazilian Atlantic Forest (BAF) brings optimism for the achievement of global restoration commitments in the next years (Rezende et al. 2018; Crouzeilles et al. 2019).

Forest restoration in the BAF has a long history (Rodrigues et al. 2009*b*). This natural laboratory' has contributed fundamentally to a better understanding of the history and restoration research of tropical forests (Romanelli et al. 2018) and the extent to which this irreplaceable biota is susceptible to major human disturbances (Joly et al. 2014). Originally, the Atlantic Forest covered an area of 1.6 Mha (Muylaert et al. 2018), and it hosts one of the world's most diverse and threatened biodiversity (Oliveira-Filho & Fontes 2000; Scarano 2009). After five centuries of colonial imperialism, most Atlantic Forest landscapes are fragmented by small forest patches surrounded by open-habitat matrices (Joly et al. 2014). However, the local socio-political issues, including land ownership disputes, deforestation pressures, policy implementation inconsistencies, limited funding, conflicts between biodiversity conservation and economic growth, integration of indigenous knowledge, and vulnerability to political changes, greatly increase the challenge of any restoration project, given they are both related to the causes of degradation and the success of restoration simultaneity (Rodrigues et al. 2009*b*). To tackle these challenges successfully, effective restoration strategies must engage stakeholders, cultivate policy coherence, and embrace adaptive approaches that harmonize ecological and societal concerns.

More than 40 years have passed since the emergence of the field of restoration ecology. In this time, restoration science and practice have been evolving, shifting, and developing new foci (Oliet & Jacobs 2012). Changing demands at the social, economic, and ecological levels (DellaSala et al. 2003; Nunez-Mir et al. 2015), along with emerging challenges, such as those associated with climate change (Jalili et al. 2010; Stanturf et al. 2014), required the simultaneous and reciprocate evolution of the field. Thus, the importance of reassessing the theoretical and practical underpinnings of restoration through the prism of rapid environmental changes becomes increasingly evident (Hobbs & Cramer 2008; Nunez-Mir et al. 2015).

Through a narrative synthesis, we summarize the evolution of forest restoration science and practice across the BAF. By sharing the Brazilian experience, we aim to contribute to more universally applicable insights into forest restoration in other tropical ecosystems. Our synthesis begins by elucidating overarching research trends and progressively narrows to the Brazilian context, succinctly delineating methodological advancements, ecological applications, and research outcomes across five discernible phases. Ultimately, our narrative concludes by succinctly exploring the broader international implications stemming from the insights garnered from the BAF restoration, imparting valuable cross-disciplinary lessons.

Forest Restoration in the BAF: Evolution of Methods, Concepts, and Research

The field of restoration ecology is relatively recent (Harrington 1999; Young et al. 2005). The further unearthing of the origins of ecology can be used as a historical landmark for the identity of restoration ecology in the twentyfirst century (Gross 2007). Ernst Haeckel is well-known for originating the science of ecology and some of his ideas converge to tighten the link between the current science and practice of ecological restoration (Gross 2007). Thus, much of basic and applied research in ecological restoration draws from established principles and concepts raised in ecology (Young et al. 2005).

The realm of restoration is divided into *restoration ecology* as the science of ecology and *ecological restoration* as the overall practices, including esthetic and economic factors, and other social dimensions (Eden & Tunstall 2006; Keulartz 2007). Echoing Murphy et al. (2018), the origins of these terms are hard to track accurately. The term *restoration* was reported in the early 1940s in documents relating to Dekalb County, Illinois, and notes from George Ward and Paul Shephard at Knox College in 1954 (Murphy et al. 2018). Nonetheless, only at the end of the 1970s, restoration ecology started to emerge as a formal research field in Brazil (Fig. 1; Rodrigues et al. 2009*a*). Since the foundation of Society for Ecological Restoration (SER) in 1988, this international nonprofit organization has been serving as a foundation for the development of the field by promoting the science and practice of ecological restoration around the world (Fig. 1; Clewell & Aronson 2013). In Brazil, the Brazilian Society for Ecological Restoration (SOBRE, the acronym in Portuguese) emerged in 2014 aiming to promote debates, technical collaboration, and exchange of experiences between different actors involved in ecological restoration efforts. Ecology faced a scientific revolution from older paradigms of succession, climax, and balance of nature, amid the agitation for environmental preservation and discussions about human-nature dichotomy (Caillon et al. 2017). These thinking chains were present when ecological restoration started to take shape, emerging as an alternative to account for socioeconomic issues, frame sustainable economic development, and preserve biodiversity (Clewell & Aronson 2013). A significant portion of the fundamental and practical

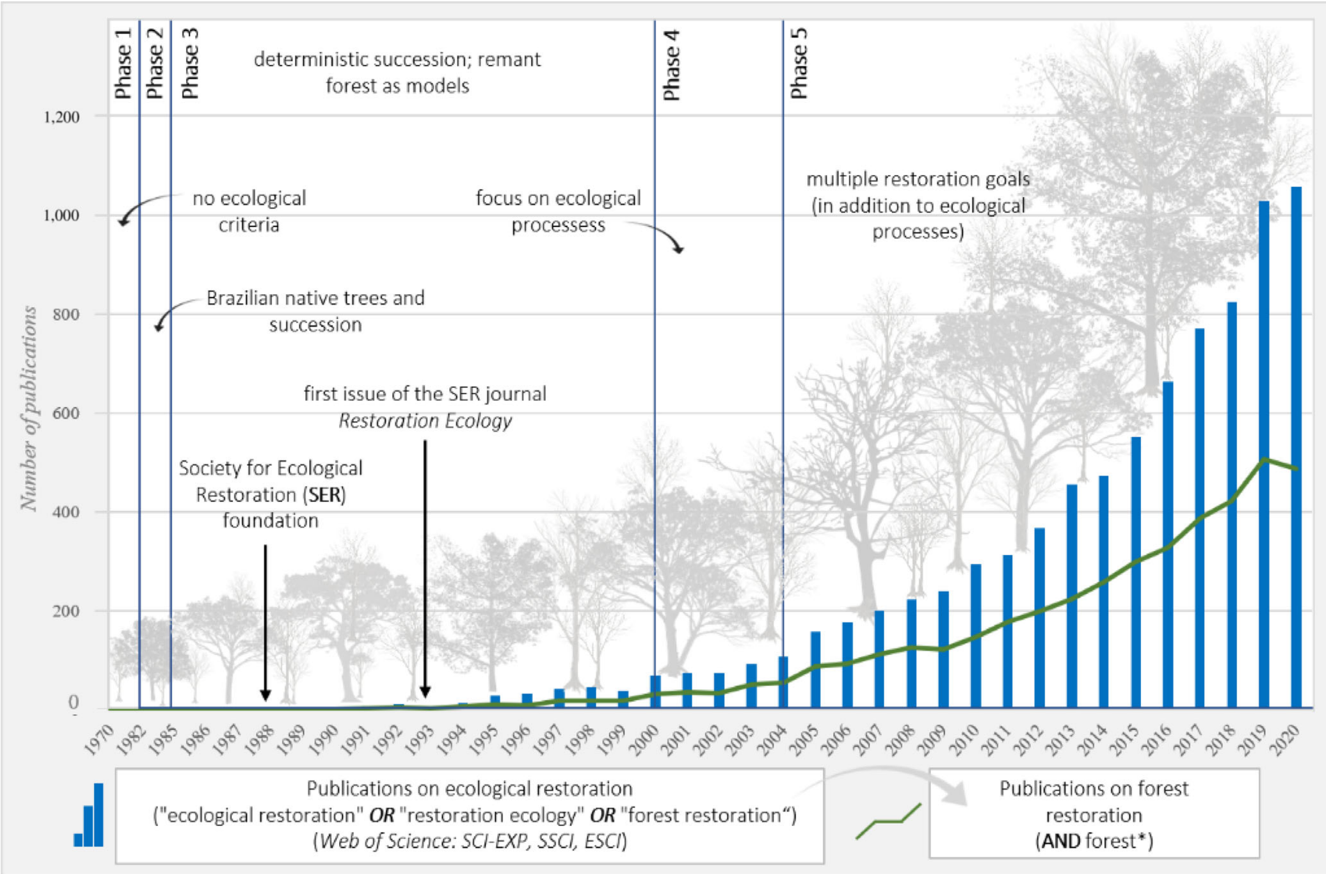

Figure 1. Total publications from Web of Science involving ecological restoration research from 1970 to 2020 and association to the growth trends on forest restoration research separated into five phases. Bars refer to global ecological restoration research. Green line refers to global forest restoration research. Phases relate to Brazilian research.

research within restoration ecology has predominantly revolved around botany, likely due to the prominent role of plants in natural communities and as the foundational components of most ecosystems (Young 2000). This emphasis is unavoidably mirrored in our review.

Over the past three decades, forest restoration has gained a strong academic foothold, addressing several different problems faced by restoration practitioners (Young et al. 2005; Guan et al. 2019). During this period, the discipline has transitioned from a fledgling niche topic to a globally recognized, scientifically based solution for humans to respond to damaged and destroyed ecosystems (Romanelli et al. 2018). Currently, restoration is part of the international trend toward "nature-based solutions." However, restorationists (e.g. scientists and practitioners) also have gone through a period of academic soul-searching, trying to discover and develop conceptual bases for the emerging science (Young 2000; Young et al. 2005). The evolution of forest restoration practice and science has become a necessary process due to shifting socioeconomic and ecological demands, coupled with the rapid pace of global change (Oliet & Jacobs 2012; Stanturf et al. 2014). The restoration goals changed and new techniques have been developed based on the best practices (Rodrigues et al. 2009*b*; Brancalion et al. 2015, 2016). Restoration ecology is indeed not only rising in prominence but also evolving and expanding in its focus to address emerging issues and challenges (Romanelli et al. 2018). In this process, it is possible to recognize phases for the Brazilian forest restoration since the early 1970s by analyzing trends in the indexed literature across worldwide and different time-spans (Romanelli et al. 2020). Although arbitrarily defined, we discussed and established so-called "restoration phases" based on previous researches (Rodrigues et al. 2009*a*, 2009*b*; Durigan & Melo 2011; Chaves et al. 2015) and academic trends, which can represent a useful simplification to understand the history of the application of the concepts in the field (Rodrigues et al. 2009*a*, 2009*b*). Thus, a proposal for dividing the restoration trajectory over time into phases is presented for the BAF, which may also be useful to understand the development of forest restoration science and practice from a broad perspective. This study conducted a bibliometric analysis on restoration of BAF research from 1970 to 2020 to understand the development of this field through the time and its association to the growth trends on forest restoration research separated into five phases. The search was made by using the Web of Science and Scopus as bibliographic sources (see Supplement S1 for details).

Phase 1 (Until 1982): No Ecological Criteria for Selecting and Combining Species

The three oldest documented forest restoration initiatives in Brazil were all motivated by the need to recover ES, long before this concept was coined in the specialized literature (Chaves et al. 2015). The first project began in 1861, and focused on the headwaters of the watershed that has become the Tijuca National Park, in Rio de Janeiro (Drummond 1996) at a time of rampant deforestation (Calmon et al. 2011). That restoration was implemented in order to protect and augment vegetation cover around natural springs, along streams and degraded lands by coffee plantations, envisioning the provision of drinking water (Calmon et al. 2011). This effort would become the first forest restoration project, at least in the tropics (Rodrigues et al. 2009*a*). The second project, initiated in 1955, aimed to restore 26 ha of riparian forests on land belonging to the sugarcane company Usina Ester, in Cosmópolis, São Paulo (Chaves et al. 2015). The third project, starting in 1972, was intended to restore 20 ha of a riparian forest at Cananeia Farm, Cândido Mota, São Paulo (Suganuma et al. 2014). These projects and other reforestation initiatives aiming to protect the reservoirs of the São Paulo Power Company and the Itaipu hydroelectric power plant were motivated by the need to protect water resources (Durigan & Melo 2011).

All these so-called "protection plantings" (Kageyama & Castro 1989; Rodrigues et al. 2009*a*), in that date established with no ecological criteria, characterizes this phase which we considered to start in 1861 and became more pronounced after the 1970s. At that date, mixed plantations with no experimental purposes did not allow inferences to be drawn about species interaction and on the effectiveness of techniques employed. Such projects were restricted to the use of exotic (i.e. *Pinus*, *Eucalyptus*, and jackfruit in the case of reforestation in Rio de Janeiro) and native tree planting, pure or mixed with low diversity, mainly intending to recreate a forest cover (Schweizer et al. 2015).

Phase 2 (1982–1985): the Planting of Brazilian Native Species Based on Forest Succession

Ecological processes, important for forest self-maintenance and sustainability were largely ignored in phase 1, and ecological criteria for the selection of species were not considered at that time. Consequently, forest physiognomies were restored, but with no capacity of perpetuating themselves (Rodrigues et al. 2009*b*). Several pioneer species reached adult age and died quickly, leaving the plant community, becoming a non-favorable environment for the establishment of non-pioneer species. Thus, many projects with these characteristics declined after approximately 10–15 years (Barbosa et al. 2003), since they were based on reforestation practices and not restoration practices. Although some projects did result in permanent forests (e.g. Mariano et al. 1982), they often required long-term maintenance activities and high costs (Rodrigues et al. 2009*a*).

Facing difficulties in conceiving, and carrying out these pioneering large-scale projects, researchers in Brazil started to develop restoration models that mimicked species turnover based on successional patterns, but now with a focus on greater diversity of native tree species and ecological strategies (Kageyama et al. 2008). Without technical or scientific support, many companies established partnerships with universities and research institutions to support restoration projects (Chaves et al. 2015). It is important to emphasize that ecological knowledge about native species was being studied in Brazil, what is not the case for many other countries, where little ecological research is conducted.

Brazil promulgated a series of legal instruments during the twentieth century to support the sustainable use of the forests. The Forest Code in 1934 (Decree #23793/1934) was the first one. Through this legal instrument, it was enacted that all native forests were of public interest, and rural properties were required to preserve forests to benefit society. Nonetheless, due to the lack of precision in the law's definitions and difficulties on compelling its observance, a revised version of the Forest Code was established in 1965, (Law #4771/1965)—which defined the areas for permanent preservation and eventually restoration (areas of permanent preservation) and the additional minimum percentage of forest cover that should be set aside as Legal Reserve, which could be explored for sustainable timber harvesting. In 1981, the National Environmental Policy (Law #6938/1981) stated that large private companies should compensate for the deforestation caused by their activities (mainly hydroelectric and mining companies) through restoration of degraded lands, as part of offsetting policies. This has been detailed extensively elsewhere (e.g. Pinto et al. 2014).

We found that one of the first published studies associating the performance of tree species and restoration models date to the early 1980s (Hessing & Johnson 1982). Important and seminal studies regarding forest succession in this period go back to the work of Tilman (1985) published in *American Naturalist*, Finegan (1984) in *Nature*, and Christensen and Peet (1984) in *Journal of Ecology*. In Brazil, the pioneer studies of Gurgel-Filho et al. (1982) and Nogueira et al. (1982) also started to bring light on silvicultural characteristics and competition between native species of the Atlantic Forest. Restoration practitioners then start using a few fast-growing species in their projects (maximum 30 species), planted in high density, with low biological and functional diversity (Rodrigues et al. 2009*a*). From this phase on, the planting of Brazilian native species became widespread, even though they were not always regionally native from the restored area (i.e. they were native from Brazil but from other regions or biomes) (Brancalion et al. 2015). For the first time, genetic issues started to be discussed in the context of the succession of forest native species (Kageyama & Castro 1989).

Phase 3 (1985–2000): Deterministic Succession Based on the Floristic and Structural Copy of Forest Remnants

During this phase, the Brazilian Constitution of 1988 was enacted, after 21 years of dictatorship, returning to democracy. To strengthen environmental protection, the Brazilian Federal Constitution established that public authorities must actively promote the restoration of ecological processes in order to secure a healthy environment for people. As a consequence, new legal instruments were created, favoring restoration in the Atlantic Forest. In 1998, the Environmental Crimes Law (Law # 9605/1998) established penal, civil, and administrative penalties for environmental crimes performed by individuals and companies, and stated forest restoration as a legal obligation for farmers and private companies (Durigan & Melo 2011). Yet, these restoration projects were reactive measures to compensate for damage rather than a proactive measure to assist recovery, enhance ecosystems, and improve land use and livelihoods.

Atlantic Forest restorationists started to consider the restoration trajectories and their endpoints in this phase (Joly et al. 2000), in synchrony with the international literature on the theme (Brown & Lugo 1994; White & Walker 1997), and calls for more attention in understanding the forecasting trajectories of restoration (Shugart 1989). In this period, restoration trajectories were already considered as the structural and functional attributes of sites relative to reference conditions, and the time required to obtain a restored state or condition (Twilley et al. 1998).

Therefore, by the end of the 1980s, projects were carried out based on "mixed native species plantations," envisioning to copy the composition and structure of natural forests (Brancalion et al. 2015). The most commonly used restoration strategy from this time was "modules of planting," a combination of plant species according to their ecological groups (i.e. light requirements, humidity, or nutrition) (Rodrigues et al. 2009*b*). Many projects conducted under these biases resulted in self-sustainable restoration projects, at least regarding forest structure (Souza & Batista 2004). The conservation and restoration of riparian forests also received special attention in this phase (Rodrigues & Gandolfi 2000).

Phase 4 (2000–2004): Focus on the Ecological Process in the Plant Community

Gradually transitioning from the 1980s to the 1990s and the early 2000s, forest restoration approaches predominated with great emphasis on phytosociology, and also on secondary succession as the basis for the implementation models (Rodrigues et al. 2009*a*; Oliveira & Engel 2011, 2017). Phase four still has a few indexed publications on forest restoration in the Atlantic Forest (Fig. 1). However, important concepts were introduced in the international restoration literature that started to influence practitioners in Brazil, such as the "assembly rules" (Temperton et al. 2004) and the concept of "ecological filters," as part of this theory (Keddy 1992; Götzenberger et al. 2012). Nevertheless, it has only been at the end of this phase that studies linking assembly rules theory to restoration ecology made progress (e.g. Moir et al. 2005; Funk et al. 2008), developing stronger linkages between these fields (Audino et al. 2017).

The focus on the assembly rules started the debate on the factors that affect the development of the regenerating community in a given ecosystem, considering both the interaction of the environment with the organisms in a community and on the interactions among organisms (Lockwood et al. 1997; Temperton et al. 2004). The concept of ecological filters, in turn, inaugurated the understanding of how species colonize new habitats by overcoming biotic limitations or limiting factors (Temperton et al. 2004; Moir et al. 2005). In practice, concern about keeping the high species diversity in restoration projects remained in force, as well as aspects such as the floristics and environmental conditions of the target region and species light requirements (Engel & Parrotta 2001).

Phase 5 (2004–Today): Multiple Restoration Goals

This phase comprises the current efforts on forest restoration science and practice across the BAF. In the political context, environmental laws changed in 2012 in Brazil with the revision of the Forest Code, now Law of Native Vegetation Protection (Law #12651/2012) (Garcia et al. 2013; Pinto et al. 2014). Academically, restoration science has developed a broad and diversified body of literature since 2004, although only after 2011 it has gained prominence in international indexed journals (Romanelli et al. 2018, 2020). In the last two decades, restoration has been receiving increasing attention because of its role in biodiversity conservation (Scarano & Ceotto 2015), the provisioning of ES (Nogueira Júnior et al. 2014), and compliance with socioeconomic (Viani et al. 2017) and cultural values (Brancalion et al. 2014).

Since the 2000s, several small-scale forest restoration initiatives have sprung up in the BAF as a result of the growing involvement of environmental non-governmental organizations (NGOs), farmers (forced by the Forest Code), and private companies—also forced by biodiversity offsetting policies, certification, and market benefits (Wuethrich 2007; Pinto et al. 2014). However, for several reasons (Pinto et al. 2014), the involvement of these three above-mentioned groups did not result in a significant enlargement of native forests. Failures in monitoring restoration forests and "openings" in public policy and enforcement culminated in poorly designed tree plantations (Maron et al. 2012; Pinto et al. 2014).

Seeking to overcome general problems that were preventing effectively scaling-up of restoration in the BAF, a group of NGOs and researchers got together in 2006 and created a coalition to foster large-scale forest restoration. The AFRP was officially launched in 2009, with the goal of restoring 15 Mha of the BAF by 2050, promoting biodiversity conservation, jobs services and income generation, the provisioning and maintenance of ES, and supporting farmers to comply with the Forest Code through the 17 Brazilian states when the Atlantic Forest occurs (Pinto et al. 2014). After the pact was launched, the coalition was committed to elaborate a multifaceted monitoring protocol, envisioning restoration success in terms of ecological, socioeconomic, and management aspects (Viani et al. 2017).

Diversity-focused approaches continue to be a central issue (Guan et al. 2019; Dimson & Gillespie 2020) in that phase. With the continuous deepening and broadening of practice, many problems are exposed; thus, improving existing approaches and developing new ones remain in force. Identifying the factors driving the success of restoration projects, or even defining what success is, in relation to a multi-dimensional context also continues to be challenges in ecological restoration (Suganuma et al. 2018). Topics related to *monitoring*, *ecological indicators*, *active restoration*, and *natural regeneration* appeared numerous times across recent publications from this phase (Fig. 2), which can further be associated with the importance of such processes in evaluating the restoration progress and taking adaptive management measures (Londe et al. 2020).

Assessing the conservation value of restoration projects by monitoring areas and improving strategies is also critical to support *large-scale restoration* (Brancalion et al. 2018). Achieving ambitious restoration targets will require minimizing implementation costs and negative outcomes for agricultural production (Molin et al. 2018), as well as be attractive to farmers (Badari et al. 2020). Accordingly, natural regeneration has been discussed steadily in the recent literature, as an effective alternative to achieve restoration commitments (Santos et al. 2019*b*; Borda-Niño et al. 2020). *Agroforestry systems* are also largely discussed and presented as a cost-effective strategy that integrates both production and *biodiversity conservation*, although their capacity to conserve biodiversity and ES provision is still poorly investigated (Santos et al. 2019*a*; Brancalion et al. 2020).

The approach of FLR is also at the forefront of Atlantic Forest's efforts to recover ES, conserve biodiversity, and mitigate the effects of climate change (Silva et al. 2017). This is considered a powerful strategy for large-scale restoration, and payment for ecosystem services (PES) is being used to support FLR programs and projects on privately owned land (Viani et al. 2019). Trade-offs in ES have received increasing attention because provisioning services often come at the expense of biodiversity loss (Marcilio-Silva et al. 2018; Gardon et al. 2020*a*). Thus, PES has been initiated throughout Brazil to encourage forest restoration on private lands, especially smaller properties that are out of compliance with national *environmental policies* requiring conservation of native vegetation (Richards et al. 2020). There is great potential for incorporating biodiversity conservation objectives into restoration projects that can be optimized by adopting a *landscape ecology* perspective in the planning and implementation of ecological restoration efforts (Rother et al. 2018; Viani et al. 2018).

The long-term ecological success of large-scale restoration programs planned for the next decades will also rely on the *conservation genetics* of reintroduced or colonizing species, a limiting factor in highly *fragmented* landscapes. Despite the paramount role of this issue for species persistence, its levels in restoration programs still fall short of optimal inclusion (Zucchi et al. 2018). Moreover, the study of some ecological

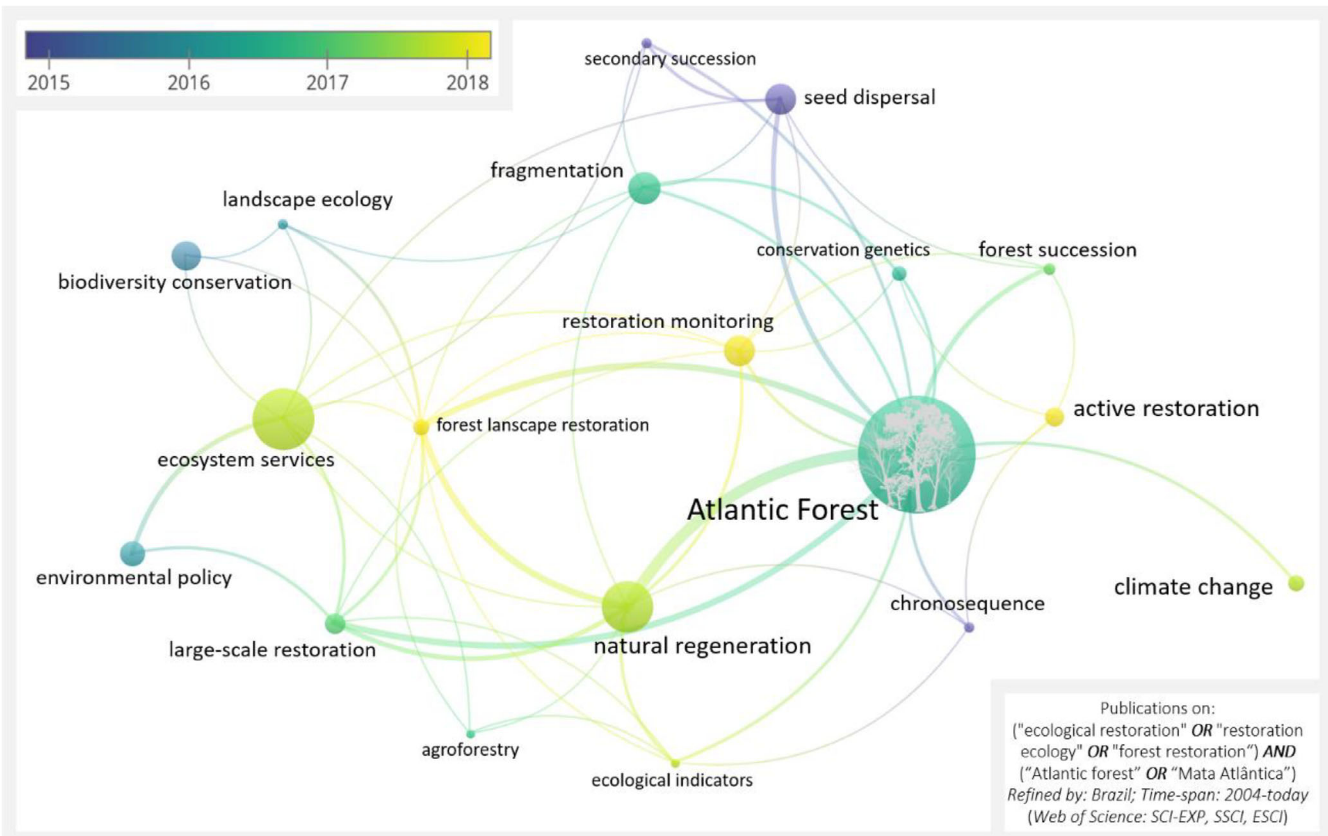

Figure 2. Results of network analysis of the main research topics addressed in studies on forest restoration in the Brazilian Atlantic Forest from 2004 to 2020 in overlay visualization (data collected on December 10, 2020), through the analysis of all keywords (author keywords and keywords plus). Network maps are limited to present keywords with a minimum of five occurrences (the same term or expression). The size of the node is proportional to the number of occurrences, and the thickness of the edges represents co-occurrences between items.

processes remains in force in this phase, such as seed dispersal (da Silva et al. 2015). In recent years, efforts have included utilizing functional traits to select species that offer specific ES during restoration and understanding species' responses to environmental filters (Carlucci et al. 2020; Zupo et al. 2022). Evolutionary relationships between co-occurring species have also been studied to provide insights into trait conservatism and community assembly processes influencing restoration forest trajectory (Schweizer et al. 2015). Additionally, a method involving a mix of native species seeds and fast-growing legumes (green manure) has been employed to overcome challenges like herbivory and invasive grasses (Reis et al. 2019).

In synthesis, several changes have occurred in the Atlantic Forest restoration since the publication of Rodrigues et al. (2009*b*) up to the present. These include pivotal events such as the adoption of the new Forest Code in 2012 (Pinto et al. 2014), the increase in programs that involve PES (Ruggiero et al. 2019), a substantial rise in direct seeding practices (Meli et al. 2018), and more recently, the proliferation of carbon sequestration initiatives (Gardon et al. 2020*b*). Studies published in the last decades collectively contribute to a comprehensive understanding of ecological restoration in the BAF by offering insights into assessing restoration effectiveness, identifying advancements and gaps, proposing strategic approaches, and highlighting research trends and gaps (Strassburg et al. 2018; Mendes et al. 2019; Guerra et al. 2020; Oliveira et al. 2021; Zupo et al. 2022). In light of its comprehensive nature compared to other phases, we have encompassed the period 2004–2022 as a single phase. This final phase is, therefore, characterized by a diverse array of novel approaches that emerged in both practical applications and scientific research within the Atlantic Forest restoration context.

Concluding Remarks

Here, we discussed the speed of evolution of restoration in Brazil and its relative contribution to the restoration science. On a critical view, the historical trajectory of BAF restoration reproduces the environmental adequacy of rural properties to environmental legislation and provision of ES for the population (e.g. public water supply reservoirs) but also an evolution of science and practice to achieve ecological success. The recovery of degraded ecosystems is an old practice around the world (Rodrigues et al. 2009*a*). However, only recently this activity acquired the character of an area of knowledge starting to incorporate knowledge of ecological theories (e.g. processes related to the dynamics of plant communities). In this way, programs for the recovery of degraded ecosystems stopped applying agronomic and silvicultural practices to assume the objective of recovering the complex ecological interactions (Rodrigues & Gandolfi 2004).

From a global outlook, the insights garnered from the BAF restoration journey can be valuable in empowering practitioners and researchers to craft more efficient strategies for rehabilitating forests in comparable biomes. This is applicable even when faced with diverse landscapes, socioeconomic scenarios, and ecological settings, all driven by varying objectives. For instance, it has been observed that relying solely on methods and techniques mirroring preserved forests leads to undesirable consequences, such as restricted biodiversity and compromised ecological resilience. These approaches have fallen short of achieving their restoration goals concerning species composition and structural integrity. Restoration developed in BAF can also influence the global political restoration agenda considering it is one of the few countries to restore on a large scale owing the size, the variety of biomes, the extent of degraded areas and the economic engine in BAF. The academic powerhouse with many masters and PhD students focused on restoration in Brazil is another important reason. Such characteristics give to Brazil a considerable contribution to the global restoration agenda. On the other hand, some fundamental disciplines to support goals and the implementation of international agendas are still poorly applied in the Brazilian restoration interventions. Human dimensions (i.e. gender equality and social inclusion), for example, need to be prioritized in the national restoration strategies and action plans.

In conclusion, the BAF restoration approach provides significant insights for restoration efforts in diverse biomes. Moving beyond basic reforestation, emphasizing natural regeneration at more resilient regions, and promoting self-sustaining ecosystems can enhance restoration effectiveness and reduce costs. The legal framework, represented by the "Código Florestal," supports and encourages the promotion of transparent reporting, adaptive management, and inventive solutions. Nevertheless, challenges persist, encompassing the continuous monitoring of ecological benchmarks, ensuring open reporting practices, and innovating outcome evaluation technologies. Achieving successful restoration outcomes mandates effective communication, seamless integration, and unwavering commitment to resilience and self-sustainability principles. This is especially pivotal in light of the escalating global investments in forest restoration.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Limitations of the study.

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