



Structural Hurdles to Large-Scale Forest Restoration in the Brazilian Amazon

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INTRODUCTION

Since August 2019, pictures of Amazonia in flames have received global attention and drawn the attention of international media, governments and nongovernmental organizations (NGOs) toward exponentially increasing deforestation rates, highlighting the need for innovations for sustainable development of the region to mitigate global climate crises and threats to biodiversity (Lovejoy and Nobre, 2019). The scientific community claims that for Amazonia 4.0, i.e., an emerging bioeconomy valuing biodiversity by aggregating new technologies and possibilities such as cyber-physical systems, internet of things, communication networks and artificial intelligence with the socioenvironmental resources of the Amazon region, large-scale forest restoration is required to prevent the world's largest tropical forest from collapsing (Levis et al., 2020). More than 60% of the Amazonia rainforest is contained within Brazil; thus, the country plays a key role in this biome's future.

The forest landscape restoration concept extends beyond pure ecological restoration, i.e., the restitution of biodiversity and ecosystem structure and functioning to original, old-growth forest levels (Mansourian et al., 2017), to include agroforestry systems, tree plantations and further initiatives to reconstitute the forest canopy (Stanturf et al., 2014) aiming to link ecological needs to enhance biodiversity and ecosystem services with the economic demands of local communities and land owners (Celentano et al., 2017; Urzedo et al., 2020a). Although carbon sequestration is often the primary driver of contemporary forest restoration (Griscom et al., 2020), further co-benefits emerge for air purification, water management, biodiversity and income possibilities, especially when native species are used (Lewis et al., 2019; Nunes et al., 2020). Income possibilities refer to income generated through supply chains, payments for ecosystem services (PES), and the trade of products from agroforestry systems. By integrating and amplifying the number of trees in gardens, farms or forests, these silvicultural activities aim to reverse soil and land degradation, increasing the productivity and functionality of the entire landscape (Besseau et al., 2018). Given these multiple benefits, forest landscape restoration initiatives have been frequently included in corporate sustainability strategies to achieve carbon neutrality and demonstrate social and environmental commitment (Seymour, 2020).

Despite the recognition of socioeconomic and environmental benefits, global movements to valorize restoration as part of climate change mitigation activities and successful implementation of small- to medium-scale forest restoration projects (Rodrigues et al., 2019), the Amazonian forest cover has steadily declined, and forest restoration is restricted to single initiatives. Weak governance is considered one of the underlying reasons, but a set of technical and socioeconomic issues further impede large-scale restoration in the Amazon. In addition to noncompliance of rural properties with environmental legislation, labor and capital-intensive forest implementation, insufficiently structured markets for diversified silviculture, knowledge gaps and logistic difficulties represent further forest restoration barriers in the Amazon

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(Nunes et al., 2020) (**Figure 1**). Here, we address these structural hurdles to overcome challenges and achieve large-scale forest restoration in the Brazilian Amazon.

STIMULATING LEGAL COMPLIANCE OF RURAL PROPERTIES

Private rural properties account for 53% of the entire Brazilian territory (Soares-Filho et al., 2014), most of it within properties larger than 1.500 ha (Costa et al., 2018), highlighting their importance for the protection of biotic resources. Environmental legislation in the Brazilian Amazon (Federal Law 12,651/2012, known as the Brazilian Forest Code) includes two main instruments to protect native vegetation in private rural properties: permanent preservation areas (APPs, in Portuguese) and Legal Reserves (RLs, in Portuguese). APPs include ecologically sensitive riparian vegetation, springs, steep slopes or hilltops where only low-impact activities such as ecotourism are allowed. The forest restoration obligation for APPs depends on the type of APP and features such as river width and property size. In RLs, which are designed to promote the sustainable use of timber and non-timber forest resources, the forest canopy must be maintained. RLs account for 80% of the Amazonian property area, but forest restoration may be required in only 50% of the property area if certain conditions are met or even less for small properties. Despite past incentives for environmental regularization, e.g., programs established by the International Climate Fund, the German Development Bank (KfW) or the

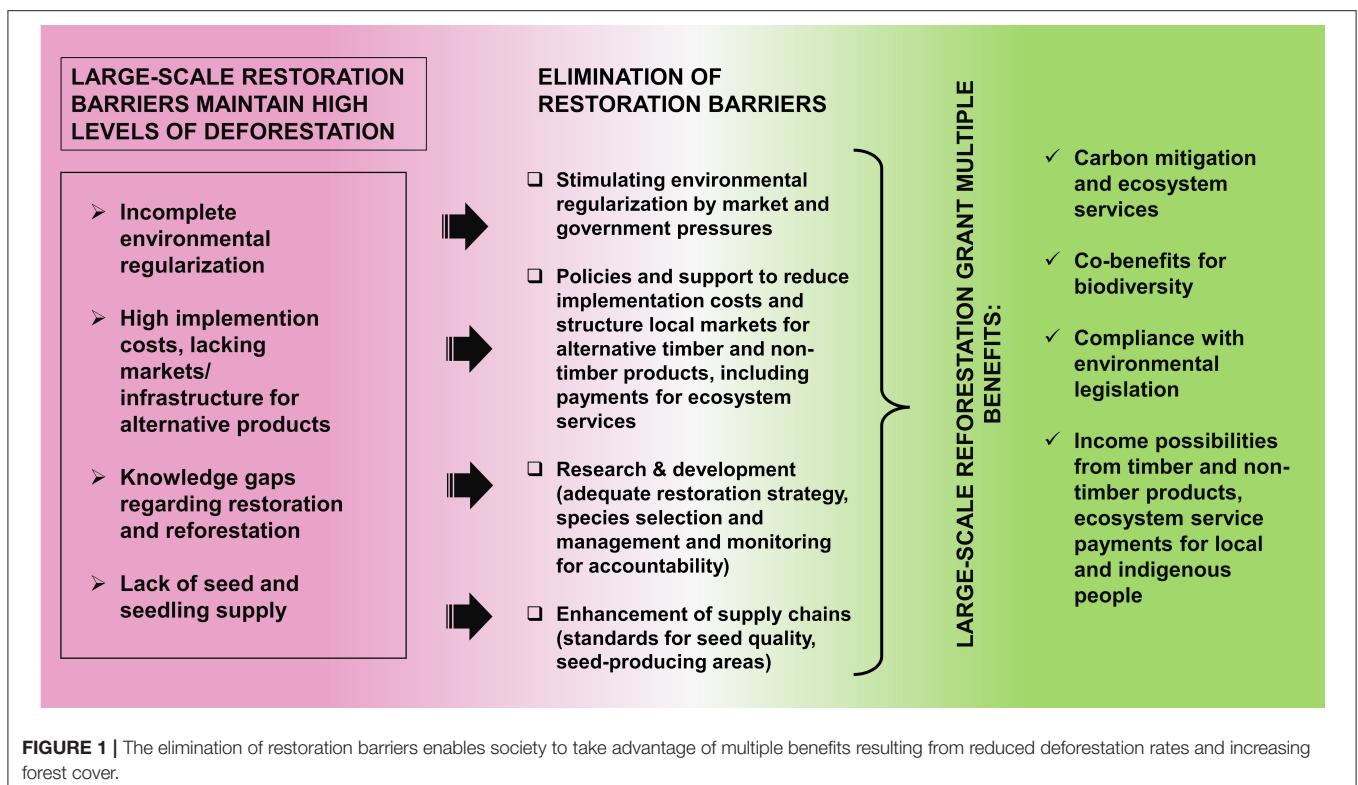
Responsible Soy Project by The Nature Conservancy and Cargill (Jung et al., 2017), these thresholds are rarely achieved (Nunes et al., 2019) because the ecological benefits of compliance do not outweigh the economic benefits of non-compliance (Stickler et al., 2013). Thus, further market and government pressures (Pacheco et al., 2017) or facilitation of the regularization process (Amaral et al., 2017) are necessary to achieve legal compliance and enable large-scale forest restoration, e.g., on low-productivity stands to maintain the profitability of rural properties (Strassburg et al., 2014).

KNOWLEDGE GAPS IN RESTORATION PRACTICES

Restoration Strategies

Depending on socioeconomic circumstances, land-use history and landscape context, forest restoration may be achieved by natural regeneration after removal of degrading agents, the installation of agroforestry systems bridging ecological and economic needs for sustainable development, and active restoration by seeding or seedling planting (Brancalion et al., 2016; Souza et al., 2016). Additionally, assisted natural regeneration with less inference, such as enrichment planting or the control of invasive grasses, may represent viable solutions in some cases (Crouzeilles et al., 2020).

The choice of a suitable restoration strategy directly influences the costs of the project and depends on the level and history of degradation and the amount and quality of the remaining



forest cover. Natural regeneration is successful in the Amazon when the remaining forest cover exceeds 50% (Brançalion et al., 2016). Landscapes and regions with higher deforestation rates may show lower natural regeneration potential, requiring active restoration approaches such as direct seeding or seedling plantation techniques. A recent biome-wide estimate indicated that only 39% of deforested areas in the Brazilian Amazon show high potential for natural regeneration (Vieira et al., 2017), indicating that more than the half of the biome's logged area may be unable to recover naturally. As the natural regeneration potential may vary as a function of the local or regional context, e.g., the presence of smaller, well-conserved, diverse forest remnants may outweigh the importance of larger, degraded or less diverse secondary forests, the development of methodologies by which the actual potential for natural regeneration in relation to the local or regional context can be detected is paramount for efficient forest restoration (Carvalho Ribeiro et al., 2020).

Species Selection and Management

The success of active restoration strategies depends on the use of species with specific adaptations to local environmental constraints, including edaphic, actual and expected future climate conditions (Zwiener et al., 2017). To date, more than 10,000 native tree species in the Amazon have already been described (Ter Steege et al., 2019), many of which can be applied for active forest restoration. Principles of functional and phylogenetic ecology may guide the identification of promising tree species for forest restoration activities aiming to compensate for or mitigate environmental impacts considering site-specific climatic or edaphic constraints (Thomas et al., 2017; Laughlin et al., 2018) but require detailed knowledge about species' ecological niches and adaptations to restore functional, resilient forests (Gastauer et al., 2020a).

The cultivation of native species for economic purposes, e.g., agroforestry systems or further commercial plantations, requires the selection of species able to provide yields, subsistence and income. Many Amazonian tree species provide timber and non-timber products that may be used as fuel, fiber, and food or in the pharmaceutical or cosmetic industry, and reintroduction of traditional knowledge regarding their potential may increase the diversity of farms and gardens (Caballero-Serrano et al., 2019). Nevertheless, low degrees of domestication and a lack of experience with the cultivation of native species result in preferences for exotic species in many cases (Rolim et al., 2019). The seed quality of most native seeds, for example, is limited by their irregular development patterns, short harvest periods and rapid dispersal (Hay and Probert, 2013), challenging the establishment of promising species in the field. Moreover, seed dormancy, i.e., evolutionary adaptations that prevent seeds from germinating under unsuitable ecological conditions, delays germination and seedling production. Species with seeds that are sensitive to desiccation (recalcitrant seeds) remain a significant challenge in terms of storage (Umarani et al., 2015). Thus, research regarding the propagation of native species (seed harvesting, processing and storage, seedlings and vegetative propagation) and plantation management (nutritional demands,

plant health, ecophysiology, plantation designs and thinning) as well as innovations and development of new biodiversity-derived products are necessary to explore the economic potential of the biome's diversity and achieve large-scale forest restoration in the Amazon.

Monitoring Restoration Success

Monitoring is necessary to evaluate the success of forest restoration activities, especially when regenerating forests are used to achieve corporate carbon neutrality or fulfill national or international environmental commitments. A range of indicators, such as the amount and monetary value of sequestered carbon, the number of created jobs, realized trainings, costs related to implementation and net gains of incomes and subsistence, are available to measure socioeconomic restoration outcomes. Environmental assessments necessary to measure the success of ecological restoration efforts should include the evaluation of the vegetation structure, biodiversity measures and ecological processes such as the return of productivity, nutrient cycling, and water management (Gastauer et al., 2020b).

Currently, environmental assessments are generally carried out through time- and money-consuming field surveys, challenging the large-scale monitoring of restoration projects, especially in remote areas. In contrast, low costs and high degrees of automatization for repeated measures covering large spatial scales qualify remote-sensing techniques for this purpose. During the last decade, considerable advances have been achieved in detecting biomass (important to account for sequestered carbon), levels of biodiversity and the successional advance of regeneration forests, but validation by ground data remains the limiting factor (Chave et al., 2019). Innovative approaches that simplify or automate this validation open new avenues for expanding our capacity to assess restoration performances over unprecedented spatial and temporal scales using satellites (Almeida et al., 2020).

SOCIOECONOMIC CONSTRAINTS IMPEDE THE DIVERSIFICATION OF AMAZONIAN FORESTRY

Implementation Costs

Restoration costs depend strongly on the restoration strategy, and the benefits can outweigh the implementation expenses. An increase in the restoration project size reduces the cost per unit area, simultaneously increasing the biodiversity benefits by reducing the edge effects (Strassburg et al., 2019). Nevertheless, high implementation costs remain major barriers to forest restoration by local communities without access to credit (Saraiva et al., 2020).

Thus, strong partnerships between local people, governments and/or the private sector are required to implement restoration activities and their long-term management. In this context, the inclusion of large-scale forest restoration activities in corporate carbon neutrality (Smith, 2020; Vale, 2020) and further sustainability strategies are promising

approaches to overcome implementation difficulties (Seymour, 2020).

Income Opportunities and Their Constraints

Forest landscape restoration may benefit rural development by increasing family incomes, employment opportunities, and community resilience, although success may depend on governance and land tenure systems (Adams et al., 2016; Erbaugh and Oldekop, 2018). Worldwide, the economic benefits of restored forests are estimated to be between 0.7 and 9 trillion dollars (Verdone and Seidl, 2017). In association with 1,000 hectares of reforested land in the Brazilian Atlantic Forest, up to 200 jobs may be created, including jobs related to seed collection, seedling production, planting, maintenance, and downstream manufacturing of timber and nontimber products (Calmon et al., 2011), as well as emerging opportunities from biodiversity-derived innovations. Additionally, PES, including those related to carbon sequestration or water production, can encourage forest restoration and provide economic and social benefits (Grima et al., 2016).

In the Amazon, this potential may not be completely realized because restoration activities compete with less sustainable land-use practices, principally cattle ranching and soy production (Jusys, 2016; Lathuillière et al., 2017), and lacking markets and value chains for alternative products handicap the diversification of the rural economy (Stabile et al., 2020). Well-structured markets are required for PES, as the measurement and monetary valorization of environmental benefits involving different stakeholders with different perceptions are not easy tasks. However, important instruments such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and Clean Development Mechanisms (CDM) are not sufficiently regulated in most Brazilian Amazonian states. Thus, the systematic structuring of alternative markets for timber and nontimber products and the roll-out of PES schemes are necessary to enlarge income opportunities and economic viability of large-scale restoration programs in the Brazilian Amazon.

LIMITED SEED AND SEEDLING SUPPLIES AS A MAJOR LOGISTIC BOTTLENECK IN LARGE-SCALE RESTORATION

The success of active forest restoration projects depends on the availability and quality of seeds or seedlings of native species, which are currently difficult to obtain. According to a recent estimate, the number of seedlings necessary to actively restore actual vegetation deficits in the Itacaiunas watershed only (1.25 Mkm²) surpasses twice the capacity of tree nurseries in the entire Brazilian Amazon (Nunes et al., 2020). The demand for native seeds for seedling production or direct seeding techniques far exceeds the capacity of harvesting from the wild (Broadhurst et al., 2016), requiring the establishment of

seed production areas to satisfy the demand. Seed networks linking seed collectors and producers from local communities with organizations and seed buyers are a promising strategy for upscaling the offered native seeds for large-scale restoration programs but require capacity building, flexibilization of actual seed regulations, and diversification of the seed market (Urzedo et al., 2020b).

CONCLUSION

Contrary to pure ecological restoration, the forest landscape restoration approach postulates that integrating different levels of forest restoration can generate multiple socioeconomic benefits that may outcompete traditional, less sustainable landforms in the long term. Despite the recognition of this potential, large-scale restoration initiatives are still challenged by knowledge gaps, insufficient supplies of seeds and seedlings, a lack of incentives, and socioeconomic constraints such as high implementation costs and competition with less-sustainable forms of land use (Figure 1). To realize the potential related to large-scale forest restoration in the Brazilian Amazon, it is thus necessary to establish and enhance the entire restoration value chain, ranging from the availability of seeds and seedlings to the processing and commercialization of timber and nontimber products. Effective monitoring systems are required to detect deviations from desired restoration trajectories and highlight the need for intervention. Governments, NGOs and the private sector should work together to (i) stimulate the environmental regularization of rural properties; (ii) close knowledge gaps through specific public or private requests for research and development; (iii) engage local communities and implement effective financial mechanisms and policies, i.e., structured markets for PES and certified timber or nontimber products, to diversify Amazonian forestry and agriculture; and (iv) create incentives to enhance the seed and seedling supply to support restoration activities using native species (Figure 1). Concentrated actions on these topics may reduce deforestation rates and encourage large-scale forest restoration to prevent the biome from collapsing.

AUTHOR CONTRIBUTIONS

SN and MG designed this study. MG wrote the paper with important contributions from RC (restoration strategies, seed, and seedling supply) and CC (species selection and management). All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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