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Challenges and opportunities for large-scale reforestation in the Eastern Amazon using native species

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ABSTRACT

Reforestation and forest restoration are recognized as an effective means of halting biodiversity loss and increasing the performance of ecosystem services such as carbon sequestration and the protection and maintenance of water resources. The objective of this review is to describe the main challenges and opportunities for large-scale forest restoration and reforestation using native species in the Amazon, focusing on Pará state and the Itacaiúnas watershed. Large-scale forest restoration and reforestation in the Eastern Amazon may contribute to meeting national and global restoration commitments and reducing/eliminating the actual forest deficit caused by noncompliance with the Brazilian Native Vegetation Protection Law, concomitantly mitigating impacts on climate change, enhancing ecosystem services (e.g., protection of water resources and reduction of soil erosion) and maintaining biodiversity. The selection of active and passive reforestation approaches depends on land-use history, landscape context and reforestation targets, and the promotion of natural regeneration reduces implementation costs. To measure the ecological and socioeconomic success of forest restoration and reforestation, a large number of on-the-ground and remote indicators are available, and the use of a combination of both methods can reduce the monitoring cost. The socioeconomic benefits of reforestation include financial gains from restoration and carbon programs; furthermore, the commercialization of timber and non-timber products and their use for subsistence may improve livelihoods and farm incomes. Nevertheless, implementation of large-scale reforestation in the Eastern Amazon requires research regarding the selection and the nutritional demands of native species and the development of adequate soil management strategies that promote the growth of native species and yields. The insufficient availability of seeds and seedlings is a major bottleneck for large-scale forest restoration and reforestation with native species. Thus, increasing the availability, diversity and quality of seedlings and seeds of native species to supply the demand for planting activities, as well as the registration of producers in the National Register of Seeds and Seedlings, is necessary to achieve compliance with national legislation and international commitments. Competition between reforestation and the expansion of agricultural and cattle ranching frontiers combined with a lack of markets for commercial products from restored areas constrains the socioeconomic viability of large-scale reforestation. To outweigh deforestation incentives, regulation and effective implementation of markets and programs such as REDD+, CDM and PES is thus paramount. To enhance the integration of human well-being, socioeconomic enhancements and ecological functionality, forest and landscape restoration concepts offer promising tools for the region.

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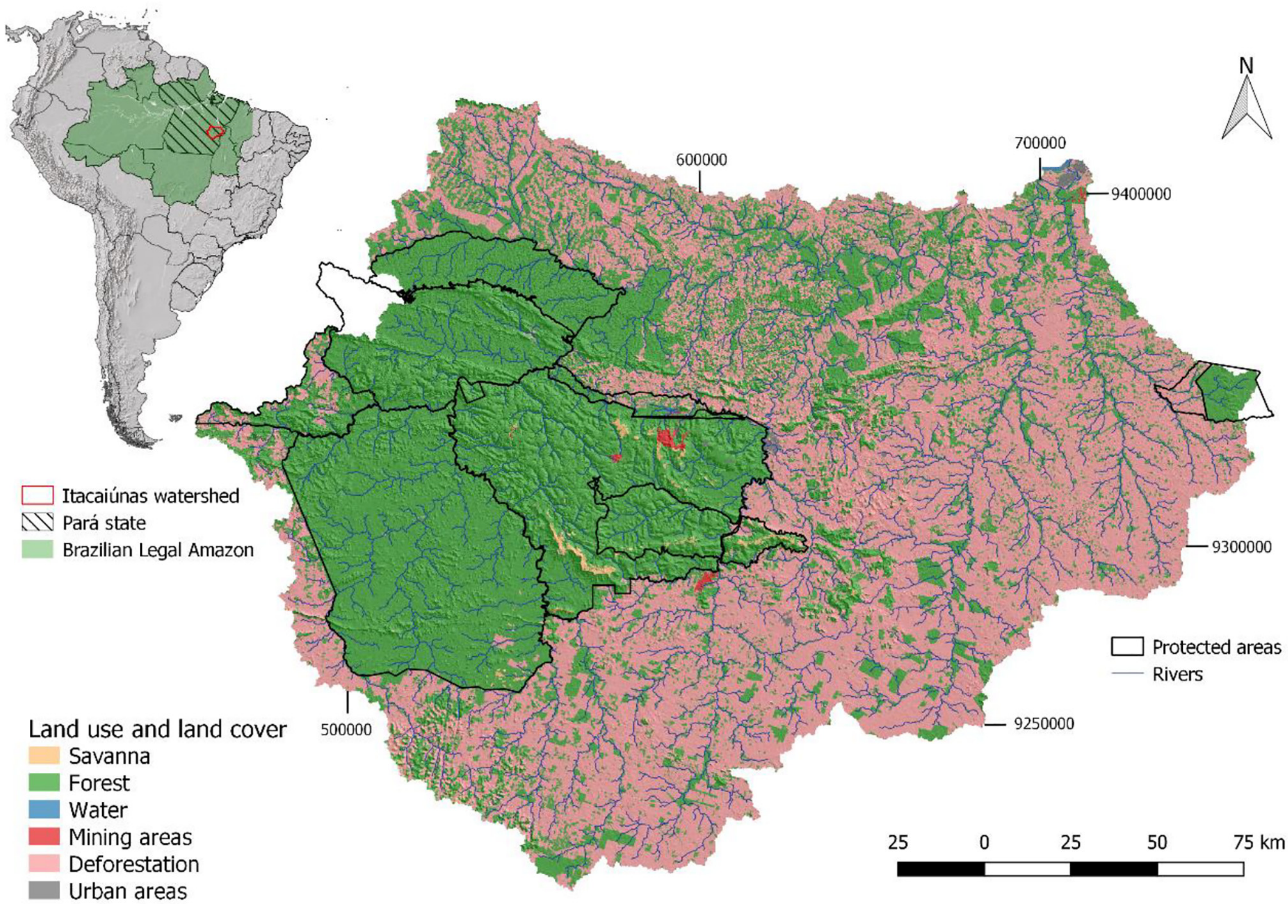

Fig. 1. Localization of the Itacaiúnas watershed in relation to Pará State, Eastern Amazon, and Brazilian Legal Amazon.

1. Context

The Amazon basin accommodates the largest continuous tropical forest in the world (Laurance et al., 2001); this forest accounts for approximately 11% of the world's tree biodiversity (Cardoso et al., 2017), comprises huge carbon stocks (Fearnside, 2018) and provides essential ecosystem services (Strand et al., 2018). However, deforestation and land degradation endanger this titanic reserve, especially in its eastern portion, which is often referred to as "the arc of deforestation" (Fearnside, 2000; Numata et al., 2011). Biodiversity conservation and mitigation of the negative impact of climate change through the maintenance of ecosystem services such as carbon sequestration depend on the protection of old-growth forests within large conservation units. By reducing edge effects and forming ecological corridors or stepping stones for associated fauna, regenerating or planted forests perform buffer functions for old-growth forests and maintain genetic diversity (Viana et al., 2018; Zucchi et al., 2018). Secondary forests also contribute significantly to the protection and maintenance of water resources (Ellison et al., 2017; Filoso et al., 2017) and to carbon stock recovery (Bustamante et al., 2019; Poorter et al., 2016), generating co-benefits for biodiversity (Matos et al., 2019).

Global efforts related to restoration and reforestation policies and commitments have been made in order to increase forest area while removing CO_2 from the atmosphere. In 2011, the German government and the International Union for Conservation of Nature (IUCN) launched the Bonn Challenge, which aims to reforest 350 Mha by 2030 (www.bonnchallenge.org). In 2014, during the Conference of the Parties (COP20), Initiative 20x20, a regional partnership to rehabilitate 20 million of degraded land by 2020 across Latin America and the Caribbean (https://initiative20x20.org/), was announced. In 2015, the United Nations General Assembly established 17 Sustainable Development Goals (SDGs) for the year 2030, including goals related to restoration and reforestation (e.g., 15.1–15.3) (United Nations, 2019a). The Nationally Determined Contribution to the Paris Agreement, set during the COP21 in 2015, relies on restoration, reforestation and other initiatives to restrict global warming to 1.5–2.0 °C or less (UNFCCC, 2018). In 2019, the UN Assembly declared 2021–2030 the UN Decade on Ecosystem Restoration to encourage scale-up of restoration and reforestation around the world and accelerate existing global restoration and reforestation goals (United Nations, 2019b).

However, restoration and reforestation at a landscape scale are challenging, especially given its cost (Benini and Adeodato, 2017; Silva and Nunes, 2017) and the increasing competition for land for use in agriculture and cattle ranching (Alves-Pinto et al., 2017), which occupies 33% of the global ice-free land surface (IPCC, 2019). Nevertheless, some experiences around the world have demonstrated that restoration and reforestation can be cost-efficient as well as ecologically appropriate (Hanson et al., 2015). From 1986 to 2005, Costa Rica implemented forests on 394,000 ha of abandoned pastures, mainly through natural regeneration (Buckingham and Hanson, 2015a). In southern Niger, 5 million hectares of land were reforested through "farmer-managed natural regeneration", a type of productive agroforest (Buckingham and Hanson, 2015b). From 1994 to 2005, more than one million hectares of land in China were restored through active restoration (Buckingham and Hanson, 2015c).

Within Brazil, the protection and rehabilitation of forests on private lands are covered by the Native Vegetation Protection Law (n° 12.651, 25 March 2012), commonly known as the Forest Code. To support the implementation of the Native Vegetation Protection Law, the Federal government created the National Policy for Native Vegetation

Rehabilitation (Decree n° 8,972, 23 January 2017) (Proveg) and the National Plan for Native Vegetation Rehabilitation (MMA, 2018a). These instruments aim to rehabilitate 12 million hectares of degraded areas by 2030. During the COP21, Brazil also committed to reduce its greenhouse emissions and to reforest 12 million hectares (MMA, 2018b). To achieve these national targets, large reforestation programs featuring native species are key not only to meeting the legal requirements but also to enhancing socioeconomic gains from the forest (Rolim et al., 2019).

This paper aims to review the main technical challenges and opportunities for large- scale forest restoration and reforestation (as defined in the next section) using native species in the Amazon, focusing on studies developed mainly in the 1.25 Mkm^2 state of Pará, the second largest state in Brazil and the region with the highest rates of deforestation in the Amazon, and in the 41,300 km^2 Itacaiúnas watershed (Fig. 1), located in the arc of deforestation. The area is characterized by a diversity of land uses and includes a large cover of protected area (29%) and deforestation (51%); much the deforestation has been caused by cattle ranching during the last 50 years (Souza-Filho et al., 2015). We focus on these areas due to the availability of detailed data sets related to environmental deficits, seed and seedling availability and a study about key success factors, lacking for further Amazonian estates/basins.

2. An overview of forest plantation and reforestation

In 2004, the Society for Ecological Restoration (SER) defined ecological restoration as any "intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (Society for Ecological Restoration International Science & Policy Working Group, 2004). This includes measures for erosion control, reforestation, removal of non-native species and weeds, revegetation of disturbed areas, daylighting streams, reintroduction of native species (preferably native species that are adapted to local conditions), and habitat and range improvement for targeted species. In the SER terminology, a restored ecosystem converges to an old-growth, undisturbed ecosystem in functionality, self-sustainability, and biodiversity without any further human input (Gastauer et al., 2019).

The increasing interest in pure ecological restoration of forests faces the expansion of agricultural and cattle ranching frontiers (Smith Pete et al., 2010), especially within private lands, which have the highest levels of overall deforestation in the Amazon (Imazon, 2019). Thus, successful large-scale reforestation in the Amazon requires the inclusion of differently managed forest systems. Programs to sequester carbon, such as Reducing Deforestation and Forest Degradation (REDD+) and the clean development mechanism (CDM), call for an increase in tree cover that includes both native forests and tree plantations consisting of native and non-native tree species for timber and non-timber products (Chazdon, 2008; Gullison et al., 2007; Thomas et al., 2010). Tree plantations increasingly meet the market demand for global pulp, energy, wood, food, and carbon storage (Berndes et al., 2003; Gullison et al., 2007). Against the trend of a globally decreasing amount of natural forest area, especially tropical forests, planted forest areas increased from 168 Mha to 278 Mha between 1990 and 2015, reaching 7% of the total global forest area (Keenan et al., 2015).

Tree plantations for industrial purposes (e.g., paper and cellulose) expanded significantly after the 1960s (Sedjo, 1999). In Brazil, most of these plantations were established with government subsidies, and most are large single-species plantations (Bull et al., 2006; Pancel, 2014), often of non-native eucalyptus and pines, totaling 7,325 km^2 in BLA in 2018 (IBÁ. Indústria Brasileira de Árvores, 2018). Tree plantations of native species represent less than 5% of the total tree plantations in Brazil and primarily feature two Amazon species, the rubber tree and paricá (IBÁ. Indústria Brasileira de Árvores, 2018). Other native species show high economic potential, but the information and technology needed for their cultivation are often lacking (Rolim et al., 2019).

Plantations of timber species can be integrated with agricultural crops and/or pastures on the same land-units to form agroforestry systems (AFS). AFS on already deforested land may thus play a paramount role in reducing both the rate of conversion of forest to agriculture and forest degradation (Unruh, 1995) while increasing local biodiversity compared to monocropping (P. Udawatta et al., 2019) and enhancing carbon storage (Montagnini and Nair, 2004; Oelbermann et al., 2004) and crop production (Schroth et al., 2016). Another environmental benefit of AFS is that farmers who are engaged in agroforestry are more likely to allow reforestation (Blinn et al., 2013). In the Amazon, traditional knowledge and practices of agroforestry are found (Miller and Nair, 2006), but organized agroforestry systems are still minor elements of the landscape, often resulting from farmers' experimentation or from initiatives funded by international cooperation (Porro et al., 2012).

Although considerable effort has been made to include environmental concerns in tree establishment (Sayer and Elliot, 2005), tree plantations are associated with lower biodiversity in comparison to native forests (Gibson et al., 2011; Stephens and Wagner, 2007). Therefore, it is important to treat tree plantations as a land cover/use independent of native forests (Holt et al., 2016). Despite their lower diversity, tree plantations in intensive agricultural landscapes can enhance conservation by providing complementary forest habitat, buffering edge effects, and increased connectivity (Brockerhoff et al., 2008), especially when native species are generally favored (Hartley, 2002). The domestication of native species can be an alternative to the industrial use of non-native species, as it has the advantage that native species generally present high survival under local environmental conditions, good adaptability to lower-intensity management and higher resilience, especially when forestry is only a marginal activity (Haggar et al., 1998). The main difficulty with this type of planting is the lack of large-scale demonstrations of its use and the lack of economic analysis (Nichols et al., 2006).

The concept of forest landscape restoration (FLR) incorporates ecological restoration and further reforestation activities including native and non-native species as far as compatible with legislation. FLR is conducted in a planning unit and is designed to increase the ecological functionality of deforested or degraded landscapes while integrating human well-being (Besseau et al., 2018). Focusing on the design of landscape functionality and productivity to meet the needs of people (Troya and Kumar, 2016), FLR is being implemented using a range of reforestation approaches, recognizing that forests and the management of degraded forest lands can provide multiple benefits and actively engage stakeholders. Despite the environmental and socioeconomic opportunities they offer, large-scale FLR programs are still being designed, and the balance between the public good and private benefits is key to the long-term sustainability of these initiatives (Sagobal et al., 2015).

3. Mapping legal requirements for reforestation

The two main instruments of the Native Vegetation Protection Law that are used to protect native vegetation within rural private properties are the Legal Reserve (RL, in Portuguese) and the permanent preservation areas (APP, in Portuguese). RLs are designed to promote the sustainable use of natural resources and the conservation of biodiversity and covers up to 80% of the property in the Amazon but only 20% of that in other regions. APPs are designed to protect particularly sensitive areas such as riparian vegetation, springs, steep slopes (> 45°) and hilltops; in APPs, only low-impact activities such as ecotourism are allowed. The restoration requirements for both APP and RL can be met through natural regeneration and through the planting of native and exotic species, with the latter limited to 50% of the area to be restored. In the APPs, exotics are allowed only within small holdings.

The controversial revision of the Native Vegetation Protection Law in 2012 led to an important reduction in the required restoration area in

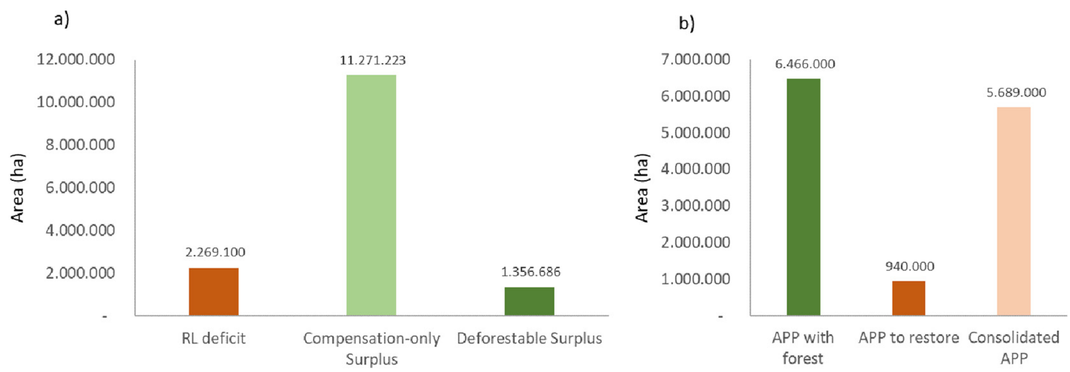

Fig. 2. Estimates of (a) Legal Reserve (RL) deficit, compensation-only surplus and deforestable surplus (Nunes et al., 2016) and (b) permanent preservation area with forest, deficit and consolidated APP (Nunes et al., 2019a) in the state of Pará.

both RL and APP due to an amnesty of deforestation before 2008 (Soares-Filho et al., 2014). The new law was a starting point for the mapping and estimation of the country's forest deficit (the shortfall in the amount of forest cover that is required to comply with the law, including both the area to be restored and the area to be compensated) as well as the forest surplus (forested areas additional to the legal obligation).

A large-scale study estimated that, relative to the legal requirements, Brazil presents a forest surplus of 78 ± 5 Mha and a deficit of 21 ± 0.6 Mha (78% from RL and 22% from APP). The Amazon region reaches 8 Mha of deficit and 20 ± 1 Mha of surplus (Soares-Filho et al., 2014). Other studies assessed patterns of forest cover and legal compliance with the Native Vegetation Protection Law in the 1.25 Mkm^2 Brazilian state of Pará using real property boundaries. The authors found that the total RL surplus (12.6 Mha) was more than five times the total area of deficit (2.3 Mha). However, of the total surplus area, only 11% can be legally deforested (deforestable surplus); the remaining 89% is already protected by law but can be rented to compensate for areas that are under deficit (compensation-only surplus) (Nunes et al., 2016) (Fig. 2a). An estimation of the total riparian APP in Pará demonstrated that although nearly half (49% or 6.4 Mha) of the total extent of riparian APP is forested, the area that does not need to be restored due to the amnesty of deforestation before 2008(43% or 5.7 Mha, consolidated APP) is six times the area obligated for reforestation (7% or 940,000 ha) (Nunes et al., 2019a) (Fig. 2b).

The first fine-scale estimation of forest surplus and deficit distribution to integrate APP and RL at the watershed scale was conducted in the 41,300 km^2 Itacaiúnas watershed in southern Pará (Nunes et al., 2019b). The results showed that the total RL deficit (438,308 Mha) was higher than the total forest surplus (above the legal obligation) (324,064 ha). However, most of this deficit (56%) can be compensated by protecting a forest area in another property within the Amazon biome, while reforestation of 44% of the area is legally required. Only 4% of the total forest surplus can be legally deforested; the remaining 96% is already protected by law but can be used to compensate for areas under the deficit (Fig. 3a). Despite the fact that 57% (301,732 ha) of the total APP is currently forested, only 26% (135,625 ha) must be restored, and 17% (88,124 ha) can remain deforested (consolidated areas) (Nunes et al., 2019b) (Fig. 3b).

According to official data from the TerraClass project, regeneration in previously deforested areas increased from 10 to 17 Mha between 2004 and 2014 (TerraClass, 2014), suggesting that 22% of the total deforested area in the Brazilian Amazon was in some stage of forest regeneration by 2014. The large amount of regenerating vegetation would be sufficient to meet the Brazilian commitment to reforest 12 Mha by 2030 as part of the Paris Agreement. However, the accountability of this area to that national commitment remains unclear.

At the property scale, it is key to conciliate production with legal compliance by developing an environmental and agricultural compliance plan for each property. This plan includes recommendations on where and how the productive area can be used more efficiently; it also indicates the areas to be reforested and protected in compliance with the law, thereby reducing the competition for land within rural properties (Rodrigues et al., 2016). For example, pasture could be concentrated in previously deforested areas with higher potential productivity when implementing intensive cattle ranching (higher animal density). This would make other areas with lower agricultural potential (e.g., sloped areas and areas with higher soil erosion risk) or higher potential to provide ecosystem services available for reforestation or protection and avoid further deforestation (Strassburg et al., 2014).

4. Implementation

4.1. Forest restoration and reforestation strategies

The main forest restoration and reforestation strategies that have been applied in the Amazon are natural regeneration (passive restoration/reforestation), total planting of seedlings and/or seeds (active restoration/reforestation) or a combination of the two methods. The choice of forest restoration/reforestation strategy depends mainly on the level of land degradation, the potential for natural regeneration, the remaining forest cover and the desired reforestation targets (Brancalion et al., 2015; Holl and Aide, 2011) (Fig. 4) and must be integrated with production activities to achieve sustainable landscapes that generate socioeconomic benefits and guarantee the performance of ecosystem services (Latawiec et al., 2015). Natural regeneration is indicated for forest restoration of minimally degraded areas for environmental purposes, given that sites have been subjected to low-tech agricultural activities and their surrounding forest fragments show high potential for natural regeneration. In contrast, land that has undergone intensive use resulting in soil compaction, excessive losses of organic matter or pauperization of soil seed banks, conditions that frequently occur after intensive agricultural use, requires active strategies to achieve forest restoration or install agroforestry systems or planted forests with economic purposes (Brancalion et al., 2016).

Natural regeneration is the most recommended option for the recently degraded areas found in the Amazon; in many of these areas, low-tech activities such as extensive pastures of low productivity dominate in landscapes that still present a reasonable forest cover. The launching of natural regeneration requires isolation of the site from the factor that caused the degradation, e.g., livestock grazing, fires or biological invasions (Brancalion et al., 2016; Mesquita et al., 2015). Natural regeneration is the least expensive option for large-scale restoration, although its outcomes may be characterized by low diversity due to lacking plant propagule arrival (Brancalion et al., 2015; Rodrigues et al., 2009; Rozendaal et al., 2019). Thus, most natural regeneration situations, even in the Amazon, may require some

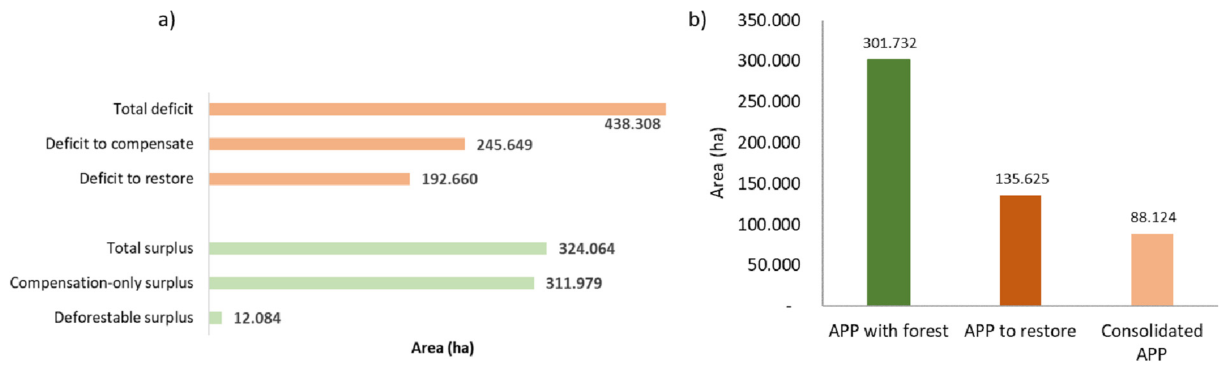

Fig. 3. Estimates of (a) Legal Reserve deficit and surplus and (b) permanent preservation area with forest, deficit and consolidated APP in the Itacaiúnas watershed (Nunes et al., 2019b).

managerial intervention to increase the canopy cover and the diversity of native species and to promote successional or functional groups and different growth forms (Jakovac et al., 2014; Rezende and Vieira, 2019). Such assisted restoration may involve the control of invasive exotic grasses and enrichment with native species belonging to certain ecological groups lacking in the restored stands (Brancalion et al., 2016; Orsi et al., 2011).

Although natural regeneration is considered an economical method of forest restoration, time delays in isolated areas or in areas with dystrophic, compacted soils may be avoided by active restoration (Sartori, 2015). Thus, the application of seed mixtures or the planting of seedlings is a priority for the restoration and reforestation of severely degraded sites that frequently arise after intensive agricultural use, mining or infrastructure projects (Brancalion et al., 2015; Rodrigues et al., 2009). Lack of experience and technical expertise about native seedling management and logistical difficulties such as long transport distances and low infrastructure represent significant challenges to the large-scale planting of seedlings. Although best practices for seed collection, treatment and storage (see the following section) are not fully resolved, direct seeding of native species is recommended as a viable alternative in many cases (Freitas et al., 2019).

Analysis of 42 restoration programs in Brazil found that although active restoration or reforestation was applied in most cases, natural regeneration was successful in the Amazon, especially when the amount

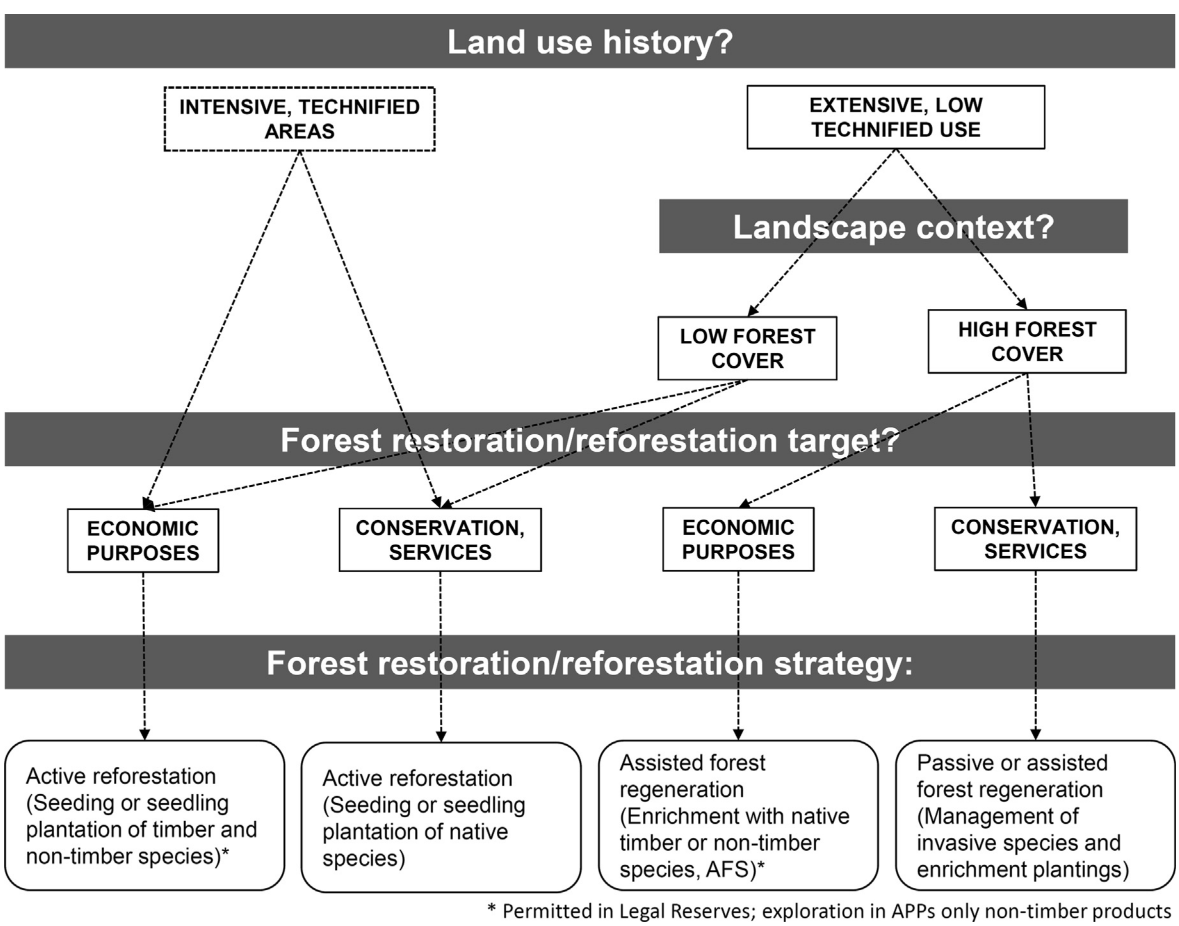

Fig. 4. Decision tree for the selection of forest restoration and reforestation strategies depending on land-use history, landscape context and desired targets. * indicates that strategies are permitted for the restoration of Legal Reserves, while the exploration in APPs is restricted to non-timber products. *AFS* are agroforestry systems.

of forest cover remaining was greater than 50% (Brancalion et al., 2016). In the Brazilian Amazon, pastures cover approximately 62% of the deforested areas and are mostly located along the so-called arc of deforestation, while secondary forests occupy 21% of this area (Almeida et al., 2016). Secondary succession occurs relatively rapidly and is more predictable in recently modified landscapes and where preserved native forests are still present (Arroyo-Rodríguez et al., 2017). Nevertheless, the continuous use of fire to maintain pastures, a common practice in the Amazon, eliminates seedlings, saplings, coppice and seeds in the soil and leads to the growth of highly simplified stands that are dominated by fire-resistant genera after abandonment (Mesquita et al., 2015), thus reducing the potential for natural regeneration.

Due to these issues, most (46%) of the deforested areas in the Eastern Amazon are classified as having low potential for natural regeneration; other areas show high (39%) or medium potential (15%) (Vieira et al., 2017). In the Itacaiúnas watershed, which has lost 51% of its forest cover, 55% of the area that must be restored in APP and RL is classified as having low potential for forest regeneration, mostly due to the low forest cover in surrounding areas and to previous intensive land use; 1% presented medium potential, and 44% presented high potential.

The actual selection of sites for reforestation projects within the FLR concept should be guided by the goals of the reforestation and should take into account the regional context. This may include the prioritization of areas that are important as climatic refugee or ecological corridors or are important in water regulation, erosion control, carbon stock maintenance, or in meeting the legal requirements (Aguirre-Salado et al., 2017; Trabucchi et al., 2014). For that, integrated, multiobjective approaches need to be implemented, as different objectives may result in trade-offs (i.e., between climate change mitigation and biodiversity conservation, as presented by Strassburg et al., 2019).

4.2. Soil fertilization and management

Land occupation and development within the Amazon has generated changes in soil cover. In addition, inadequate soil management has frequently caused loss of productive capacity within a few years of use (Reis et al., 2011). Detailed knowledge of the soil status is necessary to avoid further degradation and to guarantee the ongoing use of natural resources for agroforestry purposes (Rodrigues et al., 2010). Thus, soil conditions are deterministic for the reforestation process, influencing reforestation targets, species selection and forest regeneration trajectories (Pinho et al., 2018). Furthermore, reforestation programs involving native species are affected by the lack of information about the nutritional demands of these species, which may differ significantly from those of commercial agricultural crops or classic timber species (Berti et al., 2017; Brasil, 2009). Thus, the reversion of ecosystem degradation in the Amazon biome by large-scale reforestation requires detailed knowledge of the nutrient demands of native species in this region as well as the development of proper soil management practices.

Latosols (Oxisol) and Argisols (Ultisols) cover 74.7% of the Amazon region (Sanchez et al., 1982; Vieira and Santos, 1987) and are characterized by low cation retention and fertility (Quesada et al., 2011; Sanchez, 2019). Based on intensive research involving genetic improvement programs and the optimization of fertilization protocols, a few fast-growing forest species, mainly the exotic *Eucalyptus* and *Pinus* genera, were successfully introduced in these soils. In contrast, few native tree species such as rubber, mate, cocoa and peach palm have received similar scientific attention. Breeding strategies for target native forest species with economic potential are essential to ensure the production of seeds with desirable genetic qualities for commercial purposes as well as to meet environmental demands. This includes studies on the nutritional demands of these species and the determination of critical nutrient levels (Berti et al., 2017; Brasil, 2009).

An understanding of the nutritional requirements of native species is necessary to produce vigorous seedlings and to maximize their development in reforested areas. The fact that some native species show adaptation to nutrient-poor soils does not eliminate the possibility of a positive fertilization response (Duboc and Guerrini, 2007). Thus, the risks associated with conducting reforestation using native species increase when information on their adaptation and performance in relation to physical and chemical soil attributes is lacking (Medeiros et al., 2008; Souza and Souza, 2006).

4.3. Species selection

Overall, tree species diversity in the Amazon biome is estimated to include 16 thousand species (Steege et al., 2013), of which 10,071 tree species have already been described (Steege et al., 2019). This outstanding biodiversity illustrates the challenge of species selection for large-scale forest restoration or reforestation projects in this region. The identity and number of tree species to be planted during forest restoration or reforestation depend on the desired outcome and on the restoration/reforestation strategy. The success of natural regeneration, i.e., the exclusion of further disturbances from the site to allow successional advances, depends on the spontaneous arrival of viable populations to the site (DellaSala et al., 2003). Active restoration or reforestation programs, in contrast, require the use of adapted, preferably native species to achieve desired goals.

Commercial reforestation designed to explore new or existing markets requires healthy seeds or seedlings of a focal species that is adapted to local soils and climatic conditions (Dumroese et al., 2016). Activities aiming to establish productive AFS need a small set of species that can provide year-around availability of crops to guarantee livelihood and a rapid return on implementation costs (Peters et al., 2016). As a basis for the selection of key species for commercial reforestation, the phytosociological and socioeconomic index (PSI) was proposed (Salomão et al., 2013, 2012). This index ranks native species based on their abundance, frequency, biomass, timber volume and commercial value found in undisturbed sites (old-growth forests). Non-timber products and their market values may also be incorporated in the ranking to support species selection for restoration of APP.

During an expert workshop held in Sorocaba, São Paulo state, Brazil, in September 2018 (unpublished data), the goal of which was to identify gaps and research priorities in native tree species forestry, three dimensions comprising several indicators were proposed as a basis for effective selection of native tree species. These are (i) silvicultural criteria (growth, adaptation to varying soils and climates, resistance to pests and diseases, nitrogen fixation, stem and canopy architecture), (ii) economic criteria (consolidated market, promising market, value of timber and non-timber products) and (iii) efficiency of the research process (timeframe for obtaining results and the cost of the research). After discussion among researchers and technicians in the various working groups, a recommendation that contained 26 species was elaborated. Among these, the eight species andiroba (*Carapa guianensis* Aubl., Meliaceae), chestnut (*Bertholletia excelsa* Bonpl., Lecythidaceae), copaiba (*Copaifera multijuga* Hayne, Fabaceae), gray freijó (*Cordia goeldiana* Huber, Boraginaceae), paricá (*Schizolobium amazonicum* Huber ex. Ducke, Fabaceae), white tachi (*Tachigali vulgaris* L.F. Gomes da Silva & H.C. Lima, Fabaceae), angelim (*Dinizia excelsa* Ducke, Fabaceae) and ipe (*Handroanthus serratifolius* (Vahl) S.O. Grose, Bignoniaceae) were considered priorities for the Brazilian Amazon. Three of these species (andiroba, chestnut and copaíba) produce non-timber products, two (copaíba and freijó gray), are shade-tolerant in the early stages of succession, and the others are pioneer species. Despite this recommendation, other species important for FLR may emerge in regional contexts (Meli et al., 2014; Suárez et al., 2012).

Active ecological restoration for impact compensation or reparation or to satisfy further environmental liabilities, in contrast, requires the selection of a large number of species to meet ecological restoration targets (Giannini et al., 2017). As stated above, selected species for this purpose should be adapted to actual edaphic, hydrological and climatic conditions (Gastauer et al., 2018); the prospection of adapted species becomes increasingly challenging with increasing environmental degradation (Gastauer et al., 2020). Additionally, expected climate and land-use changes are able to shift species distribution and ecosystem ranges (IPCC, 2019), causing extinctions or restrictions to microrefugia of local species when mitigation strategies are not employed (Urban, 2015). Thus, progressive species selection for forest restoration should promote species that are adapted to the expected future conditions (Damschen et al., 2012; Zwiener et al., 2017). This includes the selection of plant materials that are genetically adapted to the restoration environment (Espeland et al., 2018). Species able to establish symbioses, e.g., mycorrhizal fungi and rhizobia (Neuenkamp et al., 2019), and trophic networks (Campbell et al., 2019) are necessary to trigger species interactions and achieve ecological restoration goals (Perring et al., 2015).

Target plant concepts are useful tools for guiding the intra- and interspecific selection of plant propagules, especially in highly degraded areas such as minelands (Dumroese et al., 2016). Based on functional traits related to management, distribution, interactions and ecosystem services, Giannini et al. (2017) validated 53 of 118 species for use in environmental restoration after mining in the Eastern Amazon. For Hawaiian reforestation programs, native and exotic tree species were successfully selected to maximize the carbon sequestration of reestablished secondary forests (Ostertag et al., 2015). Further approaches involving selection for multiple traits have been applied to increase the functional diversity, resistance and resilience of restored ecosystems (Laughlin et al., 2018; Muler et al., 2018; Werden et al., 2018), thus being able to enhance the long-term stability of reestablished forests in the Amazon.

Effective restoration programs rely on reinstating native plant populations to ensure resilient ecosystems (Broadhurst et al., 2008; Society for Ecological Restoration International Science & Policy Working Group, 2004). It is widely believed that seeds from local stands are better adapted and more suitable for restoration than nonlocal seeds. In fact, we suggest that revegetation should be started by using locally adapted genotypes with representative genetic diversity to avoid inbreeding and inferior progeny, which normally occur over time due to reduction in diversity. The identification of local adaptation by screening many individuals has become achievable thanks to recent advances in next-generation sequencing methods. By associating genetic variations (polymorphisms) with environmental and landscape variables, we can identify candidate adaptive loci and select for genotypes that show physiological adaptations necessary to overcome deeply degraded environmental constraints such as found in minelands (Lanes et al., 2018), even though the selection of specific genotypes may reduce genetic diversity and population stability on the long term.

5. Availability of seedlings and seeds

Active restoration and reforestation activities depend on the availability of seeds and seedlings. To supply the demand for planting for agricultural and forestry purposes, 316 seedling and seed producers have been registered in the National Register of Seeds and Seedlings (Renasem) in the Brazilian Legal Amazon (BLA) states (Fig. 5). Tree nurseries are concentrated in the deforested region of Rondônia, near Belém and near Manaus, while such facilities are lacking in the arc of deforestation of the Amazon biome. Of a total of 207 accredited seed or seedling laboratories listed in Renasem, only 17 are located in the BLA, and most (14) are in Mato Grosso state. The concentration of seed testing laboratories in Mato Grosso may be associated with the state's importance in Brazilian grain production. Specifically, Eastern Maranhão and Southeastern Pará have especially low densities of seed and seedling producers per deforested area.

However, many of these producers propagate seedlings and seeds of exotic species, and many native seedling and seed producers are not registered in Renasem (IPEA, 2015). For example, 195 tree nurseries with a total estimated annual capacity of more than 4 million seedlings were installed by the Forest Rehabilitation Project of the Pará Institute of Forest Development and Biodiversity (PROSAF Project, 2019, https://ideflorbio.pa.gov.br/project/pojeto-prosaf/) between 2011 and 2018 without formalization in Renasem. A study found 1,276 Brazilian tree nurseries that were potential producers of native seeds and seedlings (IPEA, 2015). Only 246 of those nurseries confirmed the actual production of native seedlings, and only 11% were located within BLA, most of them concentrated in the state of Rondônia. The accumulated annual capacity of these installations is estimated at 12 tons of seeds and 11 million seedlings, producing between a single and up to 100 different species per nursery.

Recent experiences demonstrate the difficulty of obtaining seeds and seedlings of native species for restoration projects in the Amazon (Daldegan and Sambuichi, 2017). To enable the Socio-Environmental Institute and partners to restore the APPs from the Xingu River Basin, it was necessary to structure a network of collaborators to promote the collection of seeds of native forest species in that region (Urzedo, 2014). In 2010, the Brazilian Agricultural Research Corporation and the National Institute of Colonization and Agrarian Reform, aiming to promote the restoration of approximately 2,000 ha in settlement projects, did not immediately obtain the required quantity and diversity of seeds and seedlings (Daldegan and Sambuichi, 2017).

Given the legal reforestation requirement (Section 2) and the potential for natural regeneration (Section 4.1) in Pará and the Itacaiúnas watershed, the demand for seed and seedlings for use in large-scale reforestation in this region can be estimated if a few assumptions are made (Table 1). To determine the annual demand, we considered a period of 9 years for reforest APP deficit and 30 years for RL. According to Freire et al. (2017), we considered an average of 80% seedling establishment during reforestation with native species, an average of 3,550 seeds/kg for native species and 20% of nursery seedling establishments (710 seedlings/kg seeds). For direct seeding methods, we considered 30 kg seeds/ha.

Based on these data, the total seedling demand for the entire Pará state ranges from 544 (enrichment plantings) to 1509 million seedlings (total planting, Table 1). If all seedlings are produced from seeds, this indicates a demand for 766 to 2126 tons of seeds over the next 30 years. The use of direct seeding techniques in the restoration of the entire area to be restored requires approximately 21,743 tons of seeds. Thus, the complete restoration of all Pará liabilities generates an annual seedling demand of between 50 (enrichment plantings only) and 139 million seedlings (total planting in all areas) during the first nine years of the restoration. This surpasses by far the maximum installed capacity of the Amazon nurseries identified by IPEA (2015) and the nurseries of the PROSAF project in the state of Pará, which produce a total of 15 million seedlings per year. The mapped seedling producing capacity in the entire BLA corresponds to half of what is required for total reforestation in the Itacaiúnas watershed only. It is noteworthy that the demand for native seeds by far surpasses the capacity to harvest such seeds from the wild (Broadhurst et al., 2016; Moreira da Silva et al., 2017).

Seed quality is crucial for seedling production and for the success of active forest restoration and reforestation programs. Seed production and quality are constrained by environmental variations and show high interannual variability in wild plants (Kelly, 1994). In addition, seeds of many native species have irregular developmental patterns and consequently reach maturity non-uniformly (Hay and Probert, 2013). Furthermore, short harvesting periods and rapid dispersion make seed collection difficult for many native species. When harvesting is delayed, seeds undergo predation; ground-collected seeds usually carry debris and other contamination (e.g., weed seeds and fungi), increasing handling costs (Broadhurst et al., 2016). Thus, optimization of harvesting time (to optimize maturity and moisture content) and methods of processing and storage are necessary to increase yield and seed quality (Elias et al., 2006).

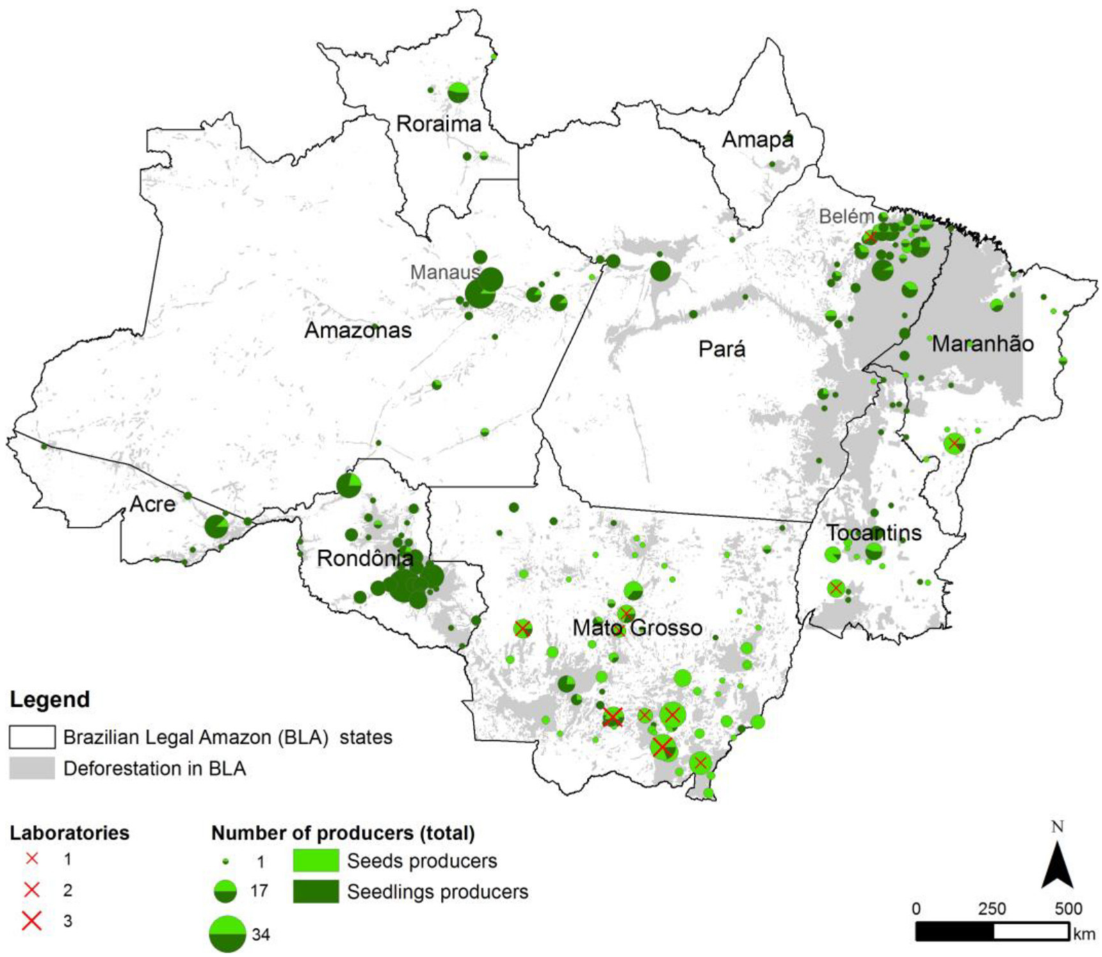

Fig. 5. Number of seed and seedling producers (indicated by light and dark green circles, respectively) and laboratories (indicated by crosses) registered in Renasem (accessed on 05/09/19) by municipality in Brazilian Legal Amazon states. The symbol size corresponds to the number of facilities in each municipality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Testing seeds for potential quality (viability, purity, and vigor) prior to storage and planting provides useful information to the market (producers and consumers) and is of paramount importance in making decisions regarding reforestation. However, seed germination tests have been consolidated for only 50 native species (Normative instruction 44/2010, 35/2011 and 26/2012 of Brazilian Ministry of Agriculture, Livestock, and Supply). Together with the lack of seed laboratories, these figures demonstrate a lack of standards regarding trade in and quality control of seeds of native species.

Reduction in seed viability over time depends on the species, the developmental stage during harvest, and the storage conditions (Calil et al., 2008; Ramos et al., 2019) and determines seed storability. Nondormant or orthodox seeds can germinate promptly after water uptake by activation of metabolic processes and elongation of the

Table 1
Estimate of annual seedling and seed demand for mandatory reforestation (APP and RL deficits that cannot be compensated) in Pará state and in the Itacaiúnas watershed.

Site	% of area with low natural regeneration potential[1]	Environmental deficit (ha)[2]		Period for reforestation (years)	Reforestation approaches				
					Total planting (1666 seedlings/ha)		Enrichment planting (600 seedlings/ha)		Direct seeding (30 kg seed/ha)
					Millions of seedlings/year	Tons of seeds/year	Millions of seedlings/year	Tons of seeds/year	Tons of seeds/year
Pará	**58%**	APP	940,000	9	127.13	179.06	45.79	64.49	1831.43
		RL*	300,000	30	12.17	17.14	4.38	6.17	175.35
		Total	**1,240,000**	**1st 9 years**	**139.30**	**196.20**	**50.17**	**70.66**	**2006.78**
Itacaiúnaswatershed	**55%**	APP	192,660	9	24.70	34.78	8.89	12.53	355.78
		RL	135,625	30	5.22	7.35	1.88	2.65	75.14
		Total	**328,285**	**1st 9 years**	**29.91**	**42.13**	**10.77**	**15.17**	**430.92**

[1] Mean percentage of deforested areas as classified by Vieira et al. (2017).
[2] APP and RL deficits according to Nunes et al. (2019a) and Nunes et al. (2019b). *The RL deficit in Pará states includes only RL areas deforested after 2018, estimated in 300,000 ha, without deforested areas larger than 50% of the properties.

embryonic axis. Nonetheless, seed dormancy is commonly observed in most vegetation types, especially in seasonal ecosystems, and the limited knowledge regarding the germination requirements of native species constrains the potential for restoring complex plant communities (Broadhurst et al., 2016). Dormancy related to seed coat impermeability to water and/or oxygen can be overcome by scarification (acid, hot water and mechanical treatment) and results in substantially increased rates of germination when applied to a set of eastern Amazonian species (Ramos et al., 2019). In contrast, desiccation-sensitive recalcitrant seeds remain a significant challenge for ex situ conservation and seedling production over time in nurseries. A short storage life of these seeds occurs when the seeds reach maturity carrying high levels of water content, a condition that is commonly observed in several tree species. Although low temperatures help extend storage life, detailed research is required to avoid injuries to seeds caused by chilling or freezing of recalcitrant seeds (Umarani et al., 2015).

6. Economic aspects

The FLR involves investments, costs, and benefits that are not equally spatially distributed (Silva and Nunes, 2017); this is especially true in the Amazon region, where the concern with reforestation is only recent and access to information on reforestation is still incipient (Diederichsen et al., 2017). Even so, the rehabilitation of forest cover provides socioeconomic and environmental benefits (Birch et al., 2010; Menz et al., 2013). Strassburg et al. (2019) show that increasing reforestation project size results in a reduction in the cost per unit area, and it is expected to increase the biodiversity outcomes given the importance of edge effects to populations living in small forest fragments. At the local level, FLR benefits rural livelihoods by improving income and increasing off-farm employment opportunities (e.g., due to the release of household labor to seek jobs and participate in the development of green enterprises) and the resilience of communities (Adams et al., 2016). For the Brazilian Atlantic Forest, some authors found that the benefits of reforestation for sediment retention compensated for the opportunity costs of agricultural production with a net present value of R$ 0.37 per reforested hectare (Strassburg et al., 2016). In the Eastern Amazon, Silvia and Nunes (2017) found that sustainable forest management is a possible approach to scaling up reforestation and paying its costs, with a potential profit of up to R$ 2,110 per hectare. However, sustainable forest management in restored areas is an activity of low liquidity and high risk compared to other agricultural activities, especially while there is still competition from illegal timber extraction (Silva and Nunes, 2017), so we are reluctant to overestimate the profitability of this practice throughout the Amazon or another biome.

Another mechanism that may be considered as an incentive for reforestation is payments for ecosystem services (PES), a market with the potential to produce economic and social benefits. In Minas Gerais, Southeastern Brazil, a PES program was developed to preserve water resources by restoring and conserving forest. The program resulted in 6,523 ha planted and in 6,300 ha of protected areas that produced a billion liters of water, and 238 families benefited from the payment of R$ 5 million by the restored forest (Pereira, 2017). However, this instrument is not regulated in most states in the Amazon, and the measurement and the monetary valorization of environmental benefits involving different stakeholders with different perceptions are not easy tasks. PES includes payments for carbon sequestration such as REDD+ and CDM. Both rely on already existing markets, although mechanisms to capture financial resources and regulations that guarantee legal certainty for the investors and beneficiaries of carbon credit are lacking (Silva and Nunes, 2017). The reforestation of the vegetation deficit in the Itacaiúnas watershed, for example, guarantees the sequestration of 15 Mton within 30 years. Based on a mean carbon price of US$ 5.00/tonC, this corresponds to US$ 75 million.

Different incentives for re-establishing tree cover have different social, economic, and environmental consequences and tradeoffs. Global and national restoration and reforestation policies may include commitments to be met through monoculture plantation of both exotic and native species, further reducing the associated biodiversity. Nevertheless, FLR has increasing marginal benefits due to economies of scale, resulting in up to 57% reduction in total costs (Strassburg et al., 2019). To achieve sustainable and long-lasting large-scale reforestation, government and the private sector should work together to (i) understand the potential demand and technologies and create economic frameworks for their implementation; (ii) involve local communities through the social gains associated with increased income and employment; and (iii) design financial mechanisms and incentives for investment in supply chains associated with restoration and reforestation (Diederichsen et al., 2017).

7. Monitoring and indicators for reforestation

Monitoring of the restoration and reforestation process is a legal requirement in Brazil and is necessary to measure its successful implementation (Soares-Filho et al., 2014) and to provide feedback on practices (Barr et al., 2017; Gastauer et al., 2018). Despite the stated goals of the Brazilian legislation on restoration, i.e., restoring biodiversity and ecosystem services such as the protection of water resources in the case of APPs, restoration success is usually estimated using structural and compositional indicators of vegetation only (Chaves et al., 2015). Thus, complete assessment of rehabilitation success should include the measurement of ecological processes as a basis for estimating the return of ecosystem services (Ruiz-Jaen and Aide, 2005; Wortley et al., 2013). Furthermore, socioeconomic goals and outcomes should also be addressed (James Aronson, 2011; Melo et al., 2013), especially when reforestation goals incorporate the generation of socioeconomic welfare (Aronson et al., 2010; Erbaugh and Oldekop, 2018).

A wide range of on-the-ground indicators that can be used for the evaluation of reforestation activities, including socioeconomic indicators (Table 2). Methods for measuring the success of ecological restoration include soil chemical, biological and biochemical analysis (de Moraes Sá et al., 2018; Oliveira Silva et al., 2018) and surveys of vegetation (Suganuma and Durigan, 2015) and fauna (Audino et al., 2014; Derhé et al., 2016) as well as barcoding or metagenomic approaches that can be used to determine the composition of microorganism communities (Valentini et al., 2016). In addition, enzyme extraction, analysis, and quantification via metaproteomic approaches provide information on the biochemical reactions that take place in restoring environments (Bastida and Jehmlich, 2016; Yao et al., 2018). For biological and environmental variables, restoration success should ideally be evaluated by comparison with reference systems, i.e.,

Table 2
Different reforestation goals and selected indicators for the evaluation of success (adapted from (Melo et al., 2013)).

Reforestation goals	Topics	Indicators
Economic	Costs and gains	Installation, timber and non-timber production, PES
Social	Employment	Number of jobs created, wealth insurance, capacity building
Ecological restoration	Forest structure, plant microorganism and animal assemblages	Tree density, basal area tree height, species richness, exotic/invasive species
	Ecological processes and ecosystem services (carbon sequestration, water supply)	Biological and biochemical soil properties, protection of riparian forests and water springs

Table 3
Result of the diagnostic of key success factors for forest landscape restoration (FLR) under the theme "Motivate" in the State of Pará in 2016 (Diederichsen et al., 2017).

Theme	Necessary conditions	Key success factors		Pará current situation
MOTIVATE	a. Benefits	1	Reforestation generates economic benefits	partly in place
		2	Reforestation generates social benefits	in place
		3	Reforestation generates environmental benefits	partly in place
	b. Awareness	4	Benefits of reforestation are publicly communicated	partly in place
		5	Opportunities for reforestation are identified	partly in place
	c. Crisis events	6	Crisis events are leveraged	partly in place
	d. Legal requirements	7	Law requiring reforestation exists	in place
		8	Law requiring reforestation is broadly understood and enforced	not in place

Table 4
Result of the diagnostic of key success factors for forest landscape restoration (FLR) under the theme "Enable" in the State of Pará in 2016 (Diederichsen et al., 2017).

Theme	Necessary conditions	Key success factors		Pará current situation
ENABLE	e. ecological conditions	9	Soil, water, climate and fire conditions are suitable for reforestation	partly in place
		10	Plants and animals that can impede reforestation are absent	partly in place
		11	Native seeds, seedlings or source populations are readily available	not in place
	f. Market conditions	12	Competing demands (e.g. food, fuel) for degraded forestlands are declining	not in place
		13	Value chains for products from restored areas exists	not in place
	g. Policy conditions	14	Land and natural resources tenure are secure	partly in place
		15	Policies affecting reforestation are aligned and streamlined	partly in place
		16	Restrictions on clearing remaining natural forests exists	in place
		17	Forest clearing restrictions are enforced	partly in place
	h. Social conditions	18	Local people are empowered to make decisions about reforestation	not in place
		19	Local people are able to benefit from reforestation	partly in place
	i. Institutional condition	20	Roles and responsibilities for reforestation are clearly defined	not in place
		21	Effective institutional coordination is in place	partly in place

undisturbed, old-growth target ecosystems (Gastauer et al., 2019).

Nevertheless, because field surveys and laboratory analyses are time-consuming and expensive, their applicability to large-scale restoration or reforestation projects comprising thousands of hectares represents a logistic and financial challenge, especially when the technical expertise needed is rare. In this sense, upscaling from point field data to entire landscapes using remote sensing technologies offers new opportunities for understanding the reforestation process from a spatial perspective (Meerdink et al., 2016).

Remote sensing technologies make it possible to monitor forest health in an effective, repetitive and comparative way (Lausch et al., 2017). Since 1972, remote sensors that operate over different spectral ranges and spatial resolutions have been developed and used to generate information that can be used to study land surface dynamics related to terrain modeling, changes in land cover and use, land surface temperature, vegetation indices (e.g., NDVI, EVI) and vegetation biomass (Gillespie et al., 2008; Reif and Theel, 2016). These data can be used for automated monitoring of larger areas during the process of reforestation or to document success metrics (Cordell et al., 2017).

Satellite-based systems that offer moderate resolution, such as Prodes (PRODES/INPE, 2018), the official government system, and the Deforestation Alert System – SAD), have been systematically used to monitor deforestation in the Brazilian Amazon (Imazon, 2019). However, these systems focus on remaining primary forests and do not track gains and losses of secondary vegetation (Assunção and Gandour, n.d.; Richards et al., 2017). Although other systems such as Global Forest Cover (GFC) (Hansen et al., 2013) and the TerraClass project (TerraClass, 2014) provide information on secondary vegetation cover, they were not designed to provide the type of information needed to assess restoration effectiveness (i.e., the quality of regeneration) or to measure differences among secondary vegetation types (e.g., monocultures, agroforestry systems, forest restoration projects, or fallow areas).

Recently, progress has been made in forest age classification and in assessing forest regrowth stages, forest diversity indicators, the presence of invasive species, canopy temperature distribution, tree height and above-ground biomass estimation, all of which can be used to monitor reforestation in the Amazon (Lausch et al., 2017; Mitchell et al., 2017; Reif and Theel, 2016). Advanced remote sensing technologies such as next-generation LiDAR sensors, airborne laser scanning and digital aerial photogrammetry have great potential to help create forest inventories, offering spatial detail and accuracy across large areas (White et al., 2016) and providing new opportunities to the tropical ecology and conservation community (Sanchez-Azofeifa et al., 2017). However, when selecting the appropriate source of data for a restoration project, some tradeoffs emerge between grounding sampling distance, map coverage area, frequency of sampling, and the costs of image acquisition and processing associated with remote sensing platforms and sensors (Cordell et al., 2017).

8. Key success factors for reforestation

To identify and evaluate FLR potential, tools such as the Restoration Opportunities Assessment Methodology (ROAM) have been developed (IUCN and WRI, 2014). ROAM is a set of protocols that was designed to support restoration and reforestation programs at the national and local scales, and it has been applied in many countries to track pledges to the Bonn Challenge target (Hanson et al., 2015; IUCN and WRI, 2014). In Brazil, preliminary results obtained through the application of ROAM show that the methodology supports processes to strengthen existing local agendas to achieve greater acceptance by public authorities and civil society organizations by coordinating initiatives more effectively (Li et al., 2018).

The diagnostic of key success factors for reforestation is one of the components of ROAM (IUCN and WRI, 2014). This diagnostic analyzes three major themes (motivate, enable and implement), 14 necessary conditions and 31 key success factors. Previous experience shows that the presence of key factors increases the likelihood of successful FLR (IUCN and WRI, 2014). The diagnostic verifies, in particular, how the institutional, marketing, legal and policy guidelines associated with selected landscapes help or hinder the development and implementation of FLR activities.

Table 5
Result of the diagnostic of key success factors for forest landscape restoration (FLR) under the theme "Implement" in the State of Pará in 2016 (Diederichsen et al., 2017).

Theme	Necessary conditions	Key success factors		Pará current situation
IMPLEMENT	j. Leadership	22	National and/or local reforestation champions exist	partly in place
		23	Sustained political commitments exist	partly in place
	k. Knowledge	24	Reforestation "know how" relevant to candidate landscapes exist	partly in place
		25	Reforestation "know how" transferred via peers or extension services	not in place
	l. Technical design	26	Reforestation design is technically grounded and climate resilient	partly in place
		27	Reforestation limits "leakage"	partly in place
	m. Finance incentives	28	Positive incentives and funds for reforestation outweigh negative incentives	not in place
		29	Incentives and funds are readily accessible	partly in place
	n. Feedback	30	Effective performance monitoring and evaluation systems is in place	partly in place
		31	Early wins are communicated	in place

In the Amazon context, ROAM was applied in Pará state, and the results show that the opportunities exceed the legal demands (Diederichsen et al., 2017). The challenges include the need to develop new financial mechanisms, the selection of priority areas for restoration and reforestation, and strengthening of the reforestation value chain. Of the 31 key success factors evaluated, 8 are absent, 19 are partially in place, and only 4 are fully in place in Pará (Tables 3–5). Although the state presents a set of programs and initiatives aimed at strengthening environmental management with a clear focus on reducing deforestation, the theme of large-scale reforestation and its contribution to biodiversity conservation is not yet effectively present. Currently, the critical missing elements for successful large-scale reforestation are the lack of market conditions and insufficient ecological, social and institutional conditions. In addition, knowledge and financial incentives must be enhanced to guarantee the large-scale implementation of FLR in the Eastern Amazon.

9. Conclusions

Brazil has one of the most complex and advanced sets of environmental laws, but the implementation of reforestation remains challenging at the landscape scale, especially in the Amazon region, where reforestation projects are still incipient. This literature review has identified a number of opportunities for and barriers to large-scale reforestation that go beyond law enforcement. The main opportunities identified were (i) environmental: mitigate impacts on climate change, enhance ecosystem services (e.g., protect water resources, reduce soil erosion) and maintain biodiversity; (ii) socioeconomic: financial gains from reforestation and carbon programs such as REDD+, CDM and PES, gains from the commercialization of timber and non-timber products or the use for subsistence, improvement in livelihood income, reduction of restoration costs by the promotion of natural regeneration where possible, use widely available on-the-ground and remote indicators for the evaluation of forests in process of reforestation, and use of a combination of the two methods can reduce the monitoring cost; and (iii) political and legal: meet national and global restoration and reforestation commitments and achieve compliance with the Native Vegetation Protection Law.

However, important challenges must be faced, mainly related to the development of the entire reforestation value chain: (i) environmental: increase knowledge about the selection and the nutritional demands of native species used for reforestation purposes, develop proper soil management practices, and promote effective technologies for on-site and remote monitoring of large-scale forest restoration and reforestation; (ii) socioeconomic: compete more effectively with the expansion of agricultural and cattle ranching frontiers, increase the availability, diversity and quality of seedlings and seeds of native species to supply the demand for planting activities, register seed and seedling producers in the National Register of Seeds and Seedlings according to its criteria, and strengthen the market for commercial products from reforested areas; (iii) political and legal: regulate and effectively implement programs such as REDD+, CDM and PES as incentives to restore forests to outweigh incentives to deforestation activities.

Declaration of Competing Interest

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

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