

Forest Restoration

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This is an update of David Lamb, Reforestation, Editor(s): Simon A Levin, Encyclopedia of Biodiversity (Second Edition), Academic Press, 2013, Pages 370–379, ISBN 9780123847201, <https://doi.org/10.1016/B978-0-12-384719-5.00121-0>.

Introduction	2
The Forest Restoration Turn	3
Ecological Basis and Local References	4
Ecological Basis	4
Local References	5
Prior Restoration: Site Selection and Diagnosis	5
Forest Restoration Plan: Methods and Techniques	6
Methods	6
Natural regeneration	6
Assisted natural restoration	6
Active forest restoration	6
Techniques	7
Techniques for passive restoration (assisted or not)	7
Techniques for active restoration	7
Pre-planting	7
Planting	8
Post-planting management	9
Monitoring	9
Adaptive Management	10
Conclusion	10
Study Cases	10
The Amazonian Muvuca	10
Rewilding Europe	10
Floodplain Forest Restoration in North America	12
The Return of Mined Australian Forests	12
African Agroforestry Parklands	13
Monoculture of Trees for Conservation of Threatened Species	13
<i>Paubrasilia echinata</i>	13
<i>Aniba rosidora</i>	13
Acknowledgments	13
Further Reading	14

Abstract

Restoring forest ecosystems and effectively conserving remnants is vital to face the global outbreak of deforestation, forest degradation, climate change, social injustice, and the biodiversity crisis. Besides scaling up forest restoration, setting reasonable goals can guide to more successful plantings that provide more ecosystem services that deliver different benefits and potential trade-offs. Therefore, monitoring forest structure, composition, and other attributes is mandatory while establishing a new forest cover. During the process, wise solutions can arise from the adaptive management process. We can overcome this era's threats based on solid knowledge and actions taken on an enormous joint effort. Therefore, forest restoration is a vital part of today's crisis solution.

Glossary

Forest "Land spanning more than 0.5 ha with trees higher than five meters and a canopy cover of more than 10%, or trees can reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use" (FAO).

Ecological restoration "Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. It seeks to initiate or accelerate ecosystem recovery following damage, degradation, or destruction" (Society for Ecological Restoration, SER).

Forest restoration Process of establishing a forest and its benefits in a place where a forest formation naturally occurred in the past. Practitioners frequently prioritize the recovery of ecosystem services for benefiting people and nature.

Reforestation Planned establishment of a forest on an area that was previously naturally forested; the conditions for planting a new forest do not need to seek for replicating the previous one. It can be composed of native or exotic species, combining one or more species.

Deforestation The removal of a native forest ecosystem.

Forest degradation Causing damage to a forest ecosystem without completely removing the forest cover. Examples: selective logging, droughts, understory fires, mining, cattle grazing, and trampling.

Key Points

- It is urgent to restore forest ecosystems which are priority areas worldwide, to safeguard biodiversity, climate, and human well-being.
- Forest benefits go far from the generation of timber and non-timber products. Forest restoration can recover multiple ecosystem services, such as water and air purification.
- Applying ecological principles and forestry expertise in forest restoration can guide achieving desired outcomes.
- Successful forest restoration is only possible with a range of transdisciplinary knowledge, well-planned implementation, monitoring, and adaptive management.

Introduction

More than ever, the world is aware of the importance of conserving and restoring forests and other natural ecosystems to regulate carbon stocks, nutrient cycles, climate, and water quality, directly affecting urban and rural population development. In this article, we will not focus on specific ecosystems but include examples of forest restoration for achieving different ends. Our objective is to bring a broad view of forest restoration, from planning to adaptively managing. For practical applications, forest restoration requires different actions depending on the biome and local conditions, considering factors such as biological composition, soil and climate conditions, land use, and geomorphology combined with socioeconomic aspects. In this article, we will not consider exotic forests (mixed or monoculture) since it usually does not aim to benefit native biodiversity. Instead, in the study cases, we give examples of reforestation with native tree species for conserving threatened species.

Forest restoration is urgent for conserving and recovering biodiversity. Human-caused deforestation and forest degradation have devastated our world, leading entire ecosystems to tipping points. Increasing forest cover in originally forested ecosystems is paramount. However, conservation efforts must be a priority since restoring all ecological functions of previous forests is likely impossible. Moreover, old forests hold the natural capital built over time, such as genetic diversity, ecological networks of diverse organisms, and ecosystem processes. Forest restoration can be achieved in different forms, such as ecological restoration with native trees, purely for conservation purposes, or by other models, like productive forests, to deliver marketable benefits. Restoring forests must consider all costs and benefits, including social and ecological aspects, as implementing a new forest is a long-term endeavor. Defining priority areas for restoration projects is crucial for maximizing benefits and reducing costs (Fig. 1). It requires local and scientific knowledge such as land use history, geomorphology information, landscape aspects, and other important ecological and social factors.

In the last three decades, governments, NGOs, scientists, and other stakeholders published studies and signed agreements at different political levels to restore ecosystems. People worldwide are mobilizing to reach huge restoration goals. Even the United Nations dedicated this decade to restoring ecosystems, incentivizing large-scale restoration actions. In addition, the Intergovernmental Panel for Climate Change (IPCC) sixth report (2021–22) emphasizes the need for increasing natural cover to mitigate emissions and avoid further climate disasters. It highlights the need for adaptation by developing nature-based solutions, attracting multiple stakeholders to act. Still, several aspects must be considered before and during the restoration process, such as social and economic synergies, landscape complexity, and integration. Some of the issues with the forest restoration process are the high cost of implementation and the invisibility of its ecosystem services, and economic potential.

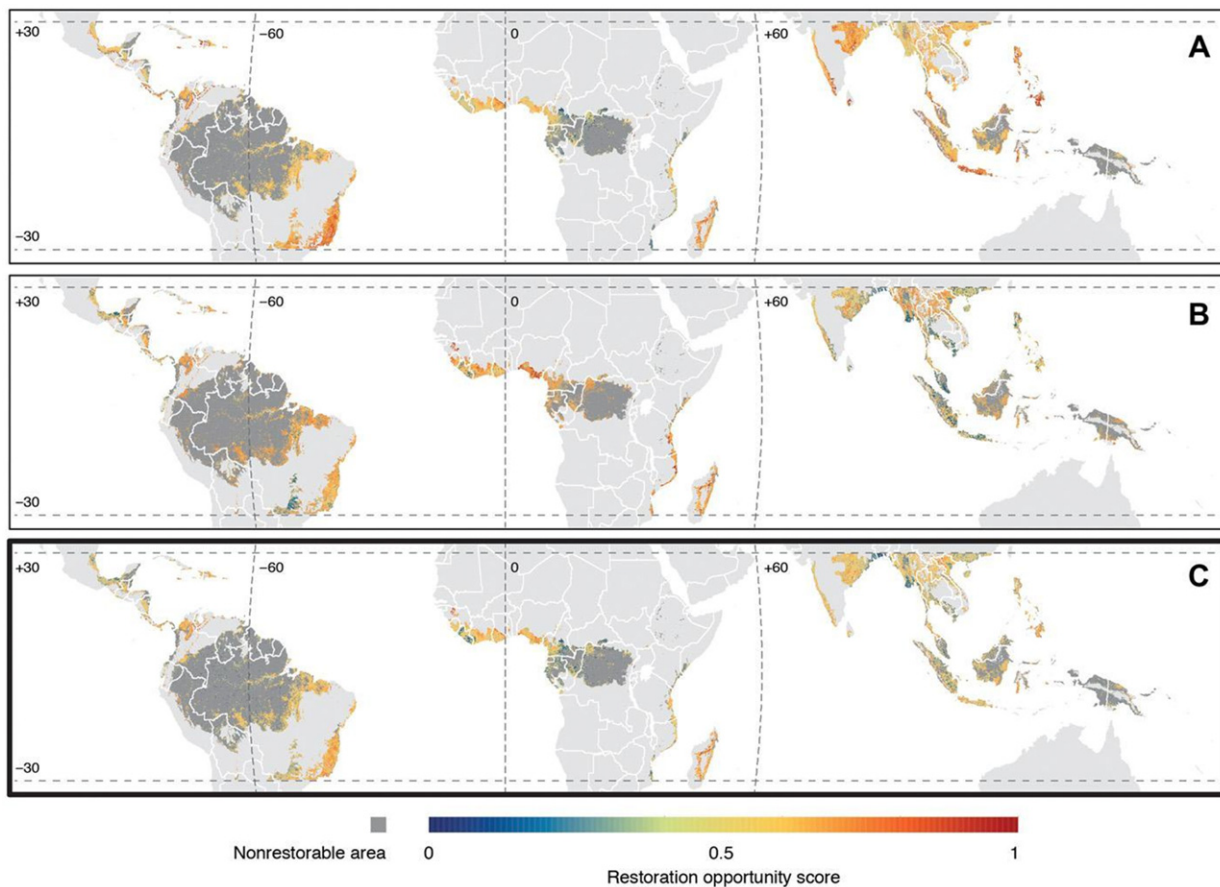


Fig. 1 Tropical world forest areas to show where we have restoration opportunities. From Brancalion, P. H., Niamir, A., Broadbent, E. *et al.* (2019). Global restoration opportunities in tropical rainforest landscapes.

Worldwide, scientists, practitioners, and investors are concerned about applying adequate models, methods, and techniques for implementing forests, combined with in-loco and remote monitoring and adaptive management, to guarantee that such efforts will result in functional, well-established forest ecosystems. Forest restoration, as well as restoration ecology, is a multi and transdisciplinary science, including several factors like legal aspects, botany, soil science, ecology, agronomy, economy, and anthropology. The recipe for successful restoration projects is the balance between different knowledge, since solutions arise from collaborative work. No single measure can save the world, but a collective set of efforts on multiple fronts, where forest restoration is a modest part, is the way to get there.

The Forest Restoration Turn

Human history shows our transformative capacity, which led to the overexploitation of natural resources, soil erosion, river sedimentation, deforestation, and water pollution. However, we have the tools to face environmental degradation and climate change impacts from harmful human-nature interactions. The environmental problems we have faced in the last decades forced society to recognize that ecosystems are providers of vital ecosystem services and have high value to people and nature. Only conserving the remnant ecosystems is not enough anymore, and ecological restoration is urgent and necessary, including restoring the world's forests.

The UN decade on Ecological Restoration (2021–2030) is an iconic benchmark since it directly addresses the need for halting and reversing ecosystem degradation on a global scale, pointing out forest restoration as a priority. Hundred-fifth signatory countries gave life to the Convention on Biological Diversity during the 1992 Rio Earth Summit, recognizing the importance of fauna, flora, and human needs to biological diversity, and the compromise has been renewed and improved since then. Climate agreements such as the Kyoto protocol (1997) and the Paris agreement (2015) also reinforce the role of forests in atmospheric carbon removal, biodiversity maintenance, and climate change adaptation. Besides, UN Sustainable Development Goals (SDGs) also, directly and indirectly, consider the relevance of conserving and restoring forests and other ecosystems. Other pledges, such as the Bonn Challenge (launched in 2011) and Trillion Trees, are global programs encouraging forest restoration.

People and nature in urban and agricultural areas suffer from long-term climate changes, such as increasing temperatures, droughts, and floods. Forests can help mitigate and adapt to the changing climate, providing nature-based solutions. The



Fig. 2 Newly implanted forest restoration planting (A) and the same area 2 years old (B) in the mountainous region of Teresópolis, Rio de Janeiro, Brazil. Source: Pedro H. S. Brancalion.

expansion of markets for ecosystem services and goods brings an opportunity for developing nature-based solutions and increasing natural capital conservation and biotechnology uses. Forest restoration promotes increasing habitat coverage for biodiversity, protecting soils, providing hydrological services, and assisting crop pollination. Besides, it offers models that can attend the carbon market. Responsible countries with multifunctional conserved or restored forests must keep track of the ecosystem services market, protecting the sociobiodiversity and valuing forests' productive potential. Forest ecosystem services must pass from invisibility to a valued and marketable natural wealth.

The absence of forests in previously forested areas leads to social injustice since vulnerable people often rely on forest resources for food, fuel, natural medicine, and small-scale non-timber products market. Furthermore, without forests, vulnerable people will be less adapted to extreme climate events such as inundations and landslides. Forest restoration leads to ecosystem services that can improve quality of life (e.g., providing shade and a milder microclimate), which is why forest recovery is a central strategy to keep and establish natural capital (forest restoration example in Fig. 2).

Ecological Basis and Local References

To properly address restoration interventions, practitioners need to be informed by knowledge created by scientists and other practitioners, while the science should consider local knowledge from practitioners to develop scientific guidance. Understanding critical ecological theories, such as forest succession, community assembly, ecosystem properties, and landscape ecology, undoubtedly result in better restoration settings. Nevertheless, forest restoration also needs local references as models to set goals.

Ecological Basis

Forest succession is the process by which natural communities replace (or "succeed") one another over time. While succession relates to plant communities, the biotic community and abiotic processes will also change and develop in response to plant community successional changes. Different phases of succession favor species with different beneficial traits under different conditions. The term pioneer species describes the species that first colonize new habitats created by disturbance, in contrast with late successional species that come in later.

Community assembly focuses on constructing and maintaining local communities through sequential, repeated immigration of species from the regional species pool. When designing restoration plans, the primary motivation for understanding how communities assemble is to predict how communities will develop over time.

Ecosystem properties describe the structures and processes of ecosystems and landscapes in their spatial and temporal variability, for instance, soil properties, biotic material production, nutrient cycles, and biological diversity. Ecosystem properties characterize its size, biodiversity, stability, functions, and processes. In restoration, ecosystem properties influence how a site responds to disturbance and degradation. Knowing ecosystem properties allows us to decide which restoration methods are adequate for the project goal and the ecosystem per se.

Landscape ecology studies patterns and interactions between ecosystems and ecological processes within a region of interest. It can happen in different scales and includes understanding how the interactions among social and ecological components affect and are affected by spatial configuration.

Natural or anthropic ecosystems are dynamic and complex. In any forest restoration case, but especially when the goal is to achieve *ecological restoration* (see Section "Glossary"), it is essential to deeply understand the ecology of restoration and the

socioeconomic determinants of conservation or use of natural resources. After setting the region and place of forest restoration, practitioners must gather a comprehensive review of literature on the ecological basis of the forests once found in the region and gather local specificities such as climate and social data. Complementary studies may be necessary to avoid setbacks, complementing the knowledge available. In many cases, it is possible to adapt experiences from different ecosystems. Before implementing a forest restoration project, several ecological factors, such as forest structure, species richness, functional diversity, and natural interactions and disturbances, must be considered.

Forest recovery occurs in a sequence of intertwined stages in natural forest ecosystems, typically called forest succession. The species that colonize early stages, where plenty of light is available and soil conditions can be harsh, are not the same species that grow in a forest-like environment, with shade, covered soils, and some structural complexity. Thus, inadvertently, a practitioner can introduce a tree species that do not thrive because it is not at its proper moment in succession; this species may need the 'facilitation' provided by other pioneer species, like shade, absence of invasive grasses, and more air humidity.

Tree species depend on several interactions with biotic and abiotic factors. For example, a tree species may only be pollinated with the presence of some specific insects, such as bees or ants. Even the acquisition of nutrients may depend on the presence of soil microorganisms. For example, legume tree species need bacteria interaction to absorb nitrogen. A net of fungi mycelium (called mycorrhizae) facilitates nutrient absorption by amplifying tree roots' contact surface on a mutualistic association. Abiotic factors such as water availability and optimum microclimate conditions are essential for plants' metabolic functioning.

Therefore, a forest is not formed only by trees, or it would be an empty forest: it has to have fauna (mammals, birds, insects, soil fauna, etc.), non-tree plant species like vines and epiphytes, fungi, and their functions, and interactions. For restoration projects with conservation goals, a practitioner may need to plan interventions to guarantee the return of specific groups. On the other hand, planning a large-scale restoration with multifunctional goals is complex and sometimes unmanageable once several variables in a dynamic condition over space and time influence the forest restoration outputs. A way to overcome such complexity is to have a multidisciplinary approach, such as a complementary collaborative team, to deal with different issues.

Local References

For ecological restoration, the aim is to achieve similar conditions to the forest that once occurred in the same area or nearby natural forests. Therefore, studying such reference forests, conducting historical research with literature, and consulting local communities are crucial steps to the understanding of biological patterns such as forest structure (tree sizes and composition, fauna interactions) and identifying natural disturbances that may be important for that ecosystem and may need to be restored before or during the new forest implementation. One can find an example of natural disturbance restoration in the study cases session, where practitioners had to restore the hydrological regime of the river to allow the recovery of the associated wetland riparian ecosystem, achieving the restoration goals.

When an old forest fragment is available in the region, it is essential to establish some forest plots and conduct inventories to serve as references. A clear view of the reference forest's several aspects combined with the project area's diagnosis makes it easier to visualize what to expect from a restoration project. Such understanding is necessary for setting feasible goals and determining where further action is needed.

Prior Restoration: Site Selection and Diagnosis

Restoration projects can be costly and long-lasting, reinforcing the need for careful planning, well-defined goals and objectives, and a viable implementation, maintenance, and monitoring plan. The goals can guide choosing the restoration methods, and objectives need to be practical and measurable and follow timeframes. Practitioners must carefully plan the new forest, considering its ecology, sociobiodiversity, economic aspects, and other peculiarities. Local population knowledge must be considered as much as possible. Defining and mobilizing stakeholders from the beginning can benefit the project, guaranteeing its permanency and avoiding future disagreements.

Previously defining priority areas to restore is mandatory in most cases, and it can follow political agreements, opportunity costs, or law enforcement. It is also essential to consider the existence of local infrastructure (roads, companies, markets, forest restoration inputs - e.g., seedlings) and the degree of social importance in providing ecosystem services. On a large scale, the definition of areas for initiating forest restoration programs can be driven by spatial studies aiming to minimize costs and maximize benefits.

Once the forest restoration area is defined, baseline inventories must be conducted (in the reference forest and) in the chosen area for restoration to allow an accurate diagnosis and support the choice of the proper techniques (e.g., soil pH correction or invasive species control). In the future, baseline inventories will also be necessary for comparison with monitoring inventories (see monitoring session). In the case of ecological restoration, an initial inventory of nearby forests will serve to build a reference model. In addition, other information must be gathered to understand local singularities, such as land use history, local and nearby degradation factors, and geomorphology, which will guide the choice of the best restoration or reforestation methods and techniques.

While in the diagnosis phase, one crucial aspect is whether forest regeneration is possible. Several strategies can be used to identify preconditions; natural regeneration can thrive in a place with a good ecological memory. For example, it is possible to use

satellite imagery to identify forest remnants in the landscape or the possibility of connecting two or more forest fragments. Sequential images may help identify previous uses or the occurrence of natural regeneration in degraded areas. Sampling soil and seed banks can help to determine the existence of viable germplasm and the possibility of spontaneous germination. In addition, it is essential to observe the occurrence of natural dispersers and pollinators such as birds and bees. Any forest restoration will benefit from well-established planning and monitoring settings.

Forest Restoration Plan: Methods and Techniques

Following the selection of the restoration area, practitioners will consider the best model. The forest restoration models generally correspond to a gradient of species composition from the simplest, such as reforestation with monocultures of native species for forest production (e.g., timber or non-timber products), to the most biodiverse model, similar to a reference area in the same region, to achieve strong ecological objectives. In both cases, the method used for forest restoration can be determined - from natural regeneration to active tree planting. For each method, several techniques - technical strategies applied to restoration, specific for a given area in a given model and method - can be applied to promote the restoration.

Considering the need for management interventions, multiple factors evolving the planned goals and objectives must be considered. The planned implementation strategies must consider logistics to effectively employ chosen methods and techniques.

Methods

Conducting natural regeneration is relatively cheap and has a high chance of success in situations where and when local ecosystems still maintain good levels of resilience. On the other hand, active restoration is indicated in situations such as old and intensively explored agro-pastoral lands (after long-term use of herbicides, fertilizers, and soil mechanization), mining with topsoil removal, and intensive slash and burn farming (e.g., soil structure fragility, low natural fertility), absence of nearby forests (causing the absence of propagules for natural regeneration). Sometimes conducting natural regeneration will promote slow and fragile recovery or even a stagnated state over time. When frequent over time, land use disturbances progressively eliminate the sources of propagules, undermining the reestablishment of the local biodiversity, determining an absence or low ecological resilience of the landscape, which reinforces the importance of knowing the land use history, a crucial part of the diagnosis of the area.

The term "passive restoration" (or natural regeneration) is used for natural forests, where practitioners do not choose the species composition to be implemented or do big intervention. While "active restoration", directly seeds or seedlings planting is performed, and it has more applications for many ends, including forestry. In between both methods, several techniques can be used for conducting an "assisted passive restoration" (or assisted natural regeneration), with an intermediary level of human intervention. Such methods should be considered on a continuum and not in categories, but for facilitating the understanding we are going to split in three categories.

Natural regeneration

Whether it is possible to use natural regeneration, assisted or not, it is the best choice for its low cost and no need for complex planning and deep ecological knowledge. In this sense, the area's first actions to be promoted aim to activate its full potential for ecological recovery. Isolating the area to avoid animal grazing and trampling and controlling competition, combined with the removal of other degradation factors, such as soil erosion, fire, and herbivory, enable the (re)colonization of native species.

In conditions where the target area has no serious degradation factors, it is possible to use a non-assisted passive regeneration, the lowest-cost forest restoration method. Adopting this method does not mean abandoning the area and must be done by monitoring the recovery of ecological processes. A challenge is effectively identifying any need for assistance. The loss of attention to undesirable processes occurring inside the forest in the early stages, like insect attacks, intense competition, and colonization by one or too invasive species, may lead to setbacks on the project.

Assisted natural restoration

This intermediary method is based on directly assisting some of the regenerating seedlings and planting additional trees in empty spaces. In such cases, it is possible to adopt techniques to drive good-quality natural regeneration. Some techniques are used for this end, such as nucleation and the transplant of the soil seed bank, described in the 'techniques' session.

Active forest restoration

Sometimes, it is impossible to assist natural regeneration in the target area due to the loss of natural resilience. In that case, the alternative is to introduce an initial tree community, creating the biophysical conditions required to start the ecological succession. In addition, active restoration can benefit from agricultural species to initiate the process by planting agroforestry systems.

The success of active forest restoration depends on the correct application of methods and techniques. These interventions recreate a natural and complex system once it is necessary to establish several ecological processes in the target area in a reasonable time. Active restoration may only succeed by establishing critical ecological processes such as nutrient cycling, pollination, and

seed dispersion, combined with increased organic matter and associated microbiota. An efficient forest restoration will activate the successional replacement of species and recover functional diversity by developing an ecosystem structure.

When not well planned, in some cases, all the planted individuals can die quickly; in others, some remain, but many spaces remain open. In other cases, the fast cycle of pioneer species ends, and there is no continued natural regeneration. If the forest dynamic is not reestablished, it is essential to note that it probably needs adjustments that can be provided in time based on a sound monitoring schedule and adaptive management decisions. The first tree planting comprises a few trees and bushes that will enable other species to colonize the area after fulfilling its required biophysical conditions. In this sense, the first individuals planted in the target area must shadow and protect the soil, avoiding the intensive colonization of exotic grasses and erosion, providing food and shelter to the first animals and insects to visit the area, and creating favorable conditions for the beginning of ecological processes.

A diverse tree community can be implemented through seedling planting, direct seeding, and propagation using forest topsoil. Therefore, following the first implementation, where many species are planted simultaneously, a good proportion of species can be planted at different moments to ensure higher biodiversity, for example, every five years until the forest reaches 25 years. The number of needed species to guarantee good biodiversity levels may vary along regions. For example, temperate forests may have less than five tree species plus understory species. At the same time, the diversity in the tropics can be very high, with more than 50 species per hectare.

Once the species are chosen, it is necessary to consider how to plant them. Generally, the main objective is to plant species in a reasonable proportion of successional (or functional) groups to allow the fast covering of the area and establish a forest structure in the shortest time possible. The groups can be composed by covering species and diverse species to ensure the presence of pioneer, secondary, and climax species in a good number and protect the soil faster, also ensuring the transition of the forest canopy through the successional path. In addition, green manure species, such as many legume shrubs, are used to improve soil conditions super quickly while shading the soil for late-successional species.

Techniques

After defining the strategy to restore a given area using adequate forest restoration models and methods, it is necessary to apply valuable techniques on soil preparation, then proceed with the active plantation (not in strict passive restoration) and, if necessary, posterior management actions. In this way, a group of operational proceedings can be used.

Competing species, such as exotic grass, may need to be controlled, allowing natural regeneration and seeds or seedlings to grow. Other techniques include the removal of invasive tree species and enrichment planting.

Techniques for passive restoration (assisted or not)

Removal of competing and invasive species: Even when the vegetation has a strong potential for recovering alone and starting the successional process, some exotic (or alien) or even native invasive species can grow faster and so intensively that they inhibit or even suppress the development of desirable native species. The suppression occurs by the dominance of the growing space (such as canopy in the case of adult trees) and the consequent deprivation of factors that could enable the total development of desirable native individuals. Therefore, removing some or all individuals of competing species may be necessary, aiming to gradually shift to a biodiverse forest from the understory to the canopy.

Tree planting in natural regeneration: This method is used when more than the natural regeneration is needed to cover the entire target area, as in cases when some spaces show no signs of native tree species growth. In such cases, it is possible to scatter plant seedlings or to sow native species aiming to recover empty spaces. This technique is usually applied in cases of assisted natural regeneration.

Enrichment planting: This technique is employed when the natural regeneration cover occupies all rooms of the target area, but the species composition presents low biodiversity or when practitioners aim to insert valuable species to enable cash flow. Therefore, this technique can use secondary, late secondary, climax species, or other species different from those already existing in the target area.

Techniques for active restoration

Some techniques are used when active forest restoration is chosen, but most can be adapted for both methods.

Pre-planting

Soil recovery: Soil recovery must precede restoration to control erosive processes caused by extensive soil exposure. Suitable nutrients, organic matter, and physical conditions must exist in the topsoil for water to infiltrate and for roots to develop. The soil recovery through a biological process (e.g., the growth of trees) will occur after the isolation of degradation factors such as soil exposure (e.g., by physical interventions, planting legume species of fast growth). It can include several other techniques to prevent erosive processes, increase organic matter, and restore the hydric balance.

Control of herbivores and plant competition: It is necessary to avoid excessive herbivory (e.g., ants, grasshoppers) in cases where this process will lead plants to die. Another situation is when ruderal plants, usually exotic, rapidly colonize the area. These plants, constituted by different kinds of exotic invasive grasses, palms, or large herbaceous, have very plastic physiology and strong

resistance to harsh conditions that could limit the establishment and development of the species of interest, representing a risk to the project. There are several procedures and instructions for conducting pest control, and the orientation material is easily found. Still, it is always important to carefully analyze if this step is necessary and how to do it to avoid high costs and harmful impacts.

Physical soil preparation: Physical impediments must be removed for plant development. For instance, plowing the ground may be necessary if dense or compact layers could result in a physical barrier to the roots. Considering situations where the forest restoration project is close to small rivers and other water courses, every soil preparation must be done in the planting lines using contour planting in slope situations or restricting to the seedling hole to avoid a vast transport of soil particles to the river.

Fertilizing: This procedure is essential to give the plants optimal resources in terms of nutrition to a good establishment on the field. The fertilizing must be done considering the chemical analysis of the soil and the plant requirements, which will drive the kind of fertilizer and its formulation. In some cases, control or correction of the soil acidity may be recommended, which will avoid immobilizing essential nutrients to plant development (e.g., phosphorus).

Planting

The planting is when the seedlings or seeds of the chosen species are placed in the soil ground, which can be done manually or mechanically after being evaluated in terms of area size, number of plants or seeds, spacing (between plants in case of seedlings), costs, and labor availability. The spacing can be defined as the area necessary for a plant to obtain resources and outcompete, considering closing the canopy at some point. When practitioners want to allow the entrance of machinery into the field or, in some cases, to thin some trees after a few years, it is necessary to set a larger space between planting rows. At the planting moment, it may be necessary to remove the seedlings recipient (if it is not organic and easily degraded) but avoid the destruction of the soil bulk that protects the roots. In dry regions, a super absorbent moisturizing gel can be used in the soil before planting, increasing the chances of plant survival in hydric-deficit conditions.

Nucleation: This technique is based on the creation of the nucleus of vegetation to create optimal microclimate conditions (e.g., humidity, temperature, and light), improve the edaphic state (e.g., nutrients cycling, organic matter, porosity and fertility, and microorganisms) and attract dispersers. Such conditions may favor the nucleus expansion until forming a forest physiognomy. Therefore, this technique is considered an excellent cost-effective forest restoration method.

Seedling planting: Planting seedlings in the full extension of the area is applicable when the local presents a high level of degradation, with reduced resilience and far from forest remnants. It may be performed after completing the previous steps, such as soil recovery, preparation, and competition control. Its basic premise is to cover the area with the desired species and allow the formation of a forest physiognomy fastly. In order for the plants to grow and adapt to field conditions, they must be planted during the rainy season. However, only planting and abandoning the area will not guarantee forest formation. It is essential to have a growth monitoring plan in the first years.

In ecological forest restoration, seedlings' species choice is based on functionality and forest succession concept but is not anchored in the classification of successional stages. In highly-diverse tropical forests (mainly in Brazil), in a general sense, it is usual to separate the tree species into two groups: "covering" (or filling) and "diversity". While the covering group is composed of a few fast-growing pioneer species with high dominance that can quickly shadow the soil and temporarily control and suppress exotic weeds, the diversity group is composed of a higher number of species that will benefit from the "filling" shading and perpetuate the forest.

Without the secondary succession, in the presence of an active seed bank of alien species in the ground and with long distances to other forest remnants, the death of trees and canopy opening may allow the recolonization of exotic species and the decay of the planted forest. To avoid this situation, it is recommended to consider using species that cover the area as quickly as possible (covering group) and a high diversity of secondary and late secondary species. Besides, it is important to avoid allowing dominance of a few species in the species proportion and, if necessary, perform silvicultural management actions in the first years after planting, which include thinning, pruning, control of insects, and competition.

Staggered planting: The diversity group usually is planted together with the covering group to avoid excessive planting and area preparation costs and to ensure the gradual shifting of the covering species by a diverse group of species. When there are enough propagules from the diversity group, this group must be implemented a few years (from 1.5 to 3 years in tropical regions) after the initial planting of the covering group. It is important to clarify that we do not recommend the best planting approach to be implemented in the field; instead, we give some examples and suggest practitioners do field experiments to find the best species combination and planting technique to adopt.

Direct seeding: Direct seeding corresponds to the distribution of seeds in the target area. This technique is known for reduced costs and allowing physiognomy formation more adapted to the condition in which the seeds germinate. Even after good soil preparation preceding the planting moment, it is necessary to use a high number of seeds since the germination rate is reduced. For choosing this technique, it is essential to evaluate the forest restoration goals, as the demand for specific species composition or the higher time needed for the forest to grow.

This technique is highly dependent on the disponibility and quality of the seeds. Therefore, the practitioners must pay attention to the phytosanitary aspects and the condition of storage and benefiting of seeds which, when in good condition, enable the maximum physiological capacity. Also, it is necessary to identify the need for additional treatment, such as seed dormancy breaking, and the proportion between species efficiency in obtaining healthy individuals after initial germination and growth. Check in the study cases session the example of "The Amazonian Muvuca", where they successfully recover forests using direct seeding.

Forest topsoil seed bank transposition: The topsoil of a healthy forest, including its leaf litter, organic matter, micro, meso, macrofauna, and set of native species seeds, is a rich material that can be used to start a forest in a degraded area. The topsoil potentializes the colonization of an area and can be used together with the nucleation technique to start succession. Regarding the species composition in this technique, it is important to note that due to years of evolution and adaptation, the soil seed bank mainly consists of pioneer species. Once the pioneer is the first to colonize an area, its dispersion is abundant and intense. After reproduction, the seeds dispersed will find a biophysical condition different from the ideal to pioneer species growth - the open and sunny space. So, under this conduction, the seeds sit on the soil, waiting for a favorable condition (e.g., canopy opening) to activate the germination process physiologically. With these aspects, it is possible to stimulate the soil seed bank in areas with recent disturbance history by exposing the seeds to their physiological requirement condition, delivering a faster colonizing.

On the other hand, secondary species are less present in seed banks since they germinate fast. The process of obtaining the topsoil involves scraping forest soil to allow the removal and transport. However, removing the topsoil can cause ecological impacts in the forest, being necessary to use only small patches in case the original forest is aimed for conservation. The best solution is to remove the topsoil from forests that will be legally suppressed, such as those authorized for companies or public interventions aimed at improving social conditions (e.g., urban area expansion, highways, etc).

Post-planting management

After performing all operational steps and implementing the new forest, post-planting management can be planned. After stimulating the initial colonization of the area, it is necessary to monitor the plantation, which constitutes a phase of the forest restoration project called maintenance. This phase covers many steps, such as replanting in case a high rate of seedlings death is identified, and avoiding open and unprotected spaces. Another maintenance step is applying covering fertilizers to add more nutrients to be absorbed mainly by leaves and monitoring and controlling undesirable plants, thinning and pruning to open spaces to the desired species (such as native tree species present in the understory), and controlling vines. All these steps must be planned regarding labor availability, equipment (costs, sizes, fuel, operation permits, and maintenance), and other technical and technological concerns.

Thinning: Thinning is a management technique applied a few years after planting. Before the thinning, a high density of plants can stimulate the plants to grow in height through the competition by light. The opening of gaps promoted by thinning accelerates the increase in diameters on the left individuals, while selling the harvested lungs may reduce the payback time.

Monitoring

Monitoring is a crucial part of a forest restoration project since it is the only way to verify its success. Monitoring is checking the status of an area of interest and periodically tracking changes. It may happen before (baseline inventory) and after implementing the restoration of a forest. Monitoring verifications may occur in pre-planned frequencies or on-demand, serving as the basis for verifying the forest restoration success or detecting the need for interventions. Traditionally, the monitoring process has been held in situ, with the placement of forest plots or other sampling designs. However, with the scaling-up of forest restoration projects and advances in remote sensing technologies, conventional monitoring can now be combined with remote monitoring to improve outcomes and reduce costs. Therefore, it is imperative to collaboratively develop monitoring protocols to have repeatability and comparability of outcomes.

Field monitoring includes a set of measures necessary to diagnose the target area situation comprehensively. In baseline, inventories of deforested areas, herbs, soil, and water analysis may be enough. Identifying weeds or the existence of native herbs is important for decision-making. Soil sampling may include a seed bank and chemical and physical analysis, while water measurements can be focused on water quality (e.g., sediment measurement) and analysis of soil infiltration. After the forest implementation, measuring and identifying vegetation components, especially tree species, is key for having comparative values to check the feasibility of pre-planned targets (e.g., for a tropical forest to reach 1000 trees per hectare distributed in at least 50 different species in the 10th year).

Multiple remote sensing systems are being used to monitor forests worldwide. Conventional photographs were probably the first remote sensing method to monitor forest recovery, followed by aerial photography, then the first sensors onboard satellites, culminating in today's imagery achieved by flying drones. Multiple sensors were developed in recent decades, allowing us to see more than the visible colors and features. Now we can build 3D forest models with canopy heights and other physical features, detect water under canopies, and see leaf details for identifying species, among others. Using image time series for monitoring forests, we can track forest restoration with a fine time scale resolution (e.g., every 15 days using Landsat or Sentinel missions, free imagery).

Not only do trees compose a forest, but it also has a set of other forms of life between plants (mosses, ferns, vines, epiphytes, etc.), animals (ants, bees, birds, mammals, etc.), and other living beings that interact among them creating complex structures. Monitoring different forest components is important for guaranteeing, for example, that animals returning to a restored area have a shelf, food, and water to keep their life cycles and are acting as disperses and pollinators for trees. There are different ways to monitor animals, like traps, cameras trap, sound recorders, observation, etc.

Adaptive Management

Adaptive management (AM) is a decision-making process that consists of experimentally applying management actions. Once the responses of forest restoration can go in different, unpredictable directions, corrective actions may be necessary, but just adapting to unexpected situations can be counterproductive. First, monitoring, then consulting previous results, and wisely applying corrective actions to learn from the outcomes will improve restoration success probability and reduce uncertainty. The correct application of AM consists in detecting what went wrong based on monitoring results, using existing knowledge to explore alternative paths, deciding on the best approach, then experimentally applying the action and monitoring again to evaluate the success or detect the need for further actions (Fig. 3).

Several factors can cause unexpected results from forest restoration. One example can be the hypothetical situation where an unforeseen frost causes the death of 80% of the seedlings. This is a situation where post-disturbance monitoring must be conducted, and further management should be considered and carefully analyzed. Unexpected results can also come from unknown sources, which requires further investigation. Adaptive management solutions, based on robust evidence, can make use of biotic elements, such as biological control with natural enemies.

The entire AM process must be recorded and, if possible, shared to provide information for future projects and adaptive management. Sharing learned lessons in scientific papers, books, booklets, online study cases, or other forms can help practitioners to find or create solutions.

Conclusion

Ecological and operational aspects of forest restoration were described in this article, and essential definitions were presented to allow a straightforward narrative following a thinking flow. This is not a forest restoration protocol since a thorough diagnosis of each situation is highly needed for planning a successful forest restoration project. The evaluation and protocol must cover the local social, biological, ecological, edaphic, and climate conditions, as well as the main goals and objectives of the restoration project.

The successful restoration of large areas worldwide demands local multidisciplinary collaboration and long-term planning. Coordinated actions may happen with the involvement of a diversity of stakeholders, robust scientific knowledge, consideration of local aspects, and well-defined goals and objectives. The implementation demands the correct models, methods, techniques, and best practices. As long-term endeavors, forest restoration projects need frequent monitoring and adaptive management. Forests are alive superorganisms and must be treated as so.

The expansion of forest restoration is an urgent need for the planet. Conserving biodiversity and recovering ecosystems and their services is unavoidable, but proper actions must be taken to succeed. There is not a single place on earth where the effects of climate change are not perceived. Still, the socially vulnerable regions are the most affected by extreme events or rising temperatures. Governments and civil societies must take synchronized actions to revert this situation. Long-term, evidence-based scientific studies highlight ecological restoration as an important action to be urgently implemented.

Study Cases

The Amazonian Muvuca

In 2007, a group formed by local indigenous and riverine people living inside the Xingu Basin (Xingu River is a large tributary of the Amazon River), with the support of NGOs and scientists, started collecting seeds of local native tree species for selling to local farmers in debt with forest cover obliged by law. The collective was formed in response to an indigenous appeal asking for protection of the basin headwaters since indigenous lands downstream were intact. Still, old deforested surrounding farms were harming the entire watershed healthy.

With seeds of a genetically trackable and diverse set of species, they directly planted new forests by sowing, on prepared soil, a mix of native tree seeds with green manure (legume) species. The seeds mix is locally called *muvuca* (which in Portuguese means agglomeration); see Fig. 4. Such a network of seed collectors is an example of multiple stakeholders' involvement in benefiting the environment and society by generating financial resources for seed collectors and recovering forests. The network of seed collectors has grown significantly since then, today with more than ten initiatives around Brazil.

Besides the local governance success, the initiative to restore riparian and headwaters forests in the Xingu basin using direct seeding already has some important outcomes. In the first decade of the restoration by different techniques of direct seedling, a study reported that a resilient and stratified forest structure was being formed, not only by the planted species but also by the spontaneous entry of different species. This shows a low-cost active restoration effort that can be used to reactivate the natural forest's capacity to regenerate itself.

Rewilding Europe

Increasing forest cover is important to allow the growth and movement of many species from wild populations, but coordinated actions are required to facilitate recovery. The European wilderness has significantly grown in recent decades due to a combination



Fig. 3 Framework for the adoption of adaptive management.



Fig. 4 Muvuca, a set of native tree species and green manure species, being prepared to be mixed and directly seeded on previously prepared soils along the Xingu River Basin. (We thank Marcela Melry Mateus Deluce for kindly providing this image).

of factors since the increment in forest cover by the creation of protected areas or natural regeneration following land abandonment caused by rural-to-urban migrations, hunting regulations and management frameworks, and change in human perception on the benefits of conservation. While active reintroduction programs have been implemented to help wild animals return to their niches, lynxes, wolves, and bears, have naturally recolonized their original areas, even spreading further. To facilitate the monitoring and managing of carnivores, guidelines for populations were established by the European Commission to avoid the difficulties imposed by subnational administrative units.

A proposal for restoring Spain's Mediterranean Landscapes without reducing agricultural production is adopting strategic revegetation actions to reconcile agricultural production with wildlife. Such actions comprise combined actions, with few abandoned lands for conducting new forest fragments with the active implementation of hedgerows between crop fields, creation of woodland islets and restoration of riparian flora, and revegetation of roadsides and roundabouts.

Floodplain Forest Restoration in North America

Floodplains are rich wildlife habitats that profoundly depend on their natural river flows, all of which have been adapting to the flow regime for centuries or even millions of years. Most species, mainly plants, cannot adapt to major flow modifications caused by dams or other high-impact anthropic river interventions such as irrigation diversions. The downstream effects of river interventions range from physical changes, such as sediment depletion, to biological disruptions.

In North America, planned efforts to replicate the natural river flow as similar as possible to the original had been notably successful. The first step was recognizing the value of river corridors and then acknowledging that vegetation plantings cannot thrive without reestablishing hydrological and geomorphic processes. Then systemic approaches were proposed to focus on the entire ecosystem and not only specific targets. For example, early proposals on maintaining the river flow were based on the minimum flow acceptable to keep some target forms of life, but the minimal flow approach created several problems, such as inducing chronic stress on rivers and floodplains. As a response, researchers developed the concept of instream flow needs (IFN), which turned into a quantitative method to ensure a growth flow.

Despite many efforts to safeguard the aquatic biota, a more floodplain-focused approach was proposed for reestablishing some river flows in western North America where river managers (e.g., dam operators) were able to collaborate. One of the interventions took place in Canadian and US rivers. It combined several techniques, from minimal flow to a "recruitment box model" that aims to simulate the ideal conditions for recruiting cottonwood and sandbar willow species. The case related here successfully allowed the restoration of floodplain forests and can be adapted for application in other parts of the world.

The Return of Mined Australian Forests

In Western Australia, the Alcoa company has been mining bauxite and restoring Jarrah (*Eucalyptus marginata*) dominated forest since 1963, today recognized worldwide as a reference on the development of an adaptive management program for restoring mined areas. The restoration program is mainly based on landform sweetening, soil decompaction, and the application of stockpiled topsoil and a layer of fresh topsoil with seed banks and microorganisms combined with planting woody species seeds and the use of fertilizers.

Several aspects were notably recovered over two decades after the post-mine active restoration, including resilience to extreme climate conditions. Despite species richness and forest structure being recovered, not all functional aspects reached comparable values to the reference forests. In 2005 the first certified recovered area was returned to the State of Western Australia.

African Agroforestry Parklands

In West Africa, traditional farmers have been using an ancient agroforestry system called "Parkland", where they farm the area but usually keep individuals of some dominant tree species with value, which could provide wood or non-timber products. Despite the inevitable domestication of the common tree species used in such systems, they still have a high potential to improve production with a good improvement in research and technology.

One of the most common species is the *Vitarella paradoxa*, the shea butter tree; the fat from its seeds can be used in the place of cocoa butter in the chocolate industry. Other species, such as *Adansonia digitata* (baobab) and *Parkia biglobosa* are commonly found in parklands. They show high potential for more directed development and use, generating value for the local communities.

Monoculture of Trees for Conservation of Threatened Species

Paubrasilia echinata

An iconic case comes from the first economic activity in Brazil. The Brazilwood (*Paubrasilia echinata* (Lam.) E. Gagnon, H. C. Lima & G. P. Lewis) from the Legume family (Fabaceae) is a native tree species from the Atlantic Forest. Its exploitation was the first economic activity practiced by the Portuguese during Brazil's colonization, starting in the 16th century. The species gained importance for the Portuguese because its wood had desirable physical and mechanical characteristics and, at that time, could be used to construct numerous objects (such as furniture and boxes). However, its large exploitation was mainly driven by its "intense red" colored wood resin, which was used to dye fabrics, which led the tree to the status of a commodity sold in Europe.

At the end of the 18th century, Brazilwood wood became the most used wood to manufacture high-quality bows for stringed instruments. An estimated 200 m³ of Brazilwood from commercial plantations is used annually for this purpose. Since its history of wood exploitation, the tree has been considered an endangered species (IUCN, CITES, and Brazilian red list). Brazilwood harvesting from natural forests is now illegal, and its commercial use (in planted monocultures) has been restricted by law. Nowadays, Brazilwood plantations are not only germplasm banks of the species but also places where it is possible to investigate how to use and conserve this species better, rescuing this rich native natural resource for the also threatened Atlantic Forest.

Aniba rosidora

Another example comes from the Amazonia forest, where reforestation with monoculture represents a strategy to conserve a threatened species. The rosewood tree (*Aniba rosidora* Ducke) is an Amazonian tree species that produces an essential oil highly demanded by the world's fine perfumery industry. Given this species' economic potential, rosewood's use followed the classic predatory exploitation model, where extractive entrepreneurs' primary purpose was the highest profit in the shortest time. Harvesting was based on indiscriminately cutting young and adult plants, making natural regeneration and recomposition of populations impossible.

Sustainability principles were never considered, and Brazil's drastic reduction of rosewood's natural populations led the species to a national endangered species list (IBAMA, 1992). Later, considering the species status in the entire Amazonia, the rosewood was added to the endangered species list of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora), which aims to guarantee that the international trade in specimens of wild animals and plants does not threaten their survival. Finally, in 2021 it was also included in the IUCN red list as endangered, reinforcing its critical situation. Since the species was overexploited in Brazil for decades, the creation of a specific policy placed rosewood under complete protection.

The current legislation allows rosewood exploitation only in well-established commercial plantations, and the technical and scientific criteria for planting, managing, and harvesting are being created simultaneously with the business activity. These plantations reduce the pressure on natural populations, generating jobs and income and promoting development in rural areas while representing a source of propagules, a bank of germplasm, and scientific investigations. Maués, a small city located southeast of the Amazonas State, has a forest reserve called Rosewood National forest. Researchers conducted a forest inventory where they did not find any rosewood trees in the forest reserve. Fortunately, the region comports the biggest rosewood farm in Brazil. The use of rosewood to reforest areas allows the redistribution of trees. With the crescent demand for forest restoration and the bioeconomy agenda to boost sustainable development, the State of Amazonas and the Federal Government of Brazil have stimulated projects aiming to boost the number of rosewood stands and the use of this species in different models of reforestation.

Acknowledgments

AFR and PMK thank FAPESP for the grants (#2019/24049-5 and #2022/07712-5, respectively). AFR, PMK, PHSB, and RRR thank FAPESP and NWO for the NewFor Project Grant (#2018/18416-2). RL thanks CNPq for funding his research activities (grant #306694/2018-2).

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