Research Directions in Tropical Forest Restoration

Author(s): Karen D. Holl
Source: Annals of the Missouri Botanical Garden, 102(2):237-250.
Published By: Missouri Botanical Garden
https://doi.org/10.3417/2016036
URL: http://www.bioone.org/doi/full/10.3417/2016036

RESEARCH DIRECTIONS IN TROPICAL FOREST RESTORATION[1]

Karen D. Holl[2]

Abstract

In the past few years, numerous global, national, and regional targets have been set to restore millions of hectares of tropical forest to achieve multiple goals, including carbon sequestration, biodiversity conservation, improvements in the quality and supply of water, and support of human livelihoods. To achieve these ambitious goals, restoration decision makers need guiding principles regarding how to invest limited resources for large-scale forest restoration. Research over the past two decades has shown that a host of abiotic and biotic factors can slow tropical forest recovery, but that the specific barriers to and rate of recovery are site specific. Hence, restoration strategies must be carefully selected considering the natural resilience of a given site, localized barriers to recovery, and the ecological and human goals of the project. Despite the substantial advances in our understanding of tropical forest regeneration and restoration, to date neither the scale of scientific studies nor the restoration projects being implemented have matched the ambitious forest landscape restoration plans that are being proposed. I discuss key ways to enhance the success of tropical forest restoration efforts, citing a range of examples to illustrate each point. Specifically, restoration projects need to be planned and evaluated at larger spatial scales and over longer time periods, which requires better integration of the science and practice of forest restoration. Ultimately, forest restoration success hinges on including multiple stakeholders, such as farmers, local communities, local government leaders, regional and national policymakers, and scientists, in the planning, implementation, and evaluation processes. Finally, efforts to improve knowledge sharing across restoration projects in different regions will enhance the likelihood of implementing successful tropical forest restoration projects at the desired scale.

Key words: Forest landscape restoration, natural regeneration, seed dispersal, seedling establishment, tropical forest succession.

Increasing awareness of society's dependence on forests underlies several recent international initiatives to halt deforestation and promote restoration of millions of hectares of degraded forests globally and particularly in the tropics (table 1 in Chazdon et al., 2017). The 2011 Bonn Challenge and the 2014 New York Declaration on Forests aim to restore 150 million hectares of forest worldwide by 2020 and 350 million hectares by 2030 (United Nations, 2014). These global targets build upon regional restoration goals, such as the World Resources Institute Initiative 20×20, which has restoration commitments from individual countries to restore a total of more than 20 million hectares of forest in Latin America by 2020 (Vergara et al., 2015). Within countries, restoration projects are being implemented by national, regional, and municipal governments, as well as individuals, communities, businesses, and non-governmental organizations (Murcia et al., 2016). Considerable financial resources are being committed to these initiatives; for example, the International Union for the Conservation of Nature recently announced "The Global Restoration Initiative," an anticipated $250 million from the Global Environmental Facility and other partners to help 10 countries define and achieve landscape forest restoration commitments under the Bonn Challenge (International Union for the Conservation of Nature, 2016).

The definition of forest restoration used in both these initiatives and for individual projects at the local scale varies widely. The most commonly used definition of restoration in the scientific literature is from the Society for Ecological Restoration (Society for Ecology Restoration Science & Policy Working Group, 2004: 3): "ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." Under this definition the general target of restoration is broadly described as "a characteristic assemblage of the species that occur in the reference ecosystem and that provide appropriate community structure" (Society for Ecology Restoration Science & Policy Working Group, 2004: 3). Recently, nearly all of the large-scale tropical forest restoration initiatives have adopted the term "forest landscape restoration," which is "a process that aims to regain ecological integrity and enhance human well-being in deforested or degraded landscapes" (Maginnis & Jackson, 2007: 10). This definition encompasses a broader

[1] I appreciate thoughtful discussions and helpful feedback on earlier versions of this paper from P. Brancalion, A. Calle, E. Howard, A. Kulikowski, C. Kumar, J. Lesage, J. L. Reid, B. Stanford, D. Vieira, and an anonymous reviewer.

[2] Environmental Studies Department, University of California, Santa Cruz, California 95064, U.S.A. kholl@ucsc.edu

doi: 10.3417/2016036

range of goals, and there is less focus on restoring to specific reference conditions; rather, there is recognition of the need to balance multiple land management aims across the landscape.

These broad and variable definitions reflect the fact that tropical forest landscape restoration is motivated by a host of reasons (Chazdon et al., 2016), which in only some cases includes restoring forest on a trajectory toward a full suite of reference community composition and functions (sensu Society for Ecology Restoration Science & Policy Working Group, 2004). A primary goal in recent years has been to sequester carbon, commonly referred to as REDD+ (reducing emissions from deforestation, forest degradation, improved forest management and restoration, Elias & Lininger, 2010; Alexander et al., 2011). Many projects have been initiated with the anticipation of REDD+ payments, although there is increasing concern about if and when sufficient funds will be available, since the payments to date have been a small fraction of what was anticipated (Fletcher et al., 2016). Other tropical restoration projects have been motivated by improving water quality and supply, although the effect of forest restoration on these ecosystem services has been poorly documented (Murcia et al., 2016). Tropical forest restoration has also been promoted to improve human livelihoods through providing timber and non-timber forest products, improving agricultural productivity and conserving biodiversity of a range of different guilds of organisms (Alexander et al., 2011; Lamb, 2014; Locatelli et al., 2015). Although it is clear that forest restoration has numerous benefits, many studies and reviews clearly show that restoring forest for a single goal (e.g., carbon sequestration) does not necessarily ensure that other goals (e.g., human livelihoods, biodiversity) will be achieved, and that there are often tradeoffs between goals (Phelps et al., 2012; Panfil & Harvey, 2016).

Ongoing efforts aim to standardize the definitions of various ecological restoration and forest landscape restoration actions (e.g., Chazdon et al., 2016; McDonald et al., 2016), yet people from all sectors continue to use these terms differentially. Hence, it is critical that each global initiative and local project clearly define their goals and specific objectives. For example, is the goal of a specific forest restoration project to sequester carbon, provide habitat for an endangered bird species, restore plant community composition that is similar to reference forest, improve water quality, provide timber and/or non-timber forest products to the landowner, or more than one of the preceding goals? Explicitly stating those goals is critical for transparency and honesty in communicating the potential benefits of specific projects to community members, policymakers, and funders; to select the most appropriate restoration methods; and to evaluate whether specific restoration goals have been achieved (Zedler, 2007).

The number of experimental studies and on-the-ground tropical forest restoration projects in areas disturbed by human activities has increased manyfold in the past two decades. As diverse stakeholders increasingly undertake ambitious restoration efforts, it is important to review past successes, as well as failures, to guide future efforts. In this paper, I first briefly review what is known about tropical forest recovery and restoration from past studies. I then discuss current and future research directions to inform the large-scale forest restoration that is proposed. In this section I describe a range of approaches to restoring forests, from passive restoration (i.e., ending the prior anthropogenic disturbance to allow natural or unassisted forest recovery) to active restoration strategies (i.e., a range of human interventions that aim to accelerate and influence the successional trajectory of recovery) (sensu Holl & Aide, 2011). I primarily draw on my own research and other studies from Latin America, but include some examples from other regions. I focus on ecological aspects of restoration reflecting my own expertise, but throughout emphasize the importance of considering various stakeholders and their needs in the planning, implementation, and evaluation process.

What We Know about Tropical Forest Restoration

many barriers to forest recovery exist

A large body of literature shows that a host of different abiotic and biotic factors impede forest recovery and that the relative importance of these factors varies across forest types and individual sites (reviewed in Holl, 2012; Chazdon, 2014). In lands previously used for intensive agriculture and mining, the seed and seedling banks of forest species are typically severely depleted, so forest recovery depends on dispersal of seeds to the site and resprouting by a subset of species adapted for repeated disturbance. Many studies demonstrate that seed dispersal by animals, the primary form of dispersal in tropical rainforests, is often extremely low and limits forest recovery in former agricultural lands. Frequently, nearby sources of floral and faunal propagules are lacking or limited to the species that remain in small forest remnants and hedgerows (de Souza Leite et al., 2013). Moreover, the birds, bats, and primates that commonly disperse seeds of larger-seeded tree species often will not cross open areas and/or are missing from agricultural mosaic landscapes due to habitat fragmentation or overhunting (Martínez-Garza & Howe, 2003; Holl, 2012).

If forest plants either arrive at or are present in the site, several factors may limit their establishment (Holl, 2007; Gunaratne et al., 2014). A major factor that has been repeatedly shown to limit survival and growth of forest species in former agricultural lands is aggressive ruderal vegetation, primarily pasture grasses (e.g., *Imperata cylindrica* (L.) P. Beauv., *Pennisetum* Rich. spp., *Urochloa* P. Beauv. spp.) or ferns (e.g., *Dicranopteris* Bernh. spp., *Pteridium* Gled. ex Scop. spp.) (e.g., Cohen et al., 1995; Hooper et al., 2002; Douterlungne et al., 2010), which can slow recovery by competing for soil moisture, nutrients, light, increasing the probability of fire, reducing seed germination, and emitting allelopathic chemicals (reviewed in Holl, 2002).

Stressful microclimatic conditions, in particular low moisture availability, also may limit seed germination and seedling survival and growth, particularly in seasonally dry forests (Vieira & Scariot, 2006). High temperature and low humidity conditions in pastures, along with high grass biomass, make them particularly susceptible to fire, which kills seeds and seedlings of most forest species but not fire-adapted grasses (Janzen, 2002; Nepstad et al., 2008). In some sites, seedling growth is limited by soil conditions, both chemical and physical: in particular, soil compaction, which impedes root growth and water-holding capacity; low levels of phosphorus, nitrogen, or base cations; and in some soil types, high levels of aluminum or iron (Holl, 2012). Moreover, many tropical trees form mycorrhizal associations that facilitate phosphorus uptake, but these systems and associated nutrient cycling can be substantially altered by agricultural land uses (Carpenter et al., 2001; Allen et al., 2005).

Seed predation and seedling herbivory (Jones et al., 2003; Bagchi et al., 2014; Gunaratne et al., 2014), as well as plant pathogens (Allen et al., 2005; Bertacchi et al., 2016), can substantially reduce seedling establishment in some sites. These biotic interactions are notoriously variable among species and over time, and thus can have a strong impact in some cases but are less commonly the crucial factors limiting forest recovery.

RATES OF TROPICAL FOREST RECOVERY VARY GREATLY

The differing suite and intensity of barriers to recovery lead to high variation in the rate and trajectory of forest regrowth, even at small spatial scales. Some forests recover structure, biomass, and a diversity of species within a few decades without human intervention (Aide et al., 1996; Janzen, 2002; Letcher & Chazdon, 2009; Poorter et al., 2016). Other sites, however, may show minimal woody regeneration and remain in a state of arrested succession for many years (Ashton et al., 2001; Wheeler et al., 2016). In Costa Rica, my colleagues and I showed that above-ground tree biomass accumulation in both naturally recovering and actively restored sites varies by over an order of magnitude across sites separated by just a few kilometers (Holl & Zahawi, 2014). Likewise, many studies show that species composition of naturally recruiting plant communities often varies substantially in nearby sites (Mesquita et al., 2015; Norden et al., 2015; Holl et al., 2017).

An important question is whether there are general principles that help to predict rates of recovery across sites and thereby prioritize active restoration efforts. Numerous studies show that the type and intensity of past land use is a major predictor of recovery rate and composition (e.g., Holl & Zahawi, 2014; Mesquita et al., 2015; Crouzeilles et al., 2016). Typically, lands used for logging and shifting agriculture recover more quickly than those used for intensive, ongoing agriculture, but there is a large amount of variation within land-use types. Longer duration of a specific agricultural land use commonly results in slower forest recovery (Lawrence, 2005; Holl & Zahawi, 2014; Jakovac et al., 2015; Rocha et al., 2016).

Another factor that commonly influences the rate of recovery is proximity to sources of colonizing propagules of both plants and animals (Chazdon, 2017). Recent reviews show an overwhelmingly positive effect of the amount of surrounding forest cover on forest restoration success (e.g., de Souza Leite et al., 2013; Jakovac et al., 2015; Crouzeilles et al., 2016), particularly for the establishment of large-seeded, animal-dispersed species (Shoo et al., 2016). Some individual studies have not shown a similar trend; this is likely due to the fact that some floral and faunal species can persist in agricultural landscapes, particularly when there are trees within actively used agricultural lands and along fencerows and riparian strips (Mendenhall et al., 2011; Banks-Leite et al., 2014; Holl et al., 2017), so remnant forests alone are not the only sources of propagules in the landscape.

RESTORATION STRATEGIES NEED TO BE TAILORED TO THE NATURAL RECOVERY PROCESS AND PROJECT GOALS

Restoration strategies should be carefully selected, considering both the natural resilience of a given site and the ecological and human goals of the project.

Given that it is often the least costly approach, passive restoration should be considered in cases where recovery is rapid and successional trajectory is consistent with restoration targets. Indeed, there are large areas of regrowth forests worldwide, the majority of which are naturally regenerating (Aide et al., 2013; Chazdon & Guariguata, 2016; Uriarte & Chazdon, 2016). A wise strategy, if socially feasible, is to wait a few years before actively intervening in restoration to assess the rate and composition of natural recovery (Brancalion et al., 2016). If a site recovers a subset of native woody species quickly, planting seeds or seedlings of later-successional, large-seeded species that do not rapidly colonize (i.e., enrichment planting) may be more cost-effective than extensive, initial tree planting (Cole et al., 2011; Chechina & Hamann, 2015).

In cases where natural recovery is slow or not consistent with restoration goals, then active restoration strategies should be considered. In some cases, assisting natural regeneration by clearing around naturally establishing tree seedlings to reduce competition is an effective and low-cost strategy to accelerate forest recovery (Shono et al., 2007; Chazdon, 2017). The most common active forest restoration strategy is planting trees (Holl & Aide, 2011), but other strategies such as the direct seeding of vegetation, transplanting topsoil, recontouring land, and fertilizing are also used, particularly in heavily disturbed sites (Holl, 2012). Many studies have shown the benefit of planting native tree species to enhance seed dispersal by animals and improve site conditions to facilitate woody seedling establishment (e.g., de la Peña-Domene et al., 2013; Kauano et al., 2014; Shoo et al., 2016). However, in cases where woody species establish quickly, active restoration efforts may have neutral or negative effects on recovery by damaging naturally establishing seedlings (Sampaio et al., 2007).

Moreover, the choice of tree species composition for planting can affect the natural successional trajectory by influencing the composition of species establishing in the understory (Parrotta, 1995; Murcia, 1997; Firn et al., 2007); altering nutrient cycling (Lawrence, 2003; Nichols & Carpenter, 2006; Siddique et al., 2008); and increasing self-recruitment of planted species (Sansevero et al., 2011), which is a concern for restoration projects that aim to restore a resemblance of the pre-disturbance forest composition. Hence, species to plant should be selected carefully to be consistent with project goals; factors to consider may include growth rate and form, tolerance of stressful abiotic conditions, degree to which they facilitate the colonization of other species, ease of propagation, and value to landowners (Table 1).

Given that the relative importance of the numerous barriers to recovery varies considerably across sites, conducting small-scale pilot studies to identify potential concerns (e.g., extensive leaf cutter ant activity that may completely defoliate planted seedlings) and test active restoration methods prior to implementing large-scale restoration projects is crucial. For example, small-scale studies to screen growth and survival rates of many tree species can help the selection of species that are most promising for large-scale planting, given specific soil conditions and rainfall patterns (Park et al., 2010). Small-scale studies of bird perches and bat boxes to attract seed dispersers have demonstrated that these strategies generally do not enhance seedling recruitment, and therefore should not be used to facilitate forest recovery at a large scale (Reid & Holl, 2013). These preliminary projects can be invaluable to inform the most efficient use of resources and enhance the likelihood of restoration success.

Forest restoration projects need to include both ecological and social goals to ensure longevity

It is clear from the tropical forest restoration projects undertaken to date that even the most ecologically sound projects will not succeed without taking into account social factors and stakeholder buy-in during project planning, implementation, and evaluation (Mansourian & Vallauri, 2014; Murcia et al., 2016; Chazdon et al., 2017). It is difficult to cite specific examples of forest restoration failures because they often are not reported in the literature (Zedler, 2007), but lack of land tenure and top-down planning without community involvement are recurring general factors that reduce the longevity and success of tropical forest restoration projects (Murcia et al., 2016; Chazdon et al., 2017; Reid et al., 2017). Even the choice of tree species to plant requires careful assessment of social and ecological needs, which can be conflicting (Meli et al., 2014; Chechina & Hamann, 2015). Strategies and examples to address the challenge of balancing these needs are discussed below.

Moving the Field of Tropical Forest Restoration Forward

Although much progress has been made in understanding tropical forest regeneration and designing restoration strategies over the past two decades, to date the scale of neither the scientific studies nor the restoration projects being implement-

Table 1. Potential characteristics to consider in selecting native tree species to plant for tropical forest restoration. The specific characteristic is listed in italics, followed by a rationale for selecting that characteristic and one or two example citations.

Characteristics	Rational	References
Dispersal mode	provides fruits that attract seed-dispersing fauna	de la Peña-Domene et al., 2013
Canopy	attracts seed-dispersing fauna	Rodrigues et al., 2009; Wydhayagarn et al., 2009
Growth rate	provides rapid carbon sequestration and shading out of light-demanding, ruderal vegetation	Rodrigues et al., 2009; Douterlungne et al., 2013
Tolerance of poor soils and ability to fix nitrogen	grows and improves soil conditions in degraded sites	Park et al., 2010
Tolerance of a wide range of abiotic conditions	grows well in many sites	Meli et al., 2014
Tolerance of changing climatic conditions	persists with increasing temperatures and decreasing precipitation as the climate changes	Craven et al., 2011; Stanturf, 2015
Ability to facilitate regeneration of a diversity of forest species characteristic of reference forest	facilitates forest recovery	Cusack & Montagnini, 2004; Meli et al., 2014
Likelihood of natural establishment	shows minimal unaided dispersal and establishment in sites	Martínez-Garza & Howe, 2003; Meli et al., 2014
Feasibility of collection and propagation	increases cost efficiency and ease of restoration	Meli et al., 2014
Desirability for wood, non-timber forest products, or other reasons	provides income and incentive for landowners to maintain trees	Meli et al., 2014; Chechina & Hamann, 2015

ed has matched the ambitious forest landscape restoration plans that are being proposed. Large-scale forest restoration is a relatively new human endeavor, and scientific research has a crucial role to play in guiding restoration efforts in order to use resources more efficiently and improve outcomes. The field needs to move forward in four key ways: increasing (1) the spatial and (2) the temporal scales of both restoration implementation and scientific studies; (3) better integrating a diverse set of stakeholders in the restoration planning and evaluation process; and (4) improving knowledge-sharing across restoration projects in different regions to learn from successes and failures. I discuss these needs and offer promising examples of rising to these challenges. I include examples that fall under the Society for Ecology Restoration Science & Policy Working Group (2004) definition of restoring a forest toward a reference condition, as well as the broader forest landscape restoration definition of balancing multiple ecological and human needs across the landscape (Maginnis & Jackson, 2007).

INCREASING SPATIAL SCALE

Although landscape forest restoration initiatives set targets on the order of millions of hectares, the majority of tropical forest restoration projects to date have been at the scale of a few hectares, and scientific studies often test methods in experimental plots ranging from a few to a few hundred square meters (Shoo & Catterall, 2013). As a result, many restoration methods that are tested at small scales (e.g., soil transfer, intensive manual weed removal) often are impractical at large scales. Going forward, tropical forest restoration methods are needed that will be practical at large scales, and scientific studies and long-term monitoring must be integrated with these projects.

Large-scale forest restoration methods

As discussed previously, most active tropical forest restoration to date has consisted of planting trees, which can serve to enhance animal seed dispersal, shade out ruderal vegetation, sequester carbon, enhance nitrogen inputs, provide training and employment for local people, and/or provide landowners with potential sources of income from timber and non-timber products, depending on the species selected (Brancalion et al., 2012; Holl, 2012). Although this approach often has been successful in establishing canopy cover and accelerating forest recovery, it can be quite costly given the labor required to collect, grow, plant, and then maintain seedlings by clearing ruderal vegetation over the first couple years (Craven et al., 2009; Zahawi & Holl, 2009; Brancalion et al., 2012). Some large-scale planting projects have been undertaken, such as sites greater than 250 ha in the Atlantic forest in Brazil planted with more than 50 tree species (Rodrigues et al., 2009), but such projects are the exception given the extensive resources required. Fortunately, some promising, cheaper, large-scale methods are being tested along with monitoring of their efficacy.

One example of technical innovation for restoration projects at a large scale is an initiative to restore 300,000 ha of riparian forest in the headwaters of the Xingu River Basin in the Brazilian Amazon region (Durigan et al., 2013). They seeded a diversity of tree species using agricultural machinery, which enabled planting of up to 30 ha per day, and used herbicides rather than manual weeding to reduce labor requirements. These methods resulted in extensive stem establishment after four years and cost reductions of more than a third as compared to planting seedlings (Durigan et al., 2013), but longer-term data are needed to evaluate whether the forests continue to recover toward reference conditions. Exploring further methods that build on agricultural techniques is promising, particularly in relatively flat landscapes previously used for large-scale agriculture; such methods are less likely to be applicable in areas with uneven terrain where mechanization is not practical.

Another promising approach to reforesting large areas is applied nucleation, or planting tree "islands" (Corbin & Holl, 2012). The tree islands serve to increase dispersal of animal-dispersed seeds and shade out pasture grasses, thereby enhancing seedling recruitment and enabling the tree islands to expand and coalesce over time. Fewer trees are planted, reducing costs accordingly, and the approach has the potential to create more heterogeneous habitat conditions (Holl et al., 2013). A now decade-long, well-replicated study by my colleagues and me in tropical premontane forest in southern Costa Rica shows that an applied nucleation planting approach is similarly effective in facilitating seed dispersal (Reid et al., 2015a) and seedling recruitment (Holl et al., 2017), and nearly as effective in restoring bird and bat communities (Reid et al., 2014; Reid et al., 2015b), as using plantation-style tree planting, despite our having planted only 25% of the number of trees. It may not be an appropriate choice if the focus of a restoration project is maximizing the growth of specific desired tree species (e.g., providing timber or non-timber forest products) and is somewhat more challenging to implement because of the unconventional planting design, but it shows promise as a cost-effective method for restoring large areas of land.

A third important approach to reduce restoration costs at large scales is to develop predictive models of where forest is likely to regenerate quickly by overlaying digital coverages, such as proximity to forest, past land use, soil type, rural population changes, and/or past forest regeneration (Tambosi et al., 2014; de Rezende et al., 2015). These models can be used to prioritize resource-intensive restoration efforts, such as tree planting, in locations where recovery is likely to occur more slowly.

Landscape forest restoration in human-inhabited landscapes

As noted earlier, recent landscape forest restoration initiatives propose to integrate a mixture of land uses to meet both social and ecological needs across the landscape. Although many of these approaches do not fall under the strict definition of ecological restoration, they often increase habitat quality and ecosystem services. In some highly fragmented agricultural landscapes, efforts aim at reconnecting remnant forest patches by restoring corridors (Tucker & Simmons, 2009; Tambosi et al., 2014) or enhancing faunal movement through the landscape mosaic by encouraging agricultural and agroforestry land uses that incorporate trees (Chazdon et al., 2009; Murgueitio et al., 2011; McAlpine et al., 2016). Integrating different land uses and management approaches at the landscape scale can help restoration projects meet different stakeholder needs, thereby reducing resistance to and increasing support for restoration efforts, and reducing costs of active restoration efforts over large areas.

Examples of this type of landscape-scale forest management planning include silvopastoral systems (i.e., agroforestry systems that integrate trees and nitrogen-fixing shrubs with livestock production) that are being used increasingly in Colombia and other Latin American countries (Palmer, 2014). In addition to improving habitat structure on grazing lands by increasing tree cover, silvopastoral systems have been demonstrated to increase cattle productivity per hectare. Cattle are fenced out of riparian buffer strips to allow for natural recovery and active planting of riparian forests (Calle et al., 2009, 2013). In Colombia, transition to silvopastoral systems has been incentivized by providing short-term payments to help compensate for the costs of initial tree planting and fencing, as well as providing technical support (Calle et al., 2009). Although a number of studies have documented short-term benefits of silvopastoral systems, such as improved human livelihoods, lower methane emissions and higher carbon sequestration, and improved water quality and biodiversity (Calle et al., 2013), studies are needed about whether these benefits are maintained and forest cover increases over the longer term.

Another approach that has been proposed to reduce restoration costs at larger scales is planting a nurse crop of exotic tree species (e.g., *Pinus* L. spp., *Eucalyptus* L'Hér. spp.) or interplanting these species with natives, because these fast-growing species may facilitate establishment of native species and can potentially be logged to help offset restoration costs (Janzen, 2002; Ashton et al., 2014; Brancalion & van Melis, 2017). Likewise, in some cases agricultural land uses may be combined as a transitional stage in restoring forests (i.e., agrosuccessional restoration sensu Vieira et al., 2009), since similar methods are used to grow crops and native trees and to control undesirable "weed" species. Studies of the long-term ecological and economic efficacy of such methods are needed.

Making the most of small-scale restoration experiments

The most expeditious way to scale up the science is to integrate experimental components and long-term monitoring into actual restoration projects, as discussed in the examples above. In addition, within the scientific literature there are a growing number of approaches and examples that move beyond small-scale, single-site field surveys and experiments. More studies are being replicated at multiple sites within a region, which is critical for making robust management recommendations, given the high variation in outcomes of restoration strategies at individual sites within even a specific region (Holl & Zahawi, 2014; Shoo et al., 2016). The next step is to set up parallel experiments testing the same methodologies at sites in multiple regions. For example, TreeDivNet, a global network of 18 tree diversity experiments at 36 sites, compares the advantages and disadvantages of mixed-species plantations, such as carbon sequestration and pest resistance (Verheyen et al., 2016). This approach of establishing networks of restoration sites testing similar methodologies should be used more widely to rigorously compare outcomes and make general recommendations. In addition, the number of meta-analysis studies evaluating factors affecting forest recovery and the efficacy of forest restoration methods is increasing (Shoo & Catterall, 2013; Crouzeilles et al., 2016). These syntheses provide insight into general rules of thumb that can help predict rates of recovery and inform the most promising strategies to test at the local scale.

INCREASING TEMPORAL SCALE

Land managers have the tendency to judge success of restoration project within a few years, given the need to demonstrate results to funding agencies. Likewise, the vast majority of scientific studies of forest restoration have focused on the first few years of recovery due to temporal constraints of graduate programs and the need to publish results. Nonetheless, evaluating efficacy of restoration efforts over a few years is not commensurate with the decades to centuries over which forests recover (Jones & Schmitz, 2009; Rey Benayas et al., 2009; Curran et al., 2014) and highlights the need to evaluate forest restoration success over longer time periods.

A growing body of evidence suggests that the outcomes of forest restoration efforts often change quickly over time. Patterns of seed rain, seedling recruitment, and nutrient inputs from litter in forest restoration plots in southern Costa Rica changed substantially between two and five years and six and 12 years post restoration (Reid et al., 2015a; Holl et al., 2017; O. Lanuza, unpublished data). Vegetation surveys of Gandolfi and colleagues (S. Gandolfi, unpublished data) in the Brazilian Atlantic forest suggest that native tree plantations that were initially judged as "successful" may become "pioneer deserts" if fast-growing, short-lived planted trees start to die after a decade or two, and there has been minimal dispersal and establishment of mid- to late-successional species. Intensive tree planting may increase biomass as compared to natural regeneration during the first decade or two, but a meta-analysis by Bonner et al. (2013) showed that these differences were erased by 18 years post planting.

Data from chronosequences of natural recovery have informed most of what is known about secondary forest succession, but the recovery patterns discerned from them often are not consistent with long-term studies in individual sites (Chazdon et al., 2007; Feldpausch et al., 2007). Chronosequence studies often equate a certain degree of tree biomass or cover with site age, so restoration sites that fail or recover slowly are less likely to be included, thereby providing a more optimistic measure of restoration success. Furthermore, chronosequences are particularly problematic for active restoration because the standard restoration methodologies commonly change over time, making it impossible to tease out the effects of restoration methodology and recovery time (McClain et al., 2011). Hence, long-term data within the same sites are needed to evaluate the success of restoration efforts. But, such data are notoriously difficult to collect and manage given funding constraints and turnover in personnel on projects. There is increasing recognition of the need for long-term scientific studies and monitoring of forest restoration projects (e.g., Brancalion et al., 2013;

Aguilar-Garavito & Ramírez, 2015; Murcia et al., 2016), but they are still rarely implemented.

Long-term monitoring programs that specifically evaluate whether stated restoration objectives have been achieved after specific time intervals (e.g., five, 10, 20, or 30 years) are needed (Holl & Cairns, 2002; Stanturf et al., 2014). Such procedures are not always complicated, as even well-documented photo monitoring or measures of tree growth and survival may be sufficient to evaluate certain objectives. Other cases, such as monitoring changes in water flow, may be quite expensive and require trained personnel. What is critical is that appropriate monitoring methods are used and the data are analyzed to evaluate whether stated objectives are being achieved, determine whether corrective actions are needed, and learn from ongoing efforts.

Taking a long-term view in both planning and evaluating forest restoration success is increasingly important to both adapt to and mitigate changing climatic conditions (Stanturf, 2015). A major motivation for some tropical forest restoration projects is carbon sequestration, making it critical that thought be given to restoring forests that will be resilient to changing temperature and precipitation. Many broad suggestions have been made about how to enhance forest resilience, such as removing barriers to seed dispersal and creating connectivity for migration upslope, using a diverse set of species and genetic provenance of individual species to ensure that some will be able to survive under future climatic conditions, and considering managed translocation of species upslope (Thomas et al., 2014; Locatelli et al., 2015; Stanturf, 2015). Yet most land managers and scientific studies continue to take a business-as-usual approach to forest restoration. Moving forward, it will be necessary to give careful consideration to the diversity and composition of species and the genetic provenance of individual species introduced in forest restoration projects to enhance the likelihood of ecosystems being resilient to changing climatic conditions (Thomas et al., 2014; Falk, 2017).

INTEGRATING MULTIPLE STAKEHOLDERS

As noted earlier in this paper and in multiple recent review papers (Le et al., 2014; Stanturf et al., 2014; Murcia et al., 2016; Chazdon et al., 2017), ultimately the viability of landscape forest restoration efforts hinges on the ability to integrate a variety of forest and non-forest land uses and restoration projects at the landscape scale. For restoration to succeed, landowners must not only be willing to participate in these programs, but to maintain the restored forest over the long term. To achieve this goal requires including multiple stakeholders, such as farmers, local communities, local government leaders, regional national policymakers, and scientists, in the planning, implementation, and evaluation process, yet few examples of integrated planning of tropical forest restoration exist (Chazdon et al., 2017). Many projects are planned top down, without including local stakeholders, and often biodiversity benefits and watershed processes are prioritized over human uses in the landscape (Le et al., 2012; Murcia et al., 2016; Chazdon et al., 2017). Chazdon et al. (2017) provide a detailed agenda for improving the landscape forest restoration planning process and the associated scientific agenda. They outline broad, interdisciplinary research questions for understanding the policy frameworks, institutional arrangements, and economic incentives needed to promote landscape forest restoration, along with information about the ecological effectiveness and cost-effectiveness of different restoration strategies under different ecological, biophysical, and social constraints.

To align the natural and social scientific research with project implementation requires including multiple stakeholders in all stages of research. Often scientists formulate questions and conduct research without consulting with those who could actually use the results of their work; the results are only communicated to the management audience at the end and the recommendations may or may not be relevant (Fig. 1). There is an increasing movement toward participatory action research in forest restoration (Campbell et al., 2016; David et al., 2016), where research agendas are co-designed by multiple stakeholders and, in some cases, landowners and managers are involved in the data collection (Fig. 1). Results are discussed among stakeholders to interpret outcomes and prioritize management actions and future research. In this way, stakeholders are more engaged in the outcome and research projects lead to direct management actions (Campbell et al., 2016). A growing number of examples show the importance of involving local landowners throughout the process to learn from local knowledge, engage stakeholders in different aspects of restoration (e.g., seed collection, growing and planting trees), and increase the likelihood of their ongoing participation in restoration efforts (Negi et al., 2015; Campbell et al., 2016).

One well-documented example of extensive stakeholder involvement in restoration planning and science at the landscape scale is the Brazilian Atlantic Forest Pact, a group of over 270 stakeholders, including non-governmental organizations, governmental institutions, private companies, and research institutions, who are working together to

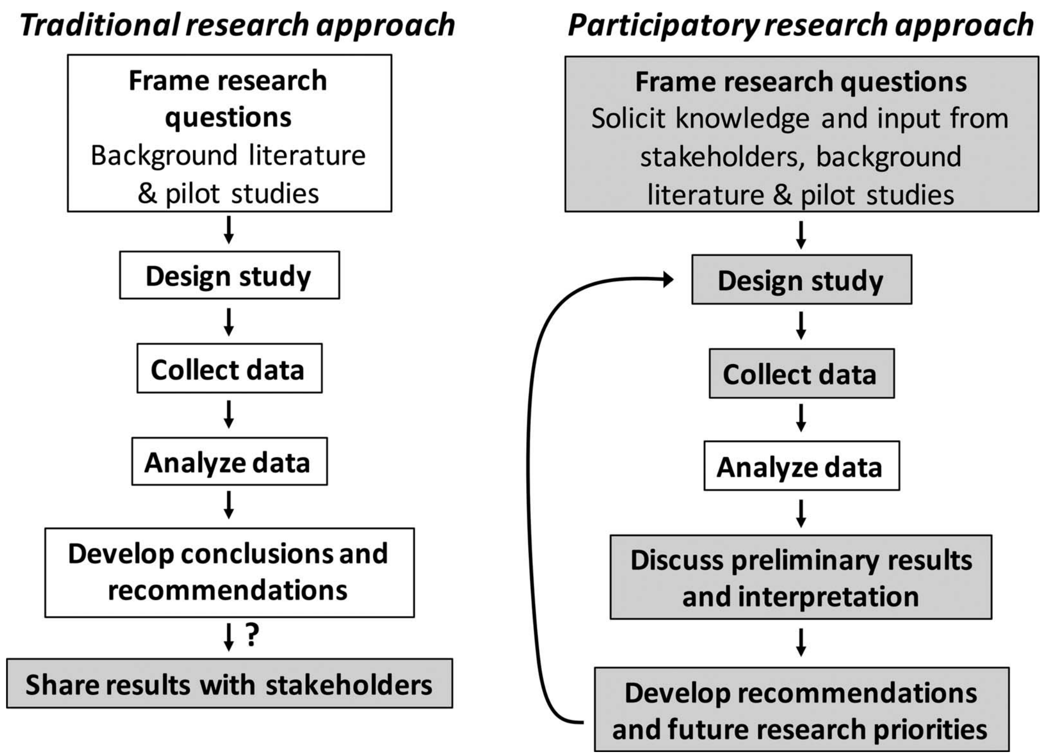

Figure 1. Models of traditional and participatory research approaches to forest restoration. White boxes indicate that only scientists are involved and shaded boxes include both scientists and other stakeholders.

realize the restoration of 15 million hectares of native forest by 2050 (Chaves et al., 2015; Brancalion & van Melis, 2017). Key successes of this effort are that the various organizations have worked together for several years to develop mutually agreed upon goals, research priorities, and monitoring plans; test and share results of different restoration methodologies; and develop a database of restoration projects, nurseries that supply seedlings for restoration, and various stakeholders to facilitate the exchange of information (Brancalion et al., 2013; Brancalion & van Melis, 2017).

IMPROVING INFORMATION EXCHANGE ABOUT FOREST LANDSCAPE RESTORATION

Finally, it is critical to improve the exchange of information between restoration practitioners and scientists regionally and globally so that different restoration efforts are informed by others' successes and failures. Results that are published only in scientific journals in English or in the gray literature in one locality are unlikely to reach a broad audience. Therefore, sharing results in multiple languages through publications highlighting key results for targeted audiences, training courses, and online resources is critical. Recent efforts are moving in this direction through organizations and networks such as the Environmental Leadership and Training Initiative at Yale University, which provides both field and online training courses in different languages on tropical forest restoration and land management (<http://elti.yale.edu>); the People and Reforestation in the Tropics (PARTNERS) interdisciplinary reforestation network, aimed at synthesizing our "understanding of the complex links and feedbacks between the social and ecological subsystems that influence the nature and extent of reforestation" (<http://partners-rcn.org/what-we-do-2>); and efforts of the International Union for the Conservation of Nature (IUCN) to develop and apply tools and build capacity to further forest landscape restoration globally (<https://www.iucn.org/theme/forests/our-work/forest-landscape-restoration>). For example, both PARTNERS and the IUCN provide short, non-technical summaries of results of landscape forest restoration research via blogs. ELTI and IUCN have hosted workshops where scientists, policymakers, and practitioners from different regions come together to visit restoration projects and share their experiences (Liu et al., 2017). IUCN and the World Resources Institute have developed a multi-stakeholder process to carry out forest restoration opportunity assessment (Laestadius et al., 2014); both the manual for this process and an online video series that outlines each phase of the process are available in Spanish, Portuguese, and French (<https://www.iucn.org/content/roam-around-world>).

Monitoring protocols are particularly ripe for sharing, because both ground-based and remotely sensed monitoring methodologies are developing quickly (Aguilar-Garavito & Ramírez, 2015; Zahawi et al., 2015) and standardized forest restoration monitoring protocols would facilitate comparing results of similar projects across multiple sites and regions (Holl & Cairns, 2002; Campbell et al., 2016). Monitoring protocols, as well as associated data sheet templates and data, could be shared online (Brancalion & van Melis, 2017). As another example, several colleagues and I are seeking funding to develop an online tropical forest tree propagation database to make such information widely available. Information about seed collection, nursery techniques, and growth rates is often known locally and sometimes published in regional manuals, but such an online database would make the information readily available to practitioners located anywhere within the range of a given tree species.

Closing Thoughts

The ambitious scales proposed for tropical forest restoration provide some optimism in light of ongoing forest loss (Hansen et al., 2013; Rosa et al., 2016). The growing number of tropical forest recovery and restoration successes suggests that it is possible to build on the considerable knowledge of forest recovery and restoration amassed over the past couple decades to scale up to forest restoration efforts. Nonetheless it will require bringing together different types of stakeholders, a challenge given their frequently different lenses, timelines, needs, and vocabularies. Scientists typically want precise terms to reduce ambiguity, whereas policymakers necessarily use vague and variable language that resonates with different constituencies (Chazdon & Laestadius, 2016). Land managers typically operate on a short timeline and want immediate results, whereas researchers want data over a sufficient time period to have confidence in their results (Campbell et al., 2016). Succeeding at the scale proposed for forest restoration requires compromising and overcoming these differences by focusing on common goals (Chazdon & Laestadius, 2016).

Improving the science of tropical forest restoration will require multifaceted studies that cross individual disciplines. To date most studies of tropical forest restoration have focused narrowly on evaluating planted and naturally establishing tree survival and growth, as well as increases in carbon sequestration and canopy cover. Even improving just "ecological" and "biodiversity" targets of restoration success requires monitoring a wider range of ecological guilds (e.g., epiphytes, insects, fungi), ecosystem functions (e.g., hydrologic cycling), and interactions between them (e.g., plant-animal interactions, McAlpine et al., 2016). Moving to the next level to evaluate the social and economic conditions needed to increase the longevity of restoration projects will require collaboration between natural and social scientists.

The many social, ecological, and economic challenges to forest restoration and the generally slow recovery of the full complement of forest species and functions highlight the importance of protecting the remaining old-growth tropical forest while simultaneously working collaboratively to restore tropical forests across the landscape.

Literature Cited

Aguilar-Garavito, M. & W. Ramírez. 2015. Monitoreo a procesos de restauración ecológica aplicado a ecosistemas terrestres. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Bogotá.

Aide, T. M., J. D. Zimmerman, M. Rosario & H. Marcano. 1996. Forest recovery in abandoned cattle pastures along an elevational gradient in northeastern Puerto Rico. Biotropica 28: 537–548.

Aide, T. M., M. L. Clark, H. R. Grau, D. López-Carr, M. A. Levy, D. Redo, M. Bonilla-Moheno, G. Riner, M. J. Andrade-Núñez & M. Muñiz. 2013. Deforestation and reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45: 262–271.

Alexander, S., C. R. Nelson, J. Aronson, D. Lamb, A. Cliquet, K. L. Erwin, C. M. Finlayson, R. S. de Groot, J. A. Harris, E. S. Higgs, R. J. Hobbs, R. R. Robin Lewis, D. Martinez & C. Murcia. 2011. Opportunities and challenges for ecological restoration within REDD+. Restorat. Ecol. 19: 683–689.

Allen, M. F., E. B. Allen & A. Gomez-Pompa. 2005. Effects of mycorrhizae and nontarget organisms on restoration of a seasonal tropical forest in Quintana Roo, Mexico: Factors limiting tree establishment. Restorat. Ecol. 13: 325–333.

Ashton, M. S., C. V. S. Gunatilleke, B. M. P. Singhakumara & I. Gunatilleke. 2001. Restoration pathways for rain forest in southwest Sri Lanka: A review of concepts and models. Forest Ecol. Managem. 154: 409–430.

Ashton, M. S., C. V. S. Gunatilleke, I. Gunatilleke, B. M. P. Singhakumara, S. Gamage, T. Shibayama & C. Tomimura. 2014. Restoration of rain forest beneath pine plantations: A relay floristic model with special application to tropical South Asia. Forest Ecol. Managem. 329: 351–359.

Bagchi, R., R. E. Gallery, S. Gripenberg, S. J. Gurr, L. Narayan, C. E. Addis, R. P. Freckleton & O. T. Lewis. 2014. Pathogens and insect herbivores drive rainforest plant diversity and composition. Nature 506: 85–88.

Banks-Leite, C., R. Pardini, L. R. Tambosi, W. D. Pearse, A. A. Bueno, R. T. Bruscagin, T. H. Condez, M. Dixo, A. T. Igari, A. C. Martensen & J. P. Metzger. 2014. Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot. Science 345: 1041–1045.

Bertacchi, M. I. F., N. T. Amazonas, P. H. S. Brancalion, G. E. Brondani, A. C. S. de Oliveira, M. A. R. de Pascoa & R. R. Rodrigues. 2016. Establishment of tree seedlings in the understory of restoration plantations: Natural regeneration and enrichment plantings. Restorat. Ecol. 24: 100–108.

Bonner, M. T. L., S. Schmidt & L. P. Shoo. 2013. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. Forest Ecol. Managem. 291: 73–86.

Brancalion, P. H. S. & J. van Melis. 2017. On the need for innovation in ecological restoration. Ann. Missouri Bot. Gard. 102(2): 227–236.

Brancalion, P. H. S., R. A. G. Viani, B. B. N. Strassburg & R. R. Rodrigues. 2012. Finding the money for tropical forest restoration. Unasylva 63: 41–49.

Brancalion, P. H. S., R. A. G. Viani, M. Calmon, H. Carrascosa & R. R. Rodrigues. 2013. How to organize a large-scale ecological restoration program? The framework developed by the Atlantic Forest Restoration Pact in Brazil. J. Sustain. Forest. 32: 728–744.

Brancalion, P. H. S., D. Schweizer, U. Gaudare, J. R. Mangueira, F. Lamonato, F. T. Farah, A. G. Nave & R. R. Rodrigues. 2016. Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: The case of Brazil. Biotropica 48: 856–867.

Calle, A., F. Montagnini & A. F. Zuluaga. 2009. Farmer's perceptions of silvopastoral system promotion in Quindío, Colombia. Bois Forêts Trop. 300: 79–94.

Calle, Z., E. Murgueitio, J. Chará, C. H. Molina, A. F. Zuluaga & A. Calle. 2013. A strategy for scaling-up intensive silvopastoral systems in Colombia. J. Sustain. Forest. 32: 677–693.

Campbell, L. K., E. S. Svendsen & L. A. Roman. 2016. Knowledge co-production at the research–practice interface: Embedded case studies from urban forestry. Environm. Managem. 57: 1262–1280.

Carpenter, F. L., S. P. Mayorga, E. G. Quintero & M. Schroeder. 2001. Land-use and erosion of a Costa Rican ultisol affect soil chemistry, mycorrhizal fungi and early regeneration. Forest Ecol. Managem. 144: 1–17.

Chaves, R. B., G. Durigan, P. H. S. Brancalion & J. Aronson. 2015. On the need of legal frameworks for assessing restoration projects success: New perspectives from São Paulo state (Brazil). Restorat. Ecol. 23: 754–759.

Chazdon, R. L. 2014. Second Growth: The Promise of Tropical Forest Renegeration in an Age of Deforestation. University of Chicago Press, Chicago.

Chazdon, R. L. 2017. Landscape restoration, natural regeneration, and the forests of the future. Ann. Missouri Bot. Gard. 102(2): 251–257.

Chazdon, R. L. & M. R. Guariguata. 2016. Natural regeneration as a tool for large-scale forest restoration in the tropics: Prospects and challenges. Biotropica 48: 716–730.

Chazdon, R. L. & L. Laestadius. 2016. Forest and landscape restoration: Toward a shared vision and vocabulary. Amer. J. Bot. 103: 1869–1871.

Chazdon, R. L., S. G. Letcher, M. van Breugel, M. Martínez-Ramos, F. Bongers & B. Finegan. 2007. Rates of change in tree communities of secondary Neotropical forests following major disturbances. Philos. Trans., Ser. B 362: 273–289.

Chazdon, R. L., C. A. Harvey, O. Komar, M. van Breugel, B. G. Ferguson, D. M. Griffith, M. Martinez-Ramos, H. Morales, R. Nigh, L. Soto-Pinto & S. Philpott. 2009. Beyond reserves: A research agenda for conserving biodiversity in tropical cultural landscapes. Biotropica 41: 141–153.

Chazdon, R. L., P. H. Brancalion, L. Laestadius, A. Bennett-Curry, K. Buckingham, C. Kumar, J. Moll-Rocek, I. C. G. Vieira & S. J. Wilson. 2016. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. Ambio 45(5): 538–550.

Chazdon, R. L., P. H. S. Brancalion, D. Lamb, L. Laestadius, M. Calmon & C. Kumar. 2017. A policy-driven knowledge agenda for global forest and landscape restoration. Cons. Lett. 10: 125–132.

Chechina, M. & A. Hamann. 2015. Choosing species for reforestation in diverse forest communities: Social preference versus ecological suitability. Ecosphere 6: 240.

Cohen, A. L., B. M. P. Singhakumara & P. M. S. Ashton. 1995. Releasing rain forest succession: A case study in the *Dicranopteris linearis* fernlands of Sri Lanka. Restorat. Ecol. 3: 261–270.

Cole, R. J., C. Keene, R. A. Zahawi & K. D. Holl. 2011. Direct seeding of late successional trees to restore tropical montane forest. Forest Ecol. Managem. 261: 1590–1597.

Corbin, J. D. & K. D. Holl. 2012. Applied nucleation as a forest restoration strategy. Forest Ecol. Managem. 265: 37–46.

Craven, D., J. Hall & J. M. Verjans. 2009. Impacts of herbicide application and mechanical cleanings on growth and mortality of two timber species in *Saccharum spontaneum* grasslands of the Panama Canal watershed. Restorat. Ecol. 17: 751–761.

Craven, D., D. Dent, D. Braden, M. S. Ashton, G. P. Berlyn & J. S. Hall. 2011. Seasonal variability of photosynthetic characteristics influences growth of eight tropical tree species at two sites with contrasting precipitation in Panama. Forest Ecol. Managem. 261: 1643–1653.

Crouzeilles, R., M. Curran, M. S. Ferreira, D. B. Lindenmayer, C. E. V. Grelle & J. M. Rey Benayas. 2016. A global meta-analysis on the ecological drivers of forest restoration success. Nat. Comm. 7: 11666.

Curran, M., S. Hellweg & J. Beck. 2014. Is there any empirical support for biodiversity offset policy? Ecol. Appl. 24: 617–632.

Cusack, D. & F. Montagnini. 2004. The role of native species plantations in recovery of understory woody diversity in degraded pasturelands of Costa Rica. Forest Ecol. Managem. 188: 1–15.

David, E., K. W. Dixon & M. H. M. Menz. 2016. Cooperative extension: A model of science–practice integration for ecosystem restoration. Trends Pl. Sci. 21: 410–417.

de la Peña-Domene, M., C. Martínez-Garza & H. F. Howe. 2013. Early recruitment dynamics in tropical restoration. Ecol. Appl. 23: 1124–1134.

de Rezende, C. L., A. Uezu, F. R. Scarano & D. S. D. Araujo. 2015. Atlantic Forest spontaneous regeneration at landscape scale. Biodivers. Conserv. 24: 2255–2272.

de Souza Leite, M., L. R. Tambosi, I. Romitelli & J. P. Metzger. 2013. Landscape ecology perspective in restoration projects for biodiversity conservation: A review. Nat. Conserv. 11: 108–118.

Douterlungne, D., S. I. Levy-Tacher, D. J. Golicher & F. R. Danobeytia. 2010. Applying indigenous knowledge to the restoration of degraded tropical rain forest clearings dominated by bracken fern. Restorat. Ecol. 18: 322–329.

Douterlungne, D., E. Thomas & S. I. Levy-Tacher. 2013. Fast-growing pioneer tree stands as a rapid and effective strategy for bracken elimination in the Neotropics. J. Appl. Ecol. 50: 1257–1265.

Durigan, G., N. Guerin & J. da Costa. 2013. Ecological restoration of Xingu Basin headwaters: Motivations, engagement, challenges and perspectives. Philos Trans., Ser. B 368: 20120165.

Elias, P. & K. Lininger. 2010. The Plus Side: Promoting Sustainable Carbon Sequestration in Tropical Forests. Union of Concerned Scientists, Washington, D.C.

Falk, D. A. 2017. Restoration ecology and the axes of change. Ann. Missouri Bot. Gard. 102(2): 201–216.

Feldpausch, T. R., C. D. Prates-Clark, E. C. M. Fernandes & S. J. Riha. 2007. Secondary forest growth deviation from chronosequence predictions in central Amazonia. Global Change Biol. 13: 967–979.

Firn, J., P. D. Erskine & D. Lamb. 2007. Woody species diversity influences productivity and soil nutrient availability in tropical plantations. Oecologia 154: 521–533.

Fletcher, R., W. Dressler, B. Büscher & Z. R. Anderson. 2016. Questioning REDD+ and the future of market-based conservation. Conserv. Biol. 30: 673–675.

Gunaratne, A., C. V. S. Gunatilleke, I. Gunatilleke, H. Madawala & D. Burslem. 2014. Overcoming ecological barriers to tropical lower montane forest succession on anthropogenic grasslands: Synthesis and future prospects. Forest Ecol. Managem. 329: 340–350.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice & J. R. G. Townshend. 2013. High-resolution global maps of 21st-century forest cover change. Science 342: 850–853.

Holl, K. D. 2002. Tropical moist forest. Pp. 539–558 *in* M. R. Perrow & A. J. Davy (editors), Handbook of Ecological Restoration. Cambridge University Press, Cambridge.

Holl, K. D. 2007. Oldfield vegetation succession in the Neotropics. Pp. 93–117 *in* R. J. Hobbs & V. A. Cramer (editors), Old Fields. Island Press, Washington, D.C.

Holl, K. D. 2012. Tropical forest restoration. Pp. 103–114 *in* J. Van Andel & J. Aronson (editors), Restoration Ecology. Blackwell Publishing, Malden, Massachusetts.

Holl, K. D. & J. Cairns, Jr. 2002. Monitoring and appraisal. Pp. 411–432 *in* M. R. Perrow & A. J. Davy (editors), Handbook of Ecological Restoration, Vol. 1. Cambridge University Press, Cambridge.

Holl, K. D. & T. M. Aide. 2011. When and where to actively restore ecosystems? Forest Ecol. Managem. 261: 1558–1563.

Holl, K. D. & R. A. Zahawi. 2014. Factors explaining variability in woody above-ground biomass accumulation in restored tropical forest. Forest Ecol. Managem. 319: 36–43.

Holl, K. D., V. M. Stout, J. L. Reid & R. A. Zahawi. 2013. Testing heterogeneity-diversity relationships in tropical forest restoration. Oecologia 173: 569–578.

Holl, K. D., J. L. Reid, J. M. Chaves-Fallas, F. Oviedo-Brenes & R. A. Zahawi. 2017. Local tropical forest restoration strategies affect tree recruitment more strongly than does landscape forest cover. J. Appl. Ecol. doi:10.1111/1365-2664.12814.

Hooper, E., R. Condit & P. Legendre. 2002. Responses of 20 native tree species to reforestation strategies for abandoned farmland in Panama. Ecol. Appl. 12: 1626–1641.

International Union for the Conservation of Nature. 2016. IUCN and partners launch global effort to boost restoration of degraded forests. <https://www.iucn.org/news/iucn-and-partners-launch-global-effort-boost-restoration-degraded-forests>, accessed 4 July 2016.

Jakovac, C. C., M. Pena-Claros, T. W. Kuyper & F. Bongers. 2015. Loss of secondary-forest resilience by land-use intensification in the Amazon. J. Ecol. 103: 67–77.

Janzen, D. H. 2002. Tropical dry forest: Area de Conservación Guanacaste, northwestern Costa Rica. Pp. 559–583 *in* M. R. Perrow & A. J. Davy (editors), Handbook of Ecological Restoration. Cambridge University Press, Cambridge.

Jones, F. A., C. J. Peterson & B. L. Haines. 2003. Seed predation in neotropical pre-montane pastures: Site, distance, and species effects. Biotropica 35: 219–225.

Jones, H. P. & O. J. Schmitz. 2009. Rapid recovery of damaged ecosystems. PLoS One 4: e5653.

Kauano, E. E., F. C. G. Cardoso, J. M. D. Torezan & M. C. M. Marques. 2014. Micro- and meso-scale factors affect the restoration of Atlantic forest. Nat. Conservação 11: 145–151.

Laestadius, L., S. Maginnis, J. Rietbergen-McCracken, C. Saint-Laurent, D. Shaw & M. Verdone. 2014. A Guide to the Restoration Opportunities Assessment Methodology (ROAM): Assessing Forest Landscape Restoration Opportunities at the National or Sub-national Level. International Union for the Conservation of Nature, Gland, Switzerland.

Lamb, D. 2014. Large-scale Forest Restoration. Routledge, New York.

Lawrence, D. 2003. The response of tropical tree seedlings to nutrient supply: Meta-analysis for understanding a changing tropical landscape. J. Trop. Ecol. 19: 239–250.

Lawrence, D. 2005. Biomass accumulation after 10–200 years of shifting cultivation in Bornean rain forest. Ecology 86: 26–33.

Le, H. D., C. Smith, J. Herbohn & S. Harrison. 2012. More than just trees: Assessing reforestation success in tropical developing countries. J. Rural Stud. 28: 5–19.

Le, H. D., C. Smith & J. Herbohn. 2014. What drives the success of reforestation projects in tropical developing countries? The case of the Philippines. Global Environm. Change 24: 334–348.

Letcher, S. G. & R. L. Chazdon. 2009. Rapid recovery of biomass, species richness, and species composition in a forest chronosequence in northeastern Costa Rica. Biotropica 41: 608–617.

Liu, J., M. Calmon, A. Clewell, J. Liu, B. Denjean, V. L. Engel & J. Aronson. 2017. South–south cooperation for large-scale ecological restoration. Restorat. Ecol. 25: 27–32.

Locatelli, B., C. P. Catterall, P. Imbach, C. Kumar, R. Lasco, E. Marin-Spiotta, B. Mercer, J. S. Powers, N. Schwartz & M. Uriarte. 2015. Tropical reforestation and climate change: Beyond carbon. Restor. Ecol. 23: 337–343.

Maginnis, S. & W. Jackson. 2007. What is FLR and how does it differ from current approaches? Pp. 5–20 *in* J. Rietbergen-McCracken, S. Maginnis & A. Sarre (editors), The Forest Landscape Restoration Handbook. Earthscan, London.

Mansourian, S. & D. Vallauri. 2014. Restoring forest landscapes: Important lessons learnt. Environm. Managem. 53: 241–251.

Martínez-Garza, C. & H. F. Howe. 2003. Restoring tropical diversity: Beating the time tax on species loss. J. Appl. Ecol. 40: 423–429.

McAlpine, C., C. P. Catterall, R. Mac Nally, D. Lindenmayer, J. L. Reid, K. D. Holl, A. F. Bennett, R. K. Runting, K. Wilson, R. J. Hobbs, L. Seabrook, S. Cunningham, A. Moilanen, M. Maron, L. Shoo, I. Lunt, P. Vesk, L. Rumpff, T. G. Martin, J. Thomson & H. Possingham. 2016. Integrating plant- and animal-based perspectives for more effective restoration of biodiversity. Front. Ecol. Environm. 14: 37–45.

McClain, C. D., K. D. Holl & D. M. Wood. 2011. Successional models as guides for restoration of riparian forest understory. Restorat. Ecol. 19: 280–289.

McDonald, T., G. Gann, J. Jonson & K. W. Dixon. 2016. International Standards for the Practice of Ecological Restoration—Including Principles and Key Concepts. Society for Ecological Restoration, Washington, D.C.

Meli, P., M. Martínez-Ramos, J. M. Rey-Benayas & J. Carabias. 2014. Combining ecological, social and technical criteria to select species for forest restoration. Appl. Veg. Sci. 17: 744–753.

Mendenhall, C. D., C. H. Sekercioglu, F. O. Brenes, P. R. Ehrlich & G. C. Daily. 2011. Predictive model for sustaining biodiversity in tropical countryside. Proc. Natl. Acad. Sci. U.S.A. 108: 16313–16316.

Mesquita, R. D. G., P. E. D. Massoca, C. C. Jakovac, T. V. Bentos & G. B. Williamson. 2015. Amazon rain forest succession: Stochasticity or land-use legacy? Bioscience 65: 849–861.

Murcia, C. 1997. Evaluation of Andean alder as a catalyst for the recovery of tropical cloud forests in Colombia. Forest Ecol. Managem. 99: 163–170.

Murcia, C., M. R. Guariguata, Á. Andrade, G. I. Andrade, J. Aronson, E. M. Escobar, A. Etter, F. H. Moreno, W. Ramírez & E. Montes. 2016. Challenges and prospects for scaling-up ecological restoration to meet international commitments: Colombia as a case study. Cons. Lett. 9: 213–220.

Murgueitio, E., Z. Calle, F. Uribe, A. Calle & B. Solorio. 2011. Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. Forest Ecol. Managem. 261: 1654–1663.

Negi, V. S., I. Bhatt, P. Phondani & B. Kothyari. 2015. Rehabilitation of degraded community land in Western Himalaya: Linking environmental conservation with livelihood. Curr. Sci. 109: 520–528.

Nepstad, D. C., C. M. Stickler, B. Soares & F. Merry. 2008. Interactions among Amazon land use, forests and climate: Prospects for a near-term forest tipping point. Philos. Trans., Ser. B 363: 1737–1746.

Nichols, J. D. & F. L. Carpenter. 2006. Interplanting *Inga edulis* yields nitrogen benefits to *Terminalia amazonia*. Forest Ecol. Managem. 233: 344–351.

Norden, N., H. A. Angarita, F. Bongers, M. Martinez-Ramos, I. Granzow-de la Cerda, M. Breugel, E. Lebrija-Trejos, J. A. Meave, J. Vandermeer, G. B. Williamson, B. Finegan, R. Mesquita & R. L. Chazdon. 2015. Successional dynamics in Neotropical forests are as uncertain as they are predictable. Proc. Natl. Acad. Sci. U.S.A. 112: 8013–8018.

Palmer, L. 2014. A new climate for grazing livestock. Nat. Clim. Change 4: 321–323.

Panfil, S. N. & C. A. Harvey. 2016. REDD+ and Biodiversity conservation: A review of the biodiversity goals, monitoring methods, and impacts of 80 REDD+ projects. Cons. Lett. 9: 143–150.

Park, A., M. van Breugel, M. S. Ashton, M. Wishnie, E. Mariscal, J. Deago, D. Ibarra, N. Cedeno & J. S. Hall. 2010. Local and regional environmental variation influences the growth of tropical trees in selection trials in the Republic of Panama. Forest Ecol. Manage. 260: 12–21.

Parrotta, J. A. 1995. Influence of overstory composition on understory colonization by native species in plantations on a degraded tropical site. J. Veg. Sci. 6: 627–636.

Phelps, J., D. A. Friess & E. L. Webb. 2012. Win-win REDD+ approaches belie carbon-biodiversity trade-offs. Biol. Conserv. 154: 53–60.

Poorter, L., F. Bongers, T. M. Aide, A. M. Almeyda Zambrano, P. Balvanera, J. M. Becknell, V. Boukili, P. H. S. Brancalion, E. N. Broadbent, R. L. Chazdon, D. Craven, J. S. de Almeida-Cortez, G. A. L. Cabral, B. H. J. de Jong, J. S. Denslow, D. H. Dent, S. J. DeWalt, J. M. Dupuy, S. M. Durán, M. M. Espírito-Santo, M. C. Fandino, R. G. César, J. S. Hall, J. L. Hernandez-Stefanoni, C. C. Jakovac, A. B. Junqueira, D. Kennard, S. G. Letcher, J.-C. Licona, M. Lohbeck, E. Marín-Spiotta, M. Martínez-Ramos, P. Massoca, J. A. Meave, R. Mesquita, F. Mora, R. Muñoz, R. Muscarella, Y. R. F. Nunes, S. Ochoa-Gaona, A. A. de Oliveira, E. Orihuela-Belmonte, M. Peña-Claros, E. A. Pérez-García, D. Piotto, J. S. Powers, J. Rodríguez-Velázquez, I. E. Romero-Pérez, J. Ruíz, J. G. Saldarriaga, A. Sanchez-Azofeifa, N. B. Schwartz, M. K. Steininger, N. G. Swenson, M. Toledo, M. Uriarte, M. van Breugel, H. van der Wal, M. D. M. Veloso, H. F. M. Vester, A. Vicentini, I. C. G. Vieira, T. V. Bentos, G. B. Williamson & D. M. A. Rozendaal. 2016. Biomass resilience of Neotropical secondary forests. Nature 530: 211–214.

Reid, J. L. & K. D. Holl. 2013. Arrival ≠ survival. Restorat. Ecol. 21: 153–155.

Reid, J. L., C. D. Mendenhall, J. A. Rosales, R. A. Zahawi & K. D. Holl. 2014. Landscape context mediates avian habitat choice in tropical forest restoration. PLoS One 9: e90573.

Reid, J. L., K. D. Holl & R. A. Zahawi. 2015a. Seed dispersal limitations shift over time in tropical forest restoration. Ecol. Appl. 25: 1072–1082.

Reid, J. L., C. D. Mendenhall, R. A. Zahawi & K. D. Holl. 2015b. Scale-dependent effects of forest restoration on Neotropical fruit bats. Restor. Ecol. 23: 681–689.

Reid, J. L., S. J. Wilson, G. S. Bloomfield, M. E. Cattau, M. E. Fagan, K. D. Holl & R. A. Zahawi. 2017. How long do restored ecosystems persist? Ann. Missouri Bot. Gard. 102(2): 258–265.

Rey Benayas, J. M., A. C. Newton, A. Diaz & J. M. Bullock. 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: A meta-analysis. Science 325: 1121–1124.

Rocha, G. P. E., D. L. M. Vieira & M. F. Simon. 2016. Fast natural regeneration in abandoned pastures in southern Amazonia. Forest Ecol. Managem. 370: 93–101.

Rodrigues, R. R., R. A. F. Lima, S. Gandolfi & A. G. Nave. 2009. On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic forest. Biol. Conserv. 142: 1242–1251.

Rosa, I. M., M. J. Smith, O. R. Wearn, D. Purves & R. M. Ewers. 2016. The environmental legacy of modern tropical deforestation. Curr. Biol. 26: 2161–2166.

Sampaio, A. B., K. D. Holl & A. Scariot. 2007. Does restoration enhance regeneration of seasonal deciduous forests in pastures in central Brazil? Restorat. Ecol. 15: 462–471.

Sansevero, J. B. B., P. V. Prieto, L. F. D. de Moraes & P. J. P. Rodrigues. 2011. Natural regeneration in plantations of native trees in lowland Brazilian Atlantic forest: Community structure, diversity, and dispersal syndromes. Restorat. Ecol. 19: 379–389.

Society for Ecology Restoration Science & Policy Working Group. 2004. The SER primer on ecological restoration. <https://nau.edu/uploadedFiles/Centers-Institutes/ERI/_Forms/Resources/ser-primer.pdf>, accessed 28 September 2009.

Shono, K., E. A. Cadaweng & P. B. Durst. 2007. Application of assisted natural regeneration to restore degraded tropical forestlands. Restorat. Ecol. 15: 620–626.

Shoo, L. P. & C. P. Catterall. 2013. Stimulating natural regeneration of tropical forest on degraded land: Approaches, outcomes, and information gaps. Restorat. Ecol. 21: 670–677.

Shoo, L. P., K. Freebody, J. Kanowski & C. P. Catterall. 2016. Slow recovery of tropical old-field rainforest regrowth and the value and limitations of active restoration. Conserv. Biol. 30: 121–132.

Siddique, I., V. L. Engel, J. A. Parrotta, D. Lamb, G. B. Nardoto, J. Ometto, L. A. Martinelli & S. Schmidt. 2008. Dominance of legume trees alters nutrient relations in mixed species forest restoration plantings within seven years. Biogeochemistry 88: 89–101.

Stanturf, J. A. 2015. Future landscapes: Opportunities and challenges. New Forests 46: 615–644.

Stanturf, J. A., B. J. Palik & R. K. Dumroese. 2014. Contemporary forest restoration: A review emphasizing function. Forest Ecol. Managem. 331: 292–323.

Tambosi, L. R., A. C. Martensen, M. C. Ribeiro & J. P. Metzger. 2014. A framework to optimize biodiversity restoration efforts based on habitat amount and landscape connectivity. Restorat. Ecol. 22: 169–177.

Thomas, E., R. Jalonen, J. Loo, D. Boshier, L. Gallo, S. Cavers, S. Bordács, P. Smith & M. Bozzano. 2014. Genetic considerations in ecosystem restoration using native tree species. Forest Ecol. Managem. 333: 66–75.

Tucker, N. I. G. & T. Simmons. 2009. Restoring a rainforest habitat linkage in north Queensland: Donaghy's Corridor. Ecol. Managem. Restorat. 10: 98–112.

United Nations. 2014. New York Declaration on Forests. <http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forest-%E2%80%93-Action-Statement-and-Action-Plan.pdf>, accessed 25 October 2016.

Uriarte, M. & R. L. Chazdon. 2016. Incorporating natural regeneration in forest landscape restoration in tropical regions: Synthesis and key research gaps. Biotropica 48: 915–924.

Vergara, W., L. Gallardo Lomeli, M. Franco Chuaire, S. Weber & R. Zamora Cristales. 2015. Initiative 20 × 20: A landscape restoration movement rises in Latin America and the Caribbean. <http://www.wri.org/blog/2015/12/initiative-20x20-landscape-restoration-movement-rises-latin-america-and-caribbean>, accessed 26 August 2016.

Verheyen, K., M. Vanhellemont, H. Auge, L. Baeten, C. Baraloto, N. Barsoum, S. Bilodeau-Gauthier, H. Bruelheide, B. Castagneyrol, D. Godbold, J. Haase, A. Hector, H. Jactel, J. Koricheva, M. Loreau, S. Mereu, C. Messier, B. Muys, P. Nolet, A. Paquette, J. Parker, M. Perring, Q. Ponette, C. Potvin, P. Reich, A. Smith, M. Weih & M. Scherer-Lorenzen. 2016. Contributions of a global network of tree diversity experiments to sustainable forest plantations. Ambio 45: 29–41.

Vieira, D. L. M. & A. Scariot. 2006. Principles of natural regeneration of tropical dry forests for restoration. Restorat. Ecol. 14: 11–20.

Vieira, D. L. M., K. D. Holl & F. M. Peneireiro. 2009. Agro-successional restoration as a strategy to facilitate tropical forest recovery. Restorat. Ecol. 17: 451–459.

Wheeler, C. E., P. A. Omeja, C. A. Chapman, M. Glipin, C. Tumwesigye & S. L. Lewis. 2016. Carbon sequestration and biodiversity following 18 years of active tropical forest restoration. Forest Ecol. Managem. 373: 44–55.

Wydhayagarn, C., S. Elliott & P. Wangpakapattanawong. 2009. Bird communities and seedling recruitment in restoring seasonally dry forest using the framework species method in Northern Thailand. New Forests 38: 81–97.

Zahawi, R. A. & K. D. Holl. 2009. Comparing the performance of tree stakes and seedlings to restore abandoned tropical pastures. Restorat. Ecol. 17: 854–864.

Zahawi, R. A., J. P. Dandois, K. D. Holl, D. Nadwodny, J. L. Reid & E. C. Ellis. 2015. Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. Biol. Conserv. 186: 287–295.

Zedler, J. B. 2007. Success: An unclear, subjective descriptor of restoration outcomes. Ecol. Restorat. 25: 162–168.