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Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits

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Abstract

Urgent solutions to global climate change are needed. Ambitious tree-planting initiatives, many already underway, aim to sequester enormous quantities of carbon to partly compensate for anthropogenic CO_2 emissions, which are a major cause of rising global temperatures. However, tree planting that is poorly planned and executed could actually increase CO_2 emissions and have long-term, deleterious impacts on biodiversity, landscapes and livelihoods. Here, we highlight the main environmental risks of large-scale tree planting and propose 10 golden rules, based on some of the most recent ecological research, to implement forest ecosystem restoration that maximizes rates of both carbon sequestration and biodiversity recovery while improving livelihoods. These are as follows: (1) protect existing forest first; (2) work together (involving all stakeholders); (3) aim to maximize biodiversity recovery to meet multiple goals; (4) select appropriate areas for restoration; (5) use natural regeneration wherever possible; (6) select species to maximize biodiversity; (7) use resilient plant material (with appropriate genetic variability and provenance); (8) plan ahead for infrastructure, capacity and seed supply; (9) learn by doing (using an adaptive management

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approach) and (10) make it pay (ensuring the economic sustainability of the project). We focus on the design of long-term strategies to tackle the climate and biodiversity crises and support livelihood needs. We emphasize the role of local communities as sources of indigenous knowledge, and the benefits they could derive from successful reforestation that restores ecosystem functioning and delivers a diverse range of forest products and services. While there is no simple and universal recipe for forest restoration, it is crucial to build upon the currently growing public and private interest in this topic, to ensure interventions provide effective, long-term carbon sinks and maximize benefits for biodiversity and people.

KEYWORDS
afforestation, climate-change mitigation, ecological restoration, forest landscape restoration, large-scale tree planting, natural regeneration, nature-based solutions, stakeholder participation

1 | INTRODUCTION

Trees, and the forests they form, are highly complex. Their interactions with other plants, animals and fungi, and environmental phenomena such as fires and flooding, have led to the evolution of a remarkable diversity of species, genes, functions and ecosystems. In Amazonia alone, it has been estimated that there are more than 15,000 tree species (ter Steege et al., 2020). Today, trees and forests provide people with invaluable products and services (Díaz et al., 2018), including food, medicine, building materials, fibre, shade, recreational space, pollution filtration and flood risk reduction, and they are essential reservoirs of carbon, water and nutrients.

The escalating and interconnected threats of **biodiversity** loss through **deforestation**, global climate change (GCC) and poverty have increased awareness of the mitigating role that forests could play (Brancalion & Holl, 2020) and have led to some notable global initiatives. (key terms are highlighted in bold on their first occurrence and defined in Table 1.) The role of forest **restoration** in GCC mitigation first received global recognition in 2008, when 'enhancement of forest carbon stocks' was added to the United Nation's **REDD+** initiative (UNFCCC, 2008; www.un-redd.org), with measures to ensure biodiversity conservation and community participation (UNFCCC, 2011; safeguards [d] and [e]). In 2011, the Bonn Challenge (www.bonnchallenge.org) was launched, aiming to restore 350 million ha of forest globally by 2030. Currently, more than 70 pledgers from more than 60 countries are restoring 210 million hectares of degraded and deforested lands (www.bonnchallenge.org/progress). In 2020, the World Economic Forum instigated an ambitious global tree-planting programme—the 1t.org platform—to support the UN Decade on Ecosystem Restoration 2021–30 (www.decadeonrestoration.org/).

These initiatives mostly advocate **forest (and) landscape restoration (FLR)**—an approach that aims to 'regain ecological functionality and enhance human well-being in deforested or degraded landscapes' (Besseau et al., 2018). However, concerns are growing that several ambitious initiatives are falling short of delivering on the three key objectives of carbon sequestration, biodiversity recovery and sustainable livelihoods (e.g. Figure 1; Lewis et al., 2019). They may have set unrealistically high targets (Fagan et al., 2020) and may have unforeseen negative consequences. Potential problems include displacement of native biodiversity, particularly due to the destruction of non-forest ecosystems (Seddon et al., 2019); increases in invasive species (Kull et al., 2019); a reduction in pollinator services (Ricketts et al., 2004); a reduction in croplands and thus food production; disruption of water cycles; a decrease in carbon stored in aboveground biomass (Heilmayr et al., 2020); a reduction in soil organic carbon (SOC; Hong et al., 2020; Veldman et al., 2019) and a lowering of albedo in boreal zones, causing temperature rises (Betts, 2000). These negative outcomes are mostly associated with the extensive use of exotic monoculture plantations, rather than restoration approaches that encourage a diverse, carbon-rich mix of native tree species (Brancalion et al., 2018; Heilmayr et al., 2020; Lewis et al., 2019). Lewis et al. (2019) estimated that only a third of commitments under the Bonn Challenge and other schemes aim to restore natural forests.

In naturally forested regions that have become deforested by human activities, we propose a 'native forest approach' to FLR, to increase carbon sequestration and other ecosystem services, accelerate biodiversity recovery and generate sustainable livelihoods. This approach emphasizes protecting and restoring native forest elements within a mosaic of land uses, which would typically include:

(i) **Existing native forest**, prioritized for protection, to safeguard carbon stocks, reduce emissions and conserve biodiversity;
(ii) **Restored native forest**, to maximize rates of carbon sequestration and recovery of biodiversity and ecosystem services, delivering sustainable economic benefits;
(iii) **Livelihood native forest**, to maximize economic benefits to local communities while significantly increasing carbon sequestration, biodiversity and ecosystem services, compared with intensive monoculture plantations;
(iv) Restoration and sustainable management of existing agricultural land, including through **agroforestry**, to provide a mix of carbon sequestration, biodiversity and livelihood benefits and reduce pressure on native forests;

TABLE 1 Glossary (terms highlighted in bold on first occurrence in the text)

Term	Definition
Adaptive management	An intentional approach to making decisions and adjustments in response to new information and changes in context
Afforestation	Creation of forest on areas not naturally forested in recent times
Agroforestry	Restoration and sustainable management of existing agricultural land through integration of trees in the agricultural landscape
Applied nucleation	Planting trees in small groups or 'nuclei' and reliance on seed-dispersal out from such nuclei to restore forest cover across the entire restoration site
Assisted (or accelerated) Natural Regeneration (ANR)	Managing the process of natural forest regeneration to achieve forest ecosystem recovery more quickly, through interventions such as fencing, weeding and enrichment plantings
Biodiversity/Biological diversity	The variability within and between ecosystems, species and genetic material
Composite provenancing	The use of a mix of mainly local provenance material with a small amount from distant but ecogeographically matched provenances
Deforestation	Destruction and degradation of forest
Existing native forest	Old- and second-growth, degraded and planted forests
Forest (and) Landscape Restoration (FLR)	Ongoing process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes
Forest restoration	See Restoration
Framework species approach	Planting a mix of tree species, typical of the target forest ecosystem, that catalyse forest regeneration by shading out herbaceous weeds and attracting seed-dispersing animals.
Livelihood native forest	Mixed species forest with entirely or mostly native species, managed sustainably to provide local economic benefits
Natural Regeneration (NR)	The process of natural forest regrowth, which can occur spontaneously following land abandonment or be assisted by human interventions (see Assisted Natural Regeneration)
Non-Timber Forest Products (NTFPs)	Commodities obtained from a forest without logging, for example, fruit, honey, mushrooms, medicinal plants
Old-growth forest	Also called primary or virgin forest. Forest that has not been recently disturbed
Orthodox seeds	Seeds that tolerate drying to 5% moisture content and freezing at −20°C (approximately 92% of all plant species), as opposed to recalcitrant seeds that do not survive such conditions and would require cryopreservation (storage at around −196°C in liquid nitrogen) or direct cultivation
Outcrossing species	Species that reproduce by fertilization between gametes produced by different individuals
Payments for ecosystem services (PES)	Financial incentives for managing land that provides an ecological service, for example, watershed protection
Predictive provenancing (also called provenance transfer)	The use of distant genotypes that are experimentally determined to be adapted to projected conditions
Proforestation	Protecting existing natural forests
REDD+	Programme from the United Nations for 'Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries'
Reforestation	Re-creation of forest on a previously forested area
Restoration (forest restoration)	'The process of assisting the recovery of a forest ecosystem that has been degraded, damaged, or destroyed' (Gann et al., 2019)
Restored native forest	Native forest ecosystems reinstated on degraded land
Second-growth (or secondary) forest	Forest grown after recent human disturbance
Seed zone	An area within which plant materials can be transferred with little risk of being poorly adapted to their new location
Selfing species	Species that reproduce by fertilization between gametes within the same hermaphrodite individual
Soil organic carbon (SOC)	The carbon component of organic matter in the soil

(v) Protected native non-forest ecosystems (e.g. grasslands, savannas, wetlands).

Here, we build on current evidence and our own experiences to propose 10 golden rules (Figure 2) to support the delivery of the native forest elements of the FLR approach (i, ii and iii above), to jointly increase carbon sequestration and deliver benefits for biodiversity, ecosystem services and sustainable livelihoods. Agroforestry and intensively managed plantations are not within the scope of this paper.

FIGURE 1 Example of a problematic tree-planting initiative. In the highly degraded but previously mega-diverse lowlands of eastern Madagascar, large scale reforestation was carried out in the 1980s, covering thousands of hectares with the Australian *Grevillea banksia* and other non-native species. The initial intention was to provide communities with a source of firewood. This goal met with some success, but there were unintended consequences, such as displacement of croplands and exclusion of native biodiversity by the introduced species, with such species showing potential to become significantly invasive (Kull et al., 2019; Credit: AA)

These golden rules provide guidance designed to help policymakers, advisors and practitioners of reforestation projects avoid many of the pitfalls of large-scale tree-planting initiatives that are currently causing concern. They are in line with the International Principles and Standards for the Practice of Ecological Restoration (Gann et al., 2019). We use the term '**reforestation**' in a general sense to refer to the creation of restored or livelihood native forests by either tree planting or **natural regeneration (NR),** where forest formerly occurred naturally but has been lost recently. High-quality reforestation can be considered a nature-based solution (NbS) to the problems of biodiversity loss and climate change (Seddon et al., 2020) and, as such, our rules are allied to the IUCN Global Standard for Nature-based Solutions and associated guidance (IUCN, 2020), which sets out criteria to assess whether a proposed NbS addresses a societal challenge and guides users through aspects of its implementation.

2 | THE 10 GOLDEN RULES

2.1 | Protect existing forest first

Before planning reforestation, always look for ways to protect existing forests, including old- and second-growth, degraded and planted forests.

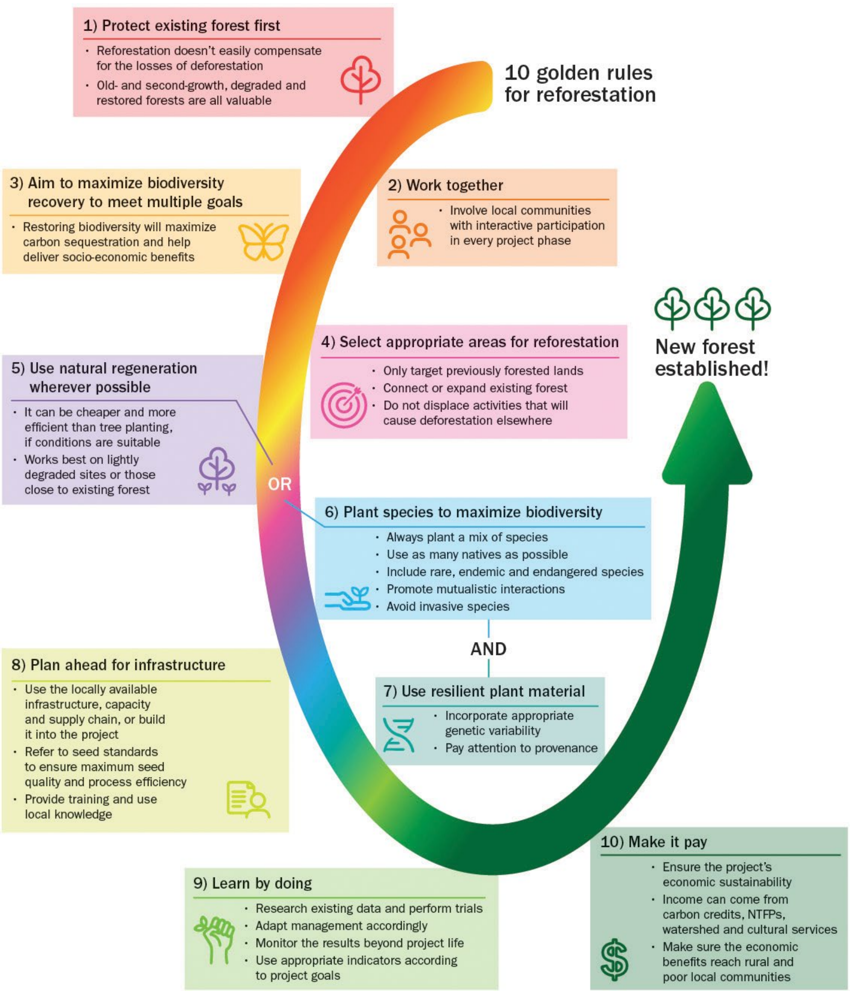

FIGURE 2 Ten golden rules for a successful reforestation project. The order of the rules matches the order in which tasks should be considered during project planning and implementation, although some are interdependent and should be considered in parallel. See text for details

The loss of natural forests continues relentlessly, despite global efforts to arrest it. In the humid tropics, an average of 4.3 million ha of **old-growth forest** was destroyed each year between 2014 and 2018 (NYDF Assessment Partners, 2019). The New York Declaration on Forestry (NYDF; https://forestdeclaration.org) aimed to reduce deforestation by 50% by 2020, while the United Nations Sustainable Development Goals aimed to end it by 2020. Not only have both these targets been missed, but tropical deforestation has actually accelerated by 44%, compared with the 13-year period immediately before the NYDF in 2014 (NYDF Assessment Partners, 2019). Deforestation on this scale results in huge CO_2 emissions (Seymour & Busch, 2016).

These losses of natural forest are not readily compensated for by reforestation (Brancalion & Chazdon, 2017; Meli et al., 2017; Wheeler et al., 2016), and neither forest protection nor restoration should be invoked as a reason to destroy natural areas elsewhere (Gann et al., 2019). Intact, old-growth forest is a major long-term carbon sink due to its complex structure, large trees, accumulating soils and relative resilience to fire and drought (Luyssaert et al., 2008; Maxwell et al., 2019). The IPCC acknowledges that '*most [destroyed] forest ecosystems will take longer than 100 years to return to the level of biomass, soil and litter pools* [found in forest in an] *undisturbed state*' (Aalde et al., 2006). Recovery of ecosystem services and biodiversity may take centuries, especially the return of rare or endemic species, which are particularly vulnerable to disturbance (Gibson et al., 2011; Rey Benayas et al., 2009). Extinct species, of course, will never return. Such a steep decline in intact forest also threatens indigenous cultures and human health (Watson et al., 2018). Large areas of remnant forest, with healthy, genetically diverse populations of common plant species are essential to supporting reforestation efforts. They provide the seed rain for NR (Rule 4); a source of seeds, wildings and cuttings for the production of resilient planting stock (Rule 7); and they provide habitat for supporting biodiversity, including seed dispersers and pollinators.

It is therefore vital to protect remaining natural forests—'**proforestation**', sensu Moomaw et al. (2019). Intact, old-growth forest is of the greatest value for carbon storage (Maxwell et al., 2019) and wildlife (Deere et al., 2020) and should be prioritized for protection. However, degraded or logged-over forest often dominates the remaining forested land (especially in Southeast Asia; Bryan et al., 2013) and also needs protection to prevent continued disturbance and further long-term carbon emissions (Maxwell et al., 2019; Reid et al., 2019). If allowed or encouraged to regenerate (see Rule 5), it will often rapidly recover biomass, resulting in high rates of carbon sequestration, especially in areas of high water availability (Poorter et al., 2016).

Action at both national and local levels is needed to protect forests. Persuading governments and corporations to create and enforce protected areas and legislate against forest conversion can be effective. For example, Brazil's Soy Moratorium (2006) and Cattle Agreement (2009) achieved some success in reducing soy and cattle-driven deforestation in the Amazon (Nepstad et al., 2014), although they may have displaced forest conversion to the Cerrado biome, which saw a spike in deforestation in 2011 (Soares-Filho et al., 2014). The first step towards successful protection at the local level is often identification of the drivers of deforestation, among *all* stakeholders (Rule 2). Encroachment may be tackled by developing alternative livelihoods (Rule 10). When fire is a risk, collaborative community groups can take action to raise awareness, organize fire patrols and install fire breaks while overgrazing can be reduced by controlling livestock density, fencing or by instigating cut-and-carry feeding systems.

2.2 | Work together

Involve all stakeholders and make local people integral to the project.

The scale and goals of reforestation projects determine their impacts and therefore affect who should be involved. For example, reforestation on smallholder farms can be done without wider stakeholder engagement being necessary. For large-scale reforestation projects, engagement of multiple stakeholders is required, to meet the diverse goals of enhancing rural livelihoods, biodiversity conservation, carbon sequestration, watershed protection and the provision of other ecosystem services (Erbaugh et al., 2020). A survey of adaptive forest management and FLR projects around the world found that conflicting goals between local communities and project managers and lack of community involvement were the most commonly cited causes of project problems or failure (Höhl et al., 2020). Stakeholders might be directly or indirectly affected by a project's outcomes and impacts (Erbaugh & Oldekop, 2018) and may include national and local governments, forestry departments, NGOs, civil society, the private sector, landowners, farmers and other land users, as well as universities, botanic gardens, herbaria and other research institutes.

For successful outcomes in both forest protection and reforestation, it is vital to include local communities from the planning stage through to delivery and monitoring (Bloomfield et al., 2019). They are the key to success and have the most to gain from the project. If their needs are heard and taken into consideration, and they are informed about the environmental issues the project is addressing, they are more likely to support the project and help to deliver successful outcomes in the long term. Simultaneously, community provision of labour for forest protection, land preparation, planting and maintenance provides an opportunity to diversify local employment, thus improving livelihoods. The realization of multiple positive outcomes through community engagement has been documented in Nepal, through community-based forest management (Oldekop et al., 2019), in the Dodoma and Shinyanga regions of Tanzania, through the *ngitili* system that uses traditional local knowledge and participatory land use planning with the government and other stakeholders (Duguma et al., 2015), and in several other initiatives in Madagascar and the Brazilian Amazon (e.g. Dolch et al., 2015; Douwes & Buthelezi, 2016; Urzedo et al., 2016).

Five levels of community participation in projects have been recognized (Gann et al., 2019), ranging from weak or passive at Level 1 (simply informing stakeholders) to fully active at Level 5 (full support and optional involvement, self-management, benefit sharing and succession arrangements). Increasing engagement increases positive outcomes, including equitable distribution of benefits, knowledge, natural capital, economic sustainability and community well-being (Oldekop et al., 2019). Reforestation project activities should consistently aim to actively engage local communities by interactive participation or self-mobilization where their vision and objectives for reforestation are taken into full consideration. Passive participation can lead to community hostility and disputes over access rights, which may be manifestations of underlying or deep-rooted issues, such as conflicts over land tenure (Agrawal & Redford, 2009; Chomba et al., 2016).

It is crucial to note that communities are not homogeneous units (Agrawal & Gibson, 1999). They comprise groups of people differentiated by wealth, ethnicity, gender and other socio-economic stratifications that have different power relations and interests in the reforestation process. For instance, in some countries, men and women have different rights to land and trees, which affects those with insecure rights, mostly women, from effectively participating in reforestation activities. It is essential to consider those inequalities, as well as conflicts between private, communal and political interests. Stakeholders' needs may change over time, so their requests should be re-assessed throughout projects and the strategies adapted accordingly (Lazos-Chavero et al., 2016).

Sharing of both the costs (in terms of time, labour and money) and the benefits of reforestation (Rule 10) among all stakeholders should be agreed upon before the first tree goes into the ground (Figure 3).

2.3 | Aim to maximize biodiversity recovery to meet multiple goals

Restoring biodiversity facilitates other objectives—carbon sequestration, ecosystem services and socio-economic benefits.

FIGURE 3 Ensuring appropriate engagement. In a community-led reforestation project using local indigenous species in eastern Madagascar, members of the local community worked together to restore areas degraded by fire and over-exploitation (Credit: AA)

Rather than being an end goal in itself, reforestation is a means to achieving various goals, typically climate-change mitigation, biodiversity conservation, socio-economic benefits (including food security), soil and hydrological stability and other ecosystem services. These objectives should be defined beforehand, to allow appropriate project planning, implementation and monitoring (Chazdon & Brancalion, 2019). Achieving high levels of biodiversity and biomass, through the native forest approach, enables multiple outcomes to be delivered simultaneously. High species and functional trait diversity enhance productivity, ecosystem resilience and the provision of forest products and ecological services to local communities. Restoring the biodiversity levels and exact species composition of the original forest may not always be possible, at least initially, due to factors such as alteration of substrates (e.g. after agriculture and mining), species extinction, lack of propagation techniques or climate shifts away from the tolerances of the original species. In such cases, other native species may be considered to reinstate forest cover, and such decisions should be made with caution and be based on sound science, to avoid losing locally important species. The ideal achievable outcome is maximization of natural biodiversity, particularly functional diversity, within current and future climatic and edaphic limitations while acknowledging that tree species composition may differ from that of pre-deforestation tree communities.

Forest and landscape restoration allows different objectives to be prioritized in different landscape zones. However, achieving multiple objectives means accepting trade-offs (Holl & Brancalion, 2020) and these should be agreed by stakeholders at the start of projects. It is crucial that the reasons for trade-offs are substantiated, based on sound science and best practices, to achieve the 'highest and best outcomes' sensu Gann et al. (2019). While trying to maximize all the benefits of projects, one essential principle should be kept in mind: do no harm to local communities, native ecosystems and vulnerable species.

Where the main goal is timber production and/or carbon sequestration, plantations of fast-growing monocultures are widely used. However, it has been demonstrated that, in the long term, restored native forests maximize biomass and capture far more carbon while conserving biodiversity (Díaz et al., 2009; Lewis et al., 2019).

Socio-economic goals often include the improvement of economic conditions for local people, including the poorest communities. Many projects rely on agroforestry and exotic timber plantations to meet this objective, but natural, restored and livelihood native forests deliver economic returns, as well as environmental co-benefits, and should be included in a landscape-wide approach. During timber production, short harvesting cycles quickly release much of the stored carbon back into the atmosphere, negating the initial carbon sequestration. Low-intensity management of livelihood native forests, for example through selective extraction, preserves biomass by allowing long-term carbon sequestration and natural vegetation succession while also benefitting biodiversity (Crane, 2020; Hu et al., 2020; Noormets et al., 2015). Alternative livelihood measures should be supported in the interim period before harvesting, to avoid the continued conversion of forest with high carbon stocks elsewhere leading to a net emission of CO_2. Biodiverse restored native forests can provide income through carbon credits, **payments for ecosystem services (PES)** and **non-timber forest products (NTFPs**; Rule 10).

If the main priority of the project is to conserve biodiversity, it is important to prioritize areas and select species that maximize this goal (Rules 4 and 5). Different reforestation approaches, planned at different levels, can be used: (i) Tree level: plant tree species that are prioritized for conservation, such as threatened species, or those that provide resources to target animals (Brancalion et al., 2018) or fungi; (ii) Ecosystem level: plant or assist the regeneration of species that will recover the typical composition, structure and functioning of reference, undisturbed ecosystems (Gann et al., 2019), to maximize habitat provision to a diversity of native species; (iii) Landscape level: maximize landscape connectivity by creating forested corridors and stepping stones to link remnant forest patches (Newmark et al., 2017).

Restored native forests can deliver multiple products, such as food, fibre and medicine, ecosystem services, including watershed protection, shade and erosion control, as well as recreational, educational, spiritual or other cultural benefits. Despite the fact that these benefits are often recognized, needed or demanded by local people (Brancalion et al., 2014), they are frequently neglected. The guidelines in this paper aim to maximize ecosystem services, adding increased value to any tree-planting or restoration project (Burton et al., 2018).

2.4 | Select appropriate areas for reforestation

Avoid previously non-forested lands, connect or expand existing forest, and be aware of displacing activities that will cause deforestation elsewhere.

Although reforestation interventions are always implemented at the local scale, site selection usually involves a multiscale approach. With the emerging engagement of multilateral and international organizations in tree-planting initiatives (Holl & Brancalion, 2020), spatial prioritization decisions can be made at a global scale, but most restoration initiatives involve an evaluation at the landscape level or below. Decisions based on considering a combination of historical, ecological and socio-economic factors at different spatial scales are the most effective.

Key questions when selecting an area for reforestation are as follows:

(i) *Was the area previously forested and is it now degraded?* Re-establishing a species-rich forest in such a place is beneficial for both biodiversity conservation and carbon sequestration, and helps fight desertification where this is determined by socio-economic factors (Liu et al., 2020). Reforestation in such areas is generally highly recommended, and the level of tree cover increase should be calibrated with the reference values of tree cover of the target ecosystems, to avoid unintended consequences for biodiversity and ecosystem services. However, in some previously forested areas, for example South Central United States oak forest, climate change may drive a transformation to non-forest biomes, such as savanna and grassland (Millar & Stephenson, 2015). Modelling tools are needed to evaluate potential target areas and identify those that are approaching such thresholds;

(ii) *Has the area been occupied historically by a non-forested biome such as grassland, savanna, non-forested wetland or peatland?* **Afforestation** in such areas depletes both biodiversity and SOC (Bond et al., 2019; Friggens et al., 2020; Veldman et al., 2015) and must be avoided. For example, grasslands often host high biodiversity and many threatened species, as well as contributing significantly to belowground carbon sequestration (Burrascano et al., 2016; Dass et al., 2018). Non-forested peatlands contain an even higher amount of SOC, which would be released into the atmosphere if trees were planted there (Brancalion & Chazdon, 2017; Crane, 2020; NCC, 2020). Similarly, lands covered by snow at high latitudes reflect an important quantity of sun radiation due to the high albedo, providing a cooling effect on the planet that would not be compensated for by the amount of carbon slowly captured by trees grown in those cold climates (Bala et al., 2007; Betts, 2000). A critical step for tree-planting initiatives is therefore to define 'no-go zones', where restoration should focus instead on non-forest vegetation;

(iii) *What are the wider effects of reforestation in the target area, including impacts on groundwater, biodiversity, climate, ecosystem services and livelihoods?* If the area is dry and water is scarce, trees could reduce the groundwater and river flow, with negative consequences for local inhabitants (Allen & Chapman, 2001; Feng et al., 2016). However, in seasonally dry climates, restoring forests on degraded watersheds can help to increase water infiltration and reduce surface run-off during the rainy season, reducing extreme fluctuations in streamflow throughout the year (Gardon et al., 2020). In urban areas, trees can be planted to mitigate the direct effects of GCC, providing an additional contribution to the carbon sequestration needed (Parsa et al., 2019) while also delivering other ecosystem services such as the provision of recreational spaces, wildlife habitats, clean air and shade;

(iv) *How close is the land to areas of natural forest?* This affects both the capacity of the site to regenerate naturally (Rule 5) and the value of the reforested site to biodiversity, for example by creating buffer zones, corridors and stepping stones enabling native species to migrate between forest remnants and expand their distribution (Tucker & Simmons, 2009);

(v) *Who is currently using the land, how will they be compensated for any income losses and where will they move their activities?* If these factors are not considered, the land might be retaken subsequently, or further deforestation or social conflicts might be caused elsewhere (Cuenca et al., 2018; Meyfroidt et al., 2010). Issues of land tenure and forest governance are critical to the success of reforestation and are safeguarded in the Cancun Agreement (UNFCCC, 2011). Protecting and restoring degraded forest remnants is the best way to increase carbon stocks and decrease habitat fragmentation without using non-forested land that may already be in use (Brancalion & Chazdon, 2017).

More tools and tailored resources are needed to help guide these decisions. The Restoration Opportunities Assessment Methodology (IUCN, & WRI, 2014), for instance, has been used in many countries that have made pledges to the Bonn Challenge, to identify FLR opportunities. The resulting maps identify high-priority areas for intervention and provide a helpful framework for determining what method is best. Technological advances will provide new tools and resources, such as NASA's Global Ecosystem Dynamics Investigation, which will facilitate the use of LiDAR to prioritize areas of degraded forest for restoration (Deere et al., 2020).

2.5 | Use natural regeneration wherever possible

Natural regeneration can be cheaper and more effective than tree planting where site and landscape conditions are suitable.

The NR approach to forest restoration spans a spectrum of different levels of human intervention:

(i) No intervention or passive restoration (Chazdon & Uriate, 2016);
(ii) Low intervention, including protection from further damage such as grazing or fire, and rewilding, which includes the selective reintroduction of missing fauna to restore natural processes (Perino et al., 2019);
(iii) Intermediate intervention, including enrichment of naturally regenerated forest by selective planting of missing species and **assisted NR (ANR**; FAO, 2019), where weeds are cleared around naturally regenerating trees to accelerate their growth. ANR has been used to restore *Imperata* grasslands in the Philippines (Shono et al., 2007) and logged-over forest that has become dominated by lianas (Philipson et al., 2020);
(iv) High intervention, including the **framework species approach** (Rule 6) and **applied nucleation** (Zahawi et al., 2013), where parts of the site are intensively planted to facilitate NR in the rest of the site.

When carbon capture and biodiversity enhancement are primary objectives, NR can provide significant benefits over tree planting, if practised in suitable locations, as described below. Carbon sequestration in naturally regenerated areas is potentially 40 times greater than in plantations (Lewis et al., 2019) and species richness is generally higher, particularly for forest specialist species (Barlow & Peres, 2008; Brockerhoff et al., 2008; Rozendaal et al., 2019). NR is also significantly cheaper than tree planting, with studies in Brazil showing implementation costs reduced by 38% (Molin et al., 2018) or even up to 76% (Crouzeilles et al., 2019). However, this approach is unsuitable for certain ecosystems, for example those in 'old, climatically buffered infertile landscapes' ('OCBILs', sensu Hopper, 2009) found in biodiverse regions, such as the southwestern Australian biodiversity hotspot. In such landscapes, natural recolonization processes are incapable of reinstating ecosystems once the native vegetation has been removed, and substantial replanting and seeding are therefore required (Koch & Hobbs, 2007).

Once a land area has been targeted for natural or semi-natural forest cover, the two key questions are as follows: (i) *Is the forest capable of returning spontaneously?* and (ii) *What level of intervention is required to assist and accelerate the regeneration?* The site's potential for NR will depend on multiple factors, which can be considered at the landscape and site level (Elliott et al., 2013).

At the landscape level, the first step should be to identify and control the factors that led to deforestation in the first place—a task that should involve all stakeholders (Rule 1). One of the most important landscape factors is the proximity of the site to areas of remaining natural forest that can serve as a diverse source of naturally dispersed seeds. Crouzeilles et al. (2020) found that 90% of passive regeneration occurred within 192 m of forested areas while Molin et al. (2018) found best results within 100 m of the nearest forest. The presence of birds and animals in and around a site is crucial for seed dispersal of many plant species. Typically, large wild animals and birds are the first to be locally extirpated, in which case the plants they dispersed may fail to recolonize unless manually introduced (enrichment planting). Another key factor is climate, particularly mean annual precipitation (Becknell et al., 2012). In the Neotropics, biomass recovery in second-growth forests was up to 11 times higher in wetter areas (Poorter et al., 2016).

At the site level, the previous land use and degree of degradation affect the regeneration potential, with heavily degraded sites (e.g. former mine sites) invariably requiring active interventions such as planting and topsoil replacement (Meli et al., 2017). The size of the target area will clearly affect distance to the nearest forest (and thus the regeneration potential of lightly or moderately degraded sites), with central parts of the site being further away than the nearest edges. Different levels of intervention may therefore be required within a single large site.

The existing natural vegetation currently present on a site has the most immediate effect on determining the regeneration pathway. In a lightly degraded site, a dense community of tree stumps, seedlings and a diverse soil seed bank enable rapid regeneration, especially in humid tropical areas, potentially achieving canopy closure in under a year (Elliott et al., 2013). Advice on the required density of regenerants for NR ranges widely from 200/ha (Shono et al., 2007) to 3100/ha (Elliott et al., 2013) and depends on climate. The stocking density required to achieve rapid canopy closure is lower in warm wet climates, since tree crown expansion occurs more rapidly than in cool, dry climates. Herbaceous or woody weeds, usually out-compete regenerating trees and should be controlled through cutting, pressing or 'lodging' (flattening weeds with a board), mulching, herbicides or controlled grazing, that is, ANR (FAO, 2019).

Other important site factors are soil quality, topography and hydrological features (Molin et al., 2018). Given the complex interaction of all these factors, the best way to determine the site's suitability for NR and the level of human intervention required is to take an experimental and **adaptive management** approach (Rule 9).

2.6 | Select species to maximize biodiversity

Plant a mix of species, prioritize natives, favour mutualistic interactions and exclude invasive species.

Tree planting is needed to restore forest when NR is insufficient (Rule 5). The *International Standards for Ecological Restoration* specify a 'native reference ecosystem' to guide species selection (Gann et al., 2019). In heavily degraded sites, species should be selected based on their ability to establish in altered or unfavourable conditions, which might include compacted soil, drought and competitive weeds. Native pioneer species are most likely to survive initially while late successional species can be intercropped with these pioneers, be introduced with successive planting interventions or may even eventually colonize the site naturally.

The framework species approach to forest restoration in the tropics is a highly effective tree-planting option that depends on the selection of a suite of native species with specific functional traits (Goosem & Tucker, 2013). It involves planting the fewest trees needed to complement and promote NR and recapture the site from weeds in 2–3 years. Framework tree species are characteristic of the reference ecosystem and have (i) high survival and growth rates; (ii) dense, spreading crowns that shade out herbaceous weeds and (iii) traits that attract seed-dispersing wildlife (e.g. flowering/fruiting at a young age). Mixtures of 20–30 species (both pioneer and climax tree species) should be planted. Biodiversity recovery depends on remnants of the reference forest type occurring within a few kilometres of the restoration site (as a seed source) and seed-dispersing animals remaining in the landscape (Elliott et al., 2013). A successful case of framework species approach applied in Thailand is shown in Figure 4.

Maximizing biodiversity depends not only on the number of species reintroduced but also on the functions they perform. Promoting mutualistic interactions, such as those involving native tree species and fungi, seed-dispersing animals, pollinators and other organisms, is crucial to achieving a resilient, biodiverse restored ecosystem (McAlpine et al., 2016; Steidinger et al., 2019), but the importance of such interactions is often underestimated.

Rare, endemic or threatened taxa are less likely to colonize through natural succession (Horák et al., 2019), and should therefore be reintroduced at the appropriate stage of forest maturity. This practice will contribute to the survival and conservation of the most vulnerable species. Such species can contribute greatly to carbon stocks, since they tend to be late-successional species with dense wood (Brancalion et al., 2018).

The GlobalTreeSearch database (https://tools.bgci.org/global_tree_search.php) lists all known tree species and can generate checklists of native species for each country. Local specialists including botanical experts and restoration ecologists should be consulted, to determine which native species are most suitable for the particular forest type being restored. The Global Tree Assessment (www.globaltreeassessment.org/) aims to deliver tree conservation assessments for all tree species by the end of 2020. This will help identify threatened species that can be included in restoration projects.

In livelihood native forests, selecting a mix of species, rather than planting a monoculture, is crucial (Brancalion & Chazdon, 2017). A mixed-species forest, either with native species only or with a mix of native and non-native species, has a higher capacity to conserve biodiversity, create habitats for wildlife and attract seed dispersers and pollinators. Such forest can regenerate autonomously, especially if patches of native vegetation are maintained within the plantation matrix as habitat islands (Horák et al., 2019). It will also be more resilient to disease, fire and extreme weather events (Florentine et al., 2016; Verheyen et al., 2016). Monoculture plantations sequester little more carbon than the degraded lands on which they are planted, especially if they are used for fuel or timber, in which case carbon is released back into the atmosphere within a few decades (Körner, 2017; Lewis et al., 2019).

Including exotic species in livelihood native forests is controversial (Catterall, 2016). For example, eucalypts (*Eucalyptus*) may have high cash value, but eucalypt plantations support lower biodiversity than native forests (Calviño-Cancela et al., 2012) and are colonized by mainly generalist plant and animal species

FIGURE 4 Example of successful tree planting. The framework species method of forest restoration can be effective even on the most degraded sites, provided intact forest remains nearby. (a) August 2012: Siam Cement's limestone mine in Lampang Province, northern Thailand. (b) April 2013: after spreading the site with topsoil (60 cm deep), 14 framework tree species were planted, including several *Ficus* species and native legumes, to improve soil conditions. Corrugated cardboard mulch mats were also applied. (c) February 2015: by the end of the third rainy season, canopy closure was achieved and macaque monkeys started visiting the plot to eat figs, in the process naturally dispersing seeds of other species through defecation. Mean survival across species was 64% and relative annual growth rate averaged 91% (Credit: Siam Cement Group and SE)

(Brockerhoff et al., 2008). A major concern is that exotic species often become invasive, for example certain Australian *Acacia* species in South Africa (Richardson & Kluge, 2008). Invasive species rank second only to habitat loss and degradation as a cause of the current global biodiversity crisis (Bellard et al., 2016). They have long-term effects on the environment, compete with native species, reduce biodiversity and often reduce water availability (Dyderski & Jagodziński, 2020; Scott & Prinsloo, 2008). Their removal, which needs to be done before restoration interventions can commence, is invariably difficult and very expensive. Invasive exotic species should never be planted.

However, under certain circumstances, some exotic, non-invasive species can be good allies for tropical forest restoration. In a humid tropical region of Brazil, exotic eucalypts, when planted in mixed plantations with native species and selectively harvested after 5 years, allowed the NR of native trees in the understorey and substantially defrayed restoration costs (Brancalion et al., 2020). Crucially, the eucalypts did not regenerate from seed.

Further research is required to identify more high-value native species that could be used instead of, or together with, desired exotic species. For example, in Kenya, *Melia volkensii* is a popular native timber species and has a lower water demand than exotic eucalypts (Ong et al., 2006; Stewart & Blomley, 1994). The use of mainly native species in new livelihood native forests has been successful in Latin and Central America, where companies such as Symbiosis Investimentos and Sucupira Agroflorestas are developing propagation protocols for native species, promoting agroecological principles, practising sustainable forestry, and in some cases conserving and restoring natural forest alongside the plantations.

Adaptability to GCC should also be considered when selecting species for both native and livelihood native forests. When GCC is proven to negatively impact native species, non-native species could be considered on the basis of preserving ecosystem functions. Such species must be subjected to comprehensive risk assessments that includes biosecurity threats and potential invasiveness (Ennos et al., 2019). This could form part of an assisted migration programme.

2.7 | Use resilient plant material

Obtain seeds or seedlings with appropriate genetic variability and provenance to maximize population resilience.

To ensure the survival and resilience of a planted forest, it is vital to use material with appropriate levels of genetic diversity, consistent with local or regional genetic variation. Vegetative propagation or using seeds with low genetic diversity generally lowers the resilience of restored populations through reduced evolutionary potential and problems with inbreeding depression (Thomas et al., 2014). As a result, planted forests may be disease-prone and unable to adapt to long-term environmental change. Such genetic bottlenecks can result from poor seed collection strategies, such as collecting from too few parent trees or declining source populations. Using material from well-designed seed orchards, or, in the many cases where this is not available, mixtures of seed with different provenances, usually increases genetic diversity in planted forests (Ivetić & Devetaković, 2017). However, in exceptional ecosystems, such as Australian and African OCBILs, which have strong local adaptation, (Hopper, 2009; James & Coates, 2000), highly local provenancing may be required.

Best practice involves collecting seeds from many individuals, across the full extent of the parent population randomly, to include the rarest alleles (Hoban, 2019; Hoban & Strand, 2015). Similarly, Ivetić and Devetaković (2017) identified the size of the parental population as a key determinant of genetic diversity in planted forests; they viewed provenance and seed-collecting strategies as the most important management practices in tree-planting projects. As a general rule, for adequate genetic diversity, seed should be collected from at least 30 individuals of **outcrossing species** and at least 50 individuals of **selfing species** (Pedrini, Gibson-Roy, et al., 2020).

Seed collection from local parent populations is advised since genotypes are adapted to climatic and environmental conditions similar to those of restoration sites. However, more distant provenances may be considered if conditions are similar across a large part of a species' range, or to match conditions under future GCC scenarios (**predictive provenancing**). If decisions are being made based on climate predictions, then sound science and experimental evidence of why climate-adapted genetic material is being used should be articulated (Alfaro et al., 2014). A cautious strategy is to use **composite provenancing** sensu Broadhurst et al. (2008). **Seed zone** maps can help practitioners to identify appropriate provenances of material for planting target sites; however, such maps are rare for most forest systems, particularly for understorey species.

One of the main bottlenecks for forest restoration is inadequate supply of native plant material. Lack of seeds (Jalonen et al., 2018; León-Lobos et al., 2020; Merritt & Dixon, 2011) and planting stock (Bannister et al., 2018; Whittet et al., 2016) of target species from appropriate sources in the required amounts are often critically limiting. This problem is particularly acute in the tropics, where many tree species produce seeds that are difficult to store (i.e. are desiccation sensitive) and for animal-dispersed, large-seeded tree species, which are of crucial importance for forest restoration (Brancalion et al., 2018). In addition, many of the seed supply sources are forestry genebanks that often have different aims, such as conserving desired traits rather than broad genetic diversity.

2.8 | Plan ahead for infrastructure, capacity and seed supply

From seed collection to tree planting, develop the required infrastructure, capacity and seed supply system well in advance, if not available externally. Always follow seed quality standards.

For projects involving tree planting or direct seeding, appropriate infrastructure and seed supply systems are essential. Decisions should be made at least a year in advance on whether to source seeds and produce seedlings in-house, subcontract these tasks or purchase plant material from external suppliers. If seeds are purchased externally, suppliers should be able to provide information on seed quality and the legality of their collection (Pedrini & Dixon, 2020). If commercial suppliers of seeds and seedlings fail to meet project requirements for species mix, quantity, genetic diversity, provenance or quality (Rule 7), projects may need to develop their own collection, storage and propagation capacity.

Where seed is self-sourced, national legislation and local laws on access to biological material (UN Convention on Biological Diversity, 2011) (www.cbd.int/abs/) and international seed standards (e.g. ENSCONET, 2009b; Pedrini & Dixon, 2020) must be followed, to ensure seeds are high quality and to avoid damaging source populations by over-collecting (no more than 20% of the available ripe seeds should be collected). Basic equipment for wild-seed collecting, cleaning and storage is needed. Collecting from tall trees requires specialist equipment, including extendible pruners, throw lines, tarpaulins and tree-climbing harnesses. Seed collectors should be trained to use this equipment efficiently and safely. Training should include phenological monitoring and seed physiology, to ensure that collecting trips are timed efficiently at peak fruiting times and when maturity is optimum (Kallow, 2014). Involving botanists and local experts enables species identification, efficient location of trees of target species and optimum timing for collection. Data on species identification, ecological conditions and provenance should be recorded simultaneously with the seeds. Alternatively, seeds can be provided by a third party, either collected directly from the wild or from wild-origin seed orchards, usually by state agencies or commercial suppliers (Pedrini, Gibson-Roy, et al., 2020).

If collecting seeds, the seed storage behaviour of the target species should be checked first, so they are handled appropriately. **Orthodox seeds** can be stored in seed banks, increasing their longevity for decades and allowing their use over extended periods, which optimizes collecting efforts and reduces waste (De Vitis et al., 2020; ENSCONET, 2009a). Literature on seed storage behaviour is available for many taxa (Hong et al., 1998), and it is possible to predict (Wyse & Dickie, 2018) or test (Hong & Ellis, 1996; Mattana et al., 2020) the behaviour of understudied species. The Seed Information Database, https://data.kew.org/sid/, curated by the Royal Botanic Gardens, Kew (RBG Kew), stores information on a wide range of species.

Low-cost seed-storage facilities can be installed if seed banks are not available regionally. Further information from RBG Kew is freely available here: http://brahmsonline.kew.org/msbp/Training/Resources. Seed banking is particularly useful in arid and semi-arid biomes (León-Lobos et al., 2012), where over 97% of the species are estimated to have orthodox seeds but it is also a valuable option for the majority of species in humid ecosystems (Wyse & Dickie, 2017).

Propagation protocols are available for many common species, but if they are not, then germination trials are required. The seeds of most wild species have dormancy mechanisms (Baskin & Baskin, 2014), requiring specific conditions for germination. These can sometimes be deduced from the seed morphology and ecology of each species (Kildisheva et al., 2020), but empirical research may be required to achieve germination for species with deep dormancy.

If direct seeding is chosen, then seed priming (for optimal germination) and/or coating (to protect seeds from predators, desiccation and diseases) is beneficial (Madsen et al., 2012; Pedrini et al., 2020; Williams et al., 2016). The number of seeds required is much higher than the target number of trees, since conversion rates of seeds to established seedlings are usually very low and are highly species-dependent (James et al., 2011) and site-dependent (Freitas et al., 2019). The development of a seeding plan that includes site preparation and seeding strategy, as well as monitoring after planting, is crucial for success (Shaw et al., 2020), while adopting emerging technologies can help to optimize seed use efficiencies (Pedrini, Dixon, et al., 2020).

If saplings are to be planted, an in-house nursery must be built (Elliott et al., 2013) or an appropriately accredited nursery selected for their production. If such infrastructure and expertise are not available locally at the start of the project, it is important to include them in project planning. Local people are important as sources of both labour and expertise. Opportunities to convert private agricultural or horticultural facilities into the resources needed for the project should be explored.

2.9 | Learn by doing

Base restoration interventions on the best ecological evidence and indigenous knowledge. Perform trials prior to applying techniques on a large scale. Monitor appropriate success indicators and use results for adaptive management.

Planning decisions should be made by combining both scientific and indigenous knowledge. Traditional knowledge, acquired over many generations by people who have lived close to the forest, is particularly useful where field experiments to generate scientific evidence may take a long time to yield results (Wangpakapattanawong et al., 2010). International standards (e.g. Gann et al., 2019) give general guidance while Floras, previous project reports and the scientific literature can provide more specific information such as functional trait data to aid species selection (Chazdon, 2014).

Ideally, small-scale trials should be implemented before large-scale tree planting commences, to guide species choices and test the effectiveness of proposed techniques. These may include land management interventions to overcome site-specific barriers, such as degraded soils (Arroyo-Rodríguez et al., 2017; Estrada-Villegas et al., 2019), competitive weeds (FAO, 2019), fire and herbivores (Gunaratne et al., 2014; Rezende & Vieira, 2019), and the absence of mutualistic organisms in soils, such as mycorrhizal fungi (Asmelash et al., 2016; Fofana et al., 2020; Neuenkamp et al., 2019). Unfortunately, trials take years to yield results, so projects often have to be initiated through the exchange of previous knowledge. Subsequent monitoring then generates data for adaptive management, a fundamental principle of FLR since its inception (Gilmour, 2007).

For monitoring forest-restoration sites, it is useful to establish permanent sample plots in (i) the restoration site (treatment); (ii) a site where no interventions are implemented (control) and (iii) a reference forest remnant (target). Comparing (i) and (ii) determines the effectiveness of restoration interventions. Comparing (i) and (iii) tracks the progress of restoration towards the target end-state. Data should be collected before and just after restoration interventions are initiated (baseline) and annually thereafter, at least until canopy closure.

Restoration progress is indicated by the biomass, forest structure, biodiversity and ecosystem functioning in restoration sites all trending towards those of the reference (or target) ecosystem. However, monitoring can focus on biomass and biodiversity, since the other two ecological indicators and many socio-economic benefits (Table 2) stem from them.

Biomass is estimated from stocking density and tree sizes in sample plots. Allometric equations are used to derive biomass and carbon from measurements of tree diameter and height and wood density (Chave et al., 2014). Soil samples should also be collected to determine soil carbon. Ground surveys are rapidly being replaced by aerial photogrammetry (de Almeida et al., 2020) using drones to create 3D forest models, within which the heights and shapes of all trees can be measured. However, to gather species-specific data and calibrate remote sensing approaches, ground surveys remain essential.

It is impractical to monitor all species to assess biodiversity recovery, so biodiversity indicator groups are used, most commonly plants and birds. For trees and ground flora, the abundance of species in sample plots should be recorded and the data used to construct species-effort curves and calculate diversity indices (Ludwig & Reynolds, 1988). To monitor bird species richness, we recommend the Mackinnon List Technique (Herzog et al., 2002). If resources are available, more comprehensive biodiversity assessments using environmental DNA and insect traps can provide rich and cost-effective data (e.g., Ritter et al., 2019).

Monitoring should also assess progress towards project-specific goals, such as erosion control or recovery of an endangered species. Where livelihood benefits are a key objective, they may be assessed using indicators such as jobs created or changes in income, and equity in distribution at the gender, household and communal levels. Where income is to be generated from extraction of timber or NTFPs, it is vital to achieve sustainable production by ensuring that harvest rates of products do not exceed their productivity. This can be monitored through simple 'yield-per-unit-effort' techniques—recording product quantities harvested and harvesting time expended—with community-agreed reductions in harvesting intensity, if yields start to decline.

Monitoring and verification of restoration, particularly to claim income from carbon credits and other environmental services, is usually carried out by independent assessors at great expense. However, studies have shown that local people are capable of performing monitoring more cost-effectively (Boissière et al., 2017; Danielsen et al., 2013), and their indigenous knowledge is of great value to the process (Wangpakapattanawong et al., 2010).

2.10 | Make it pay

Develop diverse, sustainable income streams for a range of stakeholders, including carbon credits, NTFPs, ecotourism and marketable watershed services.

Income generation by selling forest products from livelihood forests is easily achieved, whereas marketing environmental services from existing and restored native forest is more difficult, particularly in protected areas. However, the sustainability of forest restoration depends on income streams generated from it exceeding those from alternative land-uses and on that income

TABLE 2 Why income-generating forest ecosystem services increase with both biomass accumulation and biodiversity recovery (both of which are higher in existing and restored native forests than in monoculture plantations)

Income-generating ecosystem service	Biomass accumulation	Biodiversity
Carbon storage	About half (~47%) of all tree biomass is carbon[1]	Biodiversity increases biomass accumulation[2]
Forest products	Biomass accumulation increases the quantity of products	Biodiversity increases the variety of products, providing economic security against fluctuating market prices
Watershed services I: *Flow regulation (flood/drought mitigation; irrigation for agriculture)*	Biomass accumulation increases organic matter accumulation and thereby soil moisture-holding capacity	Tree species diversity increases interception, decreases runoff (flash floods) and improves infiltration[3]
Watershed services II: *Soils (erosion landslide mitigation)*	Biomass accumulation increases belowground root biomass and thereby reduces erosion and landslides	Different tree species root to different depths, decreasing erosion[3]
Ecotourism	Biomass accumulation increases ecosystem structure, niches and biodiversity	Biodiversity-rich native forests attract more ecotourists

Sources: [1]Martin and Thomas (2011); [2]Steur et al. (2020); [3]Gardon et al. (2020).

being shared fairly among all stakeholders, including the poorest (Brancalion et al., 2012).

In 2009, The Economics of Ecosystems and Biodiversity initiative estimated the value of tropical forest ecosystem services to be USD 6120/ha/year (USD 7732 today, after inflation), based on data from 109 studies (TEEB, 2009). Watershed services contributed most (38.8%), followed by climate regulation (32.1%), provisioning services (21.5%) and recreation/tourism, (6.2%). All these values depend on the two fundamental indicators of restoration: biomass accumulation and biodiversity recovery (Table 2).

REDD+ has made some progress with monetizing forests as carbon sinks (Angelson et al., 2012). Forest carbon value alone often exceeds revenue from the main drivers of deforestation (e.g. oil palm; Abram et al., 2016), but application of REDD+ to incentivize restoration has been problematic, due to issues of governance and socio-economic conditions, particularly fluctuations in carbon credit prices. To ensure revenue flows mostly into local economies, local people should have direct access to carbon markets as well as low-interest start-up loans, to fund restoration work and support their families until break-even is achieved. Furthermore, transaction costs, including monitoring, reporting and verification, should be minimized by building local capacity, to reduce dependency on paid external agents (Köhl et al., 2020).

While NTFPs are usually less valuable than carbon, local people can easily monetize them, and start-up investment is minimal (de Souza et al., 2016). Furthermore, NTFPs can provide security and adaptability during periods of financial hardship (Pfund & Robinson, 2005), and their diversity buffers against fluctuating markets—if the price of one product falls, another can be substituted. Conversely, monoculture plantations leave farmers vulnerable to fluctuations in a single commodity market price. Thus, biodiversity recovery drives both ecological stability and economic security. However, to ensure sustainable production, harvesting rates must be sustainable and therefore monitored (Rule 9).

Watershed services are the most difficult to monetize, since they constitute 'avoided detrimental impacts', such as flood damage or decline of agricultural productivity. The need for such services is unpredictable in time and place. They are a 'public good', rather than a readily quantifiable commodity. Consequently, government funding (via taxes or water charges) is the most appropriate monetization mechanism. Several such schemes have been well documented in Latin America and China (Porras et al., 2008).

Ecotourism can be a lucrative source of local income, which directly monetizes biodiversity. However, its potential is often overestimated. Substantial start-up funding is needed, particularly for accommodation construction. Furthermore, the skilled labour required to meet the discerning demands of ecotourists is often imported from outside, sidelining local people.

Innovative marketing will be essential, to turn restoration values into financial incentives, since both investors and the public are unfamiliar with paying for some of the services outlined above (Brancalion et al., 2017). Comprehensive socio-economic monitoring will also be needed, to ensure that payments actually benefit local communities and that changes in land and resource values have no deleterious social consequences. Finally, if such financial incentives lead to a surge in restoration projects at the expense of agriculture, the prices of carbon credits and NTFPs could crash, and food production could decline, resulting in increased food prices and reduced food security. Models of the potential macro-economic effects of restoration financing are therefore also needed, to forestall such impacts.

3 | CONCLUSION AND OUTLOOK

The guidelines presented here show that reforestation is more complex than is often initially thought. There is no universal, easy solution to a successful initiative given the extraordinary diversity of species, forest types, sites, and cultural and economic environments. In many cases where livelihoods depend upon altered landscapes, restoration goals can only be achieved through creating a mosaic of land uses at the landscape level and by engaging with society at large (Figure 5).

Despite the inherent complexity of reforestation initiatives, there are successful examples to build on and develop further. Over the past 30 years, ecologists have transformed the concept of forest restoration to an attainable goal, having developed tools to overcome the technical and knowledge barriers to its implementation through robust scientific research. This means that calls by the UN and many other

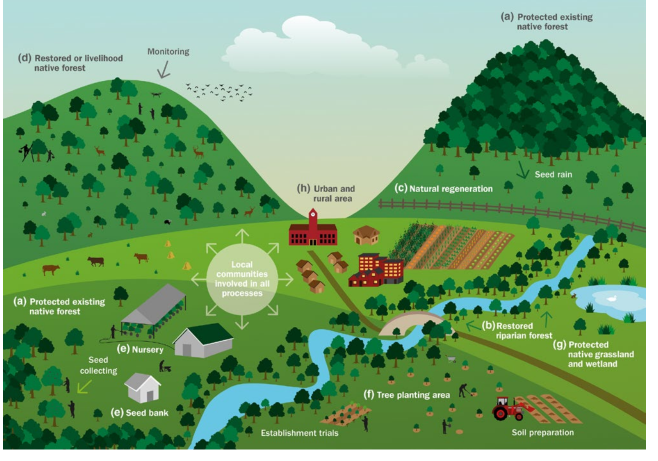

FIGURE 5 Schematic view of a successful reforestation programme. This landscape contains several components: (a) protected existing native forests, either old- or second-growth, where native seeds are collected; (b) restored riparian forest creating a biological corridor connecting remaining forest patches; (c) a naturally regenerating area, adjacent to an existing native forest that provides seed rain for natural regeneration; (d) restored or livelihood native forest, which might include non-invasive exotic useful species for timber and non-timber forest products (NTFPs), where people monitor biomass and biodiversity recovery; (e) tree nursery and seed bank where native seeds are stored and propagated; (f) tree planting area, with a section dedicated to establishment trials; (g) protected native non-forest ecosystems, such as grassland and wetland; (h) urban and rural areas, with sustainable agriculture and livestock

organizations to restore forest to hundreds of millions of hectares worldwide—inconceivable before—are becoming increasingly feasible. However, achieving such ambitious goals will only happen through careful consideration of the diverse aspects discussed in this review.

Partnerships involving multiple stakeholders (corporates, governments, NGOs, scientists, practitioners, landowners) are likely to yield the most enduring long-term benefits. Overcoming the socio-economic and political barriers to forest restoration will also require good governance, long-term funding mechanisms, enshrined legal protective measures for the restored sites, and effective communication among stakeholders at the science–policy–practice interface.

Vast reforestation programmes are now underway across the planet, and these will require monitoring so that learning opportunities are not lost. We need to rely on the best scientific evidence available and implement carefully planned, replicated, controlled experiments on large spatial scales. This is key to objectively testing and continuously improving the effectiveness of existing socio-economic constructs, such as community forestry, REDD+, FLR and PES. Crucially, politicians and policymakers need to act now to engineer a rapid paradigm shift in the way we protect existing forests and restore new ones using native species, to benefit both people and nature. They should use innovative regulations, incentives and all the levers at their disposal.

The massive reforestation initiatives currently underway, the upcoming UN Decade on Ecological Restoration and aspirations for a post-COVID green recovery, have generated unparalleled hope and optimism that forest restoration really can improve global ecology while uplifting local livelihoods. However, it will only do so if it is based on sound science, guided by indigenous knowledge and local communities, supported by fair governance and incentivized by long-term funding mechanisms. We hope that the 10 golden rules outlined here will help guide all those who are involved in restoring Earth's forests to address such issues fruitfully and to turn the hope and optimism into reality.

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AUTHOR CONTRIBUTION

Alexandre Antonelli, Kate A. Hardwick, Paul Smith and Alice Di Sacco conceived the initial outline of the article; Alice Di Sacco and Kate A. Hardwick led the writing, coordinated the author contributions and prepared the figures; all authors contributed to writing, developing and reviewing the manuscript.

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