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# The role of natural regeneration in large-scale forest and landscape restoration: Challenge and opportunity

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## Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges

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### ABSTRACT

A major global effort to enable cost-effective natural regeneration is needed to achieve ambitious forest and landscape restoration goals. Natural forest regeneration can potentially play a major role in large-scale landscape restoration in tropical regions. Here, we focus on the conditions that favor natural regeneration within tropical forest landscapes. We illustrate cases where large-scale natural regeneration followed forest clearing and non-forest land use, and describe the social and ecological factors that drove these local forest transitions. The self-organizing processes that create naturally regenerating forests and natural regeneration in planted forests promote local genetic adaptation, foster native species with known traditional uses, create spatial and temporal heterogeneity, and sustain local biodiversity and biotic interactions. These features confer greater ecosystem resilience in the face of future shocks and disturbances. We discuss economic, social, and legal issues that challenge natural regeneration in tropical landscapes. We conclude by suggesting ways to enable natural regeneration to become an effective tool for implementing large-scale forest and landscape restoration. Major research and policy priorities include: identifying and modeling the ecological and economic conditions where natural regeneration is a viable and favorable land-use option, developing monitoring protocols for natural regeneration that can be carried out by local communities, and developing enabling incentives, governance structures, and regulatory conditions that promote the stewardship of naturally regenerating forests. Aligning restoration goals and practices with natural regeneration can achieve the best possible outcome for achieving multiple social and environmental benefits at minimal cost.

Abstract in Portuguese is available with online material.

Abstract in Spanish is available with online material.

*Key words:* cost-effective restoration; ecosystem services; landscape restoration; resilience; secondary succession; seed dispersal.

OVER HALF OF THE WORLD'S TROPICAL FORESTS have been converted to other land uses, reducing available habitats and resources for forest-dependent species and people, and compromising the ecosystem services that support all life on earth (Lewis *et al.* 2015). Conservation and sound management of remaining old growth forests are essential to stem further losses of biodiversity (Gibson *et al.* 2011) and to retain global carbon stocks (Pan *et al.* 2011, Grace *et al.* 2014). But these measures alone are not sufficient to conserve species, mitigate climate change, and ensure long-term sustainability of goods and services provided by forest ecosystems (Harvey *et al.* 2008, Chazdon *et al.* 2009a, Houghton *et al.* 2015). Restoration of degraded forestland is therefore an necessary step toward ensuring a future for tropical forests around the world (Bullock *et al.* 2011, Chazdon 2014). Globally, two billion ha in forest and forest/savanna biomes have been identified as opportunities for forest and landscape restoration (FLR), using a variety of modes (Laestadius *et al.* 2012). These areas primarily constitute cleared forest land that does not

support productive agriculture or effectively generate ecosystem services.

In response to recent global and regional commitments that generate awareness and political will for implementing forest restoration (Pistorius & Freiberg 2014), organizations, communities, and governments are now making decisions about how to implement the most cost-effective approaches to restore forests at large spatial scales (Sabogal *et al.* 2015). To date, 34 countries and subnational units have committed to ambitious restoration targets (Bonn Challenge 2016), but most have not yet drawn their implementation plans. Approaches to reforestation based exclusively on industrial-scale monocultures will rarely deliver the multiple benefits that are needed to restore landscape functionality, provide sustainable livelihoods, and support biodiversity (Barlow *et al.* 2007, Lamb 2014). A cross-sector landscape approach needs to be adopted that blends forestry knowledge, ecosystem service supply, and conservation awareness with a forward-looking large-scale restoration agenda (Sayer *et al.* 2013, Laestadius *et al.* 2015, Sabogal *et al.* 2015). Forest and landscape restoration (FLR) is a holistic process that aims to regain ecological integrity and enhance human well-being in deforested, human-impacted, or degraded forest landscapes. This

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process focuses on large spatial scales, where multiple land uses and forms of land ownership coexist, and where management decisions are usually made by different sets of stakeholders (Maginnis & Jackson 2007). Various types of planted and naturally regenerating forests, including agroforests, can be established and managed in different zones of the landscape, according to environmental suitability, land managers' needs and aspirations, management goals, and financing arrangements (Chazdon 2008a).

It is unlikely that ambitious FLR goals will be achieved without a major global effort to enable natural regeneration, including economic incentives to compensate landowners. Restoration methods based on natural regeneration are considerably less costly than those based on planting trees (Chazdon & Uriarte 2016), and can potentially be applied over much larger areas, thus enabling more cost-effective, large-scale forest restoration. For example, spontaneous natural regeneration on over 3000 ha in Rio de Janeiro State, Brazil would have cost US\$15.1 million using active tree planting methods (de Rezende *et al.* 2015). Prioritizing natural regeneration in areas that are well-suited for it will allow limited funds to be targeted for restoration in other areas where more costly and intensive interventions are needed. The potential for carbon mitigation through large-scale natural regeneration in tropical regions is compelling (Chazdon *et al.* 2016b, Mukul *et al.* 2016a,b). Yet many economic, social, and legal issues challenge the viability of natural regeneration as a restoration tool in tropical landscapes.

Here, we explore the prospects and challenges for large-scale unassisted and assisted natural regeneration of tropical forests to contribute to ambitious restoration targets at both national (Ceccon *et al.* 2015, Murcia *et al.* 2016) and global levels (Chazdon *et al.* 2015a, Chazdon & Uriarte 2016). By 'large-scale' we refer to either continuous expanses in need of forest recovery in a given region or nation-wide programs that may aggregate to millions of hectares. Natural regeneration can occur in numerous patches within mosaic landscapes and can also take place at larger spatial scales in areas of lower population density within private land holdings or state-owned protected areas (described by Laestadius *et al.* 2012 as 'wide-scale' restoration).

We first define natural and assisted regeneration and describe the environmental factors that promote diverse and progressive forest regrowth. We then illustrate cases of large-scale natural regeneration and describe the social and ecological factors that drove forest transitions within particular historical contexts. We then discuss the features and multiple benefits of the self-organizing processes in naturally regenerating forests and diverse ecological restoration plantings. We also discuss economic, social, and legal factors that challenge the viability of natural regeneration as a restoration tool in tropical landscapes. We conclude by suggesting ways to enable natural regeneration to become an effective tool for planning and implementation of large-scale tropical forest restoration.

## WHAT IS NATURAL REGENERATION, AND HOW CAN IT BE ASSISTED?

Under suitable conditions, natural regeneration (secondary succession) of tropical forests occurs on its own, following ecological

processes of species colonization and community assembly (Guariguata & Ostertag 2001, Chazdon 2008b, 2014). Forest regrowth begins with the spontaneous reestablishment of plant and animal species following disturbance at a wide range of spatial scales, from small-scale disturbances within a forest matrix to expansive cattle pastures within a complex land-use mosaic. Natural regeneration is best viewed as a gradual process of recovery of the structure, function, and composition of the pre-disturbance ecosystem. Changes in vegetation are accompanied by changes in soil microbes and fauna. In tropical regions, insects and vertebrates play critically important roles in pollination, seed dispersal, and other biotic interactions affecting dynamics of plant populations. The characteristics and pace of unassisted forest regeneration are strongly influenced by climate, soils, repeated stand-level disturbances, prior land use, surrounding vegetation, and the regional species pool (Chazdon 2014). Even under favorable conditions, however, naturally regenerating forests are unlikely to recover the full complement of species present in the original ecosystem due to large-scale habitat depletion, decimation of faunal populations, and impacts of global climate change. Enrichment planting may be required to generate commercial value, increase abundance of poorly dispersed species, or to protect endangered species (Bertacchi *et al.* 2016).

When and where initial tree establishment is limited by soil conditions, competition from herbaceous vegetation, frequent burning, grazing, or other factors, natural regeneration can be assisted and encouraged through a variety of interventions including weed suppression, fertilization, tending of naturally regenerating seedlings, enhancement of seed dispersal, and protection from burning or grazing. The goal of assisted regeneration is to accelerate the establishment, growth, and survival of native tree species that naturally colonize abandoned fields (Shono *et al.* 2007). Once trees are established, or in areas with low remnant tree cover, enrichment planting of seeds or transplanted seedlings can enhance establishment of species with low colonization or dispersal potential. Careful tending of rootstocks by farmers is another form of assisted natural regeneration that significantly enhances tree regeneration in dryland agroforestry systems (Reij & Winterbottom 2015, Reij & Garrity 2016). Planting of nursery-grown seedlings and direct seeding to initiate forest regeneration across an entire area is an active restoration approach (Chazdon & Uriarte 2016). Tree planting can ameliorate poor soil conditions that limit natural regeneration, particularly in the case of nitrogen-fixing tree species that promote the recovery of organic matter and soil nutrient levels (Lamb 1998, Griscom & Ashton 2011).

In some cases, however, tree planting does not enhance natural regeneration, even when native species are used. Monocultures of even-aged trees are susceptible to disease (Abbas *et al.* 2016) and create spatially homogeneous conditions in the understory that reduce the diversity of regenerating species and alter conditions for epiphytic species. In areas of the Colombian Andes where seed sources are nearby, 30-yr old naturally regenerating forests showed higher spatial heterogeneity in species composition and higher overall plant species richness compared to same-age plantations of the native pioneer *Alnus acuminata* (Murcia 1997).

## WHAT CONDITIONS FAVOR NATURAL REGENERATION?

Natural regeneration is driven by emergent processes at both local and landscape scales (Arroyo-Rodríguez *et al.* 2016). Landscape processes implicitly incorporate human agency and livelihoods, as forest and agricultural ecosystems coexist in spatially and temporally changing arrangements. Natural regeneration is therefore shaped by changing socio-ecological processes that can be sustained, enhanced, or hindered by human activities over short to long time scales (Bhagwat *et al.* 2012, 2013, Chazdon *et al.* 2014). Natural forest regrowth is promoted by two major sets of environmental factors: (1) high local resource availability (e.g. soil nutrients, soil moisture, microbial communities, and mineral soil properties); and (2) high propagule (e.g., seeds and sprouts) availability. (Chazdon 2013a) provides a checklist of ten factors that promote successful natural regeneration. Close proximity to existing forest areas, low levels of soil disturbance, and seed dispersing fauna are the most critical factors. Recent landscape-level analyses of natural regeneration confirm the importance of proximity to mature forest patches and lack of soil disturbance (Pereira *et al.* 2013, de Rezende *et al.* 2015, Sloan *et al.* 2015, Martínez-Ramos *et al.* 2016b). Where and when these conditions are met, forest regrowth is then determined by cessation of agricultural or pastoral land use and prevention of fire, grazing or other disturbances that impede species colonization and establishment.

Seeds and/or resprouts are essential ingredients of forest regeneration. During natural regeneration, seeds disperse from sources within or close to the site (Reid *et al.* 2015). Sources of regenerating plant species can be present as seeds in the soil seed bank, rootstocks or stolons present below the soil surface, or as seeds dispersed from local or surrounding plants. These sources, which are based on biological legacies present in the local or surrounding areas can be collectively termed ‘ecological memory’ (Bengtsson *et al.* 2003, Sun *et al.* 2013) (Table 1). Ecological memory derives from components within the local site (internal memory) or from components outside of the local site (external memory). Internal memory is strongly influenced by legacies of historical land use, such as presence of topsoil and soil organic matter, presence of remnant vegetation, or legacies of repeated burning or soil compaction. External memory is strongly influenced by the amount and location of forest patches and biological corridors in the surrounding landscape and by the abundance and diversity of fauna (McAlpine *et al.* 2016, Catterall 2016, Table 1). External memory creates the potential for seed dispersal, whereas internal memory creates the potential for local regeneration within the site. Indicators of ecological memory can be quantified and mapped to assess spatial variation in the potential for natural regeneration (Sun *et al.* 2014). These indicators include a range of biological legacies such as the diversity and abundance of the plant community, soil seed bank, soil microbes, soil fauna, and bird and bat species (Sun *et al.* 2013). In the tropics, 50–90 percent of the tree species are dispersed by birds and mammals (Howe & Smallwood 1982), underscoring the

TABLE 1. Indicators of internal (within local site) and external (within surrounding landscape) ecological memory that can be used to predict the capacity for natural regeneration within degraded or deforested tropical forest landscapes (based on Sun *et al.* 2013). These indicators reflect historical legacies of land use and disturbance at local and landscape scales.

Indicator	Internal	External
Presence of topsoil and soil organic matter	X	
Soil seed bank	X	
Presence of rootstocks	X	
Abundance and cover of shrubs	X	X
Abundance of remnant trees	X	X
Abundance of animal-dispersed trees	X	X
Living fences/hedgerows	X	X
Local avian abundance and diversity	X	X
Local mammal frugivore abundance and diversity	X	X
Remnant forest patches within 100 m		X
Riparian vegetation within 100 m		X
Large forest remnants or reserves within 200 m		X
Regional avian abundance and diversity		X
Regional mammal abundance and diversity		X

importance of the landscape context for faunal conservation and forest regeneration (Reid *et al.* 2014). Retention of ecological memory in its myriad forms is the foundation for restoring resilient forest landscapes. Fig. 1 illustrates a site in Rio de Janeiro State, Brazil where ecological memory is high, and fencing to prevent grazing will likely be all that is needed to promote cost-effective large-scale natural regeneration to create biological corridors for endangered endemic wildlife.

In areas where natural regeneration does not initiate well on its own, ecosystem restoration plantings of native tree species and



FIGURE 1. Pastures with a high potential for natural regeneration near the Poço das Antas Biological Reserve, in Rio de Janeiro State, Brazil. Several indicators of this potential are the woody regeneration appearing in pastures where grazing pressures are low, large fragments of Atlantic Forest in close proximity, and lack of soil degradation (photograph by Robin Chazdon).

non-invasive exotic species can catalyze natural regeneration (Parrotta 1992, Guariguata *et al.* 1995, Powers *et al.* 1997, Ewel & Putz 2004, Bertacchi *et al.* 2015, de Rezende *et al.* 2015). Initial establishment of tree canopy cover in a plantation (Carnevale & Montagnini 2002, Sansevero *et al.* 2011, Viani *et al.* 2015) or in smaller tree islands (Cole *et al.* 2010), as well as in unmanaged or unused monoculture tree plantations (Silva Junior *et al.* 1995, Lee *et al.* 2005, Selwyn & Ganesan 2009, Brockerhoff *et al.* 2013, Piironen *et al.* 2015) can facilitate natural regeneration (Brancalion *et al.* 2016, Elliott 2016, Gilman *et al.* 2016, Latawiec *et al.* 2016). Removal of topsoil associated with mining or bulldozing (Román-Dañobeytia *et al.* 2015) severely restrict forest regrowth. Under these conditions, soil amelioration or topsoil amendments are needed to facilitate natural regeneration where surrounding seed sources are available (Parrotta & Knowles 1999). Areas isolated from forest fragments and regions where natural seed dispersal vectors have been extirpated require active planting interventions to restore forest cover (Holl & Aide 2011, Howe 2016).

## LARGE-SCALE NATURAL REGENERATION IN TROPICAL AND SUBTROPICAL REGIONS

A growing number of studies document cases of large-scale forest restoration through spontaneous natural regeneration and assisted natural regeneration (Table 2). These cases span different geographic, historical, political, social, economic, and ecological contexts. But they all demonstrate the high potential for large-scale restoration through natural regeneration processes when the appropriate ecological conditions align with socio-economic conditions that allow deforested land to revert back to forest.

Many tropical regions demonstrated net increases in forest cover during the first decade of this century, particularly in the Latin American tropics (Aide *et al.* 2013). Between 2001 and 2010, Cuba, Puerto Rico, Haiti, Mexico, Costa Rica, Honduras, El Salvador, Colombia, and Venezuela showed a net gain of

forest vegetation. Across Latin America, most of this forest regrowth occurred in the dry forest biome and in mountainous regions (Aide *et al.* 2013). Although forest cover within the Atlantic Forest Region of Brazil has fallen to 11.7 percent due to over 500 yrs of deforestation (Ribeiro *et al.* 2009), large-scale natural restoration is being observed in some areas, attesting to high levels of resilience in these cases (Baptista 2008, Cheung *et al.* 2010, Ferraz *et al.* 2014, de Rezende *et al.* 2015).

As mentioned above, each of these cases (Table 2) reflects different contexts that led to natural regeneration. In the case of Puerto Rico, most of the regenerating forests were in coffee-growing areas where smallholders predominated, agriculture was labor intensive, lands were marginal for production, and migration rates of workers to urban areas were high. The probability of reforestation through natural regeneration was 2.7 times higher on farms below 30 ha (Rudel *et al.* 2000, Yackulic *et al.* 2011). Small farm size and infrequent use of fires facilitated rapid recovery of forest structure (Grau *et al.* 2003). In South America, forest regeneration in arid zones and mountain slopes is occurring on already deforested areas on lands that are poorly suited for mechanized agriculture. In these cases, the opportunity cost of agricultural land use is low, favoring land abandonment (Aide *et al.* 2013).

Natural regeneration in northwestern Costa Rica was facilitated by the collapse of beef prices after 1980, which led smallholders in marginal areas to abandon their cattle pastures. Natural regeneration on abandoned pastures was driven by a major socioeconomic transition from employment in the agriculture and cattle ranching sector to the tourism and service sector (Calvo-Alvarado *et al.* 2009). In the Osa Peninsula region, nearly half of the natural regeneration was associated with pasture abandonment on slopes >30 percent (Algeet-Abarquero *et al.* 2015). Land purchases for development of ecotourism and foreign investment in conservation within the Osa region have also promoted natural regeneration on former pastureland (Zambrano *et al.* 2010).

TABLE 2. Cases where natural and/or assisted natural regeneration has occurred at large spatial scales. Change in forest cover is reported differently across studies.

Location	Time period	Change in forest cover	References
Puerto Rico	1948–1991	<10–42% forest cover	Helmer <i>et al.</i> (2002), Grau <i>et al.</i> (2003)
El Salvador	1990–2000	22% increase in forest cover	Hecht & Saatchi (2007)
Costa Rica, Chorotega region	1986–2005	23.1–47.0% forest cover	Calvo-Alvarado <i>et al.</i> (2009)
Costa Rica, Osa Peninsula	1998–2003	5% increase in forest cover	Algeet-Abarquero <i>et al.</i> (2015)
	2003–2009	6% increase in forest cover	
Brazil, Santa Catarina State, Florianopolis Metropolitan Area	1985–1995	23% increase in natural forest cover on private farms	Baptista (2008)
Brazil, Rio de Janeiro State, Trajano de Moraes Municipality	1978–2014	Increase in forest cover of 15.4%	de Rezende <i>et al.</i> (2015)
Madagascar, Androy region	1993–2000	4% increase in forest cover	Elmqvist <i>et al.</i> (2007)
Vietnam, northern mountains	1993–2002	Increase in forest over from 16.8 to 33%	Meyfroidt & Lambin (2008)
Ethiopia, Humbo region	2006–2010	2,700 ha of assisted natural regeneration	Brown <i>et al.</i> (2011) and Reij & Garrity (2016)
Niger, Southern region	1975–2003	5 million ha of assisted natural regeneration of woodlands	Reij <i>et al.</i> (2009) and Reij & Garrity (2016)

In the Atlantic Forest region of Rio de Janeiro state, forest gain was related to decreasing rural population and cropland cover following the economic decline of coffee (de Rezende *et al.* 2015). The widespread adoption of Farmer Managed Natural Regeneration—a form of assisted natural regeneration—in dryland regions of Niger was favored by a political, economic, and energy crisis that forced farmers to increase on-farm tree density through the protection and management of natural regeneration (Reij & Garrity 2016).

These cases of large-scale natural regeneration associated with forest transitions highlight two important issues. First, areas undergoing natural regeneration tend to be located in steep slopes with marginal value for industrialized agriculture and therefore have low opportunity costs for other uses (Ferraz *et al.* 2014). Second, these cases were not planned as part of an explicit forest landscape restoration initiative, but rather were the outcome of socio-economic driving forces largely caused by changes in global markets, rural out-migration, agricultural credit policies, or political and economic crises (Jadin *et al.* 2016). Many cases of large-scale natural regeneration in the tropics have occurred as consequence of rural-to-urban migration or remittances from abroad, which may reduce the demand for local farmland (Hecht *et al.* 2015). Such changes could be rapidly reversed if sufficient motivating and enabling factors and legal instruments for large-scale FLR are not in place (García-Barríos *et al.* 2009).

## MULTIPLE ADVANTAGES OF NATURAL REGENERATION

Natural regeneration and assisted natural regeneration of forests are the most cost-effective approaches for large-scale FLR (Lamb 2014). Aside from their lower costs of implementation, naturally regenerating forests can provide critically needed habitats for conservation of forest-dependent animal species (Chazdon *et al.* 2009b) and deliver multiple ecosystem services, including carbon sequestration (Poorter *et al.* 2016).

Naturally regenerating forests are complex adaptive systems that possess eight key properties: heterogeneity, hierarchy, self-organization, openness, adaptation, memory, non-linearity, and uncertainty (Chazdon & Arroyo-Mora 2013, Filotas *et al.* 2014). These properties confer resilience, or the capacity for recovery or persistence of the system following disturbances or major shocks (Cumming 2011). In contrast, monoculture tree plantations have low resilience, particularly if genetic diversity is low, increasing the risk of susceptibility to plant disease. In Hong Kong, large-scale reforestation using monocultures of the native species *Pinus massoniana* after World War II was a total failure due to widespread disease during the 1970s (Abbas *et al.* 2016). Large-scale plantations of native and east Asian varieties of rubber, *Hevea brasiliensis*, in Pará, Brazil succumbed to caterpillars, root disease, leaf blight, viral, and fungal infections, dashing Henry Ford's hopes for a resurgence of the rubber industry (Resor 1977).

The hierarchical organization of species interactions during the self-assembly of forests contributes to resilience. The species

that self-organize during natural regeneration are adapted to local conditions and bring with them their mutualist partners, who generate further diversity and heterogeneity within the landscape (Howe 2016, McAlpine *et al.* 2016). Seed dispersal networks tend to have a modular and nested structure where specialists interact with generalists, providing stability in response to the loss or gain of mutualist partners (Bascompte & Jordano 2007, Mello *et al.* 2011). Spatial heterogeneity due to small-scale disturbance or topographic variation creates diverse environmental conditions for species recruitment and survival, promoting local taxonomic and functional diversity (Nicolson *et al.* 1999, Lasky *et al.* 2014). Openness of forest ecosystems allows exchange of species and information across ecosystem boundaries, supporting migratory species and linking systems across latitudes and elevations (Lindell *et al.* 2012, McGuire & Boyle 2013). Numerous understory bird species recolonized forest fragments that were previously isolated but later became reconnected through regenerating vegetation in Central Amazonia (Stouffer *et al.* 2011).

Uncertainty is another major feature of regenerating forests that sets them aside from restoration through tree planting, at least during the initial stages of canopy formation (Norden *et al.* 2015, Arroyo-Rodríguez *et al.* 2016). Although uncertainty can create problems for predicting or orchestrating changes in species composition or forest structure, changes in functional attributes that influence biomass accumulation and that determine the supply of goods and services may be more predictable (Lohbeck *et al.* 2014, Poorter *et al.* 2016). Uncertainty derives, in part, from the stochastic nature of forest dynamics, where particular species colonize opportunistically in one site but are completely absent in another site (Chazdon 2008b). These stochastic processes ultimately lead to higher landscape-level diversity and heterogeneity. Planted forests using a high-diversity of native tree species can also create a highly resilient forest ecosystem, but at considerably higher economic cost and a far more restricted spatial scale (Rodrigues *et al.* 2011). Moreover, tree species used in restoration plantings do not represent the full range of functional traits present within the local or regional species pool.

Allowing nature to choose which species predominate during natural regeneration allows for local adaptation and higher functional diversity. However, natural regeneration can promote the colonization and persistence of undesirable herbaceous or woody species, which can arrest or alter successional pathways (Catterall 2016, Cordell *et al.* 2016, Tymen *et al.* 2016). Limited plant establishment can lead to species-poor assemblages with low local or commercial value. In these cases, naturally regenerating forests can potentially be managed to reduce the effects of exotic invasive species (Friday *et al.* 2015, Nghiem *et al.* 2015), and species composition can be enhanced through enrichment planting or other silvicultural treatments (Bertacchi *et al.* 2015).

Properly controlled comparative studies of the outcomes of mixed-species plantings versus naturally regenerating forests are rare (Brancalion *et al.* 2016, Gilman *et al.* 2016), and further research is urgently needed. Compared to a mixed-species restoration plantation, naturally regenerating forests are expected to exhibit a more diverse age structure of canopy trees and a more

heterogeneous and patchy spatial structure within the understory. These features will permit the forest to better withstand or recover from subsequent disturbances. Associated animal diversity is also expected to be high, as many species are attracted to regrowing vegetation as sources of food, shelter, and nesting/breeding sites. For example, the regeneration of understory palms in young second growth forests creates important roosting sites for tent-making bats that disperse seeds from over 80 tree species (Melo *et al.* 2009).

The beneficial features of natural regeneration as compared to mixed-species plantings take time to emerge, however. Brancalion *et al.* (2016) report that during the first five years of restoration, naturally regenerating sites within Semideciduous and Dense Ombrophilous Atlantic Forest regions of Brazil showed lower vegetation cover, basal area, and tree species richness than actively planted sites. An experimental study in northeastern Costa Rica showed that total basal area was higher in planted than naturally regenerating plots after five years of regrowth, but species richness of recruits did not differ with planting treatment (Gilman *et al.* 2016).

Natural regeneration leads to the gradual recovery of multiple ecosystem functions (soil organic matter accumulation, carbon sequestration, hydrologic regulation, nutrient cycling, pollination) due to the diversity of canopy and understory species (Aryal *et al.* 2014, Poorter *et al.* 2016) and the changing structure, composition, and function of regenerating forests (Chazdon & Rey Benayas in press, Rozendaal & Chazdon 2015). Carbon farming can be a potential source of income for landowners who restore agricultural land back into forest. Based on values of multiple ecosystem services, the cost-effectiveness of natural regeneration of dryland forests in four regions of Latin America was greater than tree planting approaches (Birch *et al.* 2010). Economic analyses of the costs and benefits of different forms of restoration are sensitive to the net present value of agricultural land, discount rates, and market values of carbon (Strassburg *et al.* 2016). Naturally regenerating forests in the western Andes of Colombia reached about half of the carbon stocks in old growth forests within a period of 15–30 yrs (Gilroy *et al.* 2014). A median carbon price of US\$1.99 per ton of CO<sub>2</sub> over a 30-yr period was sufficient to compensate landowners for the opportunity costs of allowing natural regeneration on pastures. Apart from the carbon storage benefit, restored communities of bird and dung beetles closely resembled those of old growth forests after 15–30 yr, and regenerating forests provided suitable habitats for many of the threatened bird taxa in the study region (Gilroy *et al.* 2014). In Queensland, Australia 30.6 million ha of relatively recently deforested landscapes may be suitable for carbon farming via different modes of forest restoration. Assisted natural regeneration was found to provide a more cost-effective alternative for sequestering carbon compared to tree plantings and provided additional benefits for biodiversity conservation in areas with low-to-intermediate levels of degradation (Evans *et al.* 2015).

Naturally regenerating forests can be important sources of timber and non-timber products, which support local livelihoods

(Ashton *et al.* 2014, Adams *et al.* 2016, De Souza *et al.* 2016). (Toledo *et al.* 2003) identified 595 plant species that indigenous people harvest from second growth forests in Mexico. In four 1-ha plots of natural regeneration after pasture abandonment in NE Costa Rica, the relative abundance of commercial tree species with a dbh  $\geq 10$  cm ranged from 53.5 to 61.1 percent and the relative basal area ranged from 62.2 to 76.6 percent (Vílchez Alvarado *et al.* 2008). Naturally regenerating forests also produce a wealth of non-timber products that are used by rural peoples and that help to perpetuate and enhance cultural traditions. These include bushmeat and other foods, palm thatch for shelter, cordage, palm leaves for the ornamental market, and a wide variety of medicinal plants (Chazdon & Coe 1999, Gavin 2004, Voeks 2004, Pulido & Caballero 2006, Junqueira *et al.* 2011, Hernández-Barrios *et al.* 2015). Regenerating forests also hold high spiritual and cultural value as sacred forests, church forests, and forest gardens (Bhagwat *et al.* 2013, Ford & Nigh 2015). Enrichment and improvement of fallows with fruit trees, palms with commercial foliage, medicinal plants, oil- and resin-producing plants, rattans, and bamboos are common practices that promote forest regeneration, enhance local biodiversity, and support local livelihoods (Michon *et al.* 2007, Lopez-Toledo *et al.* 2011, Kartawinata & Abdulhadi 2015).

## CHALLENGES FOR IMPLEMENTING LARGE-SCALE NATURAL REGENERATION

Although the role that natural forest regeneration can play in landscape restoration is becoming increasingly recognized, many obstacles stand in the way. In many tropical forest areas, such as Hainan Island, China, reforestation policies promote large-scale establishment of commercial exotic tree plantations (primarily rubber, *Hevea brasiliensis*), and do not include natural regeneration as a component (Zhai *et al.* 2014). Natural regeneration is often not even considered to be an option for large-scale FLR, as reforestation is often implemented by forestry companies that are closely allied with government interests (Chazdon *et al.* 2016a). Large-scale commercial monoculture tree plantations can present potential conflicts with the broader social and ecological objectives of FLR.

The essential features of natural regeneration—heterogeneity, openness, self-organization, and uncertainty—may pose challenges to large-scale social acceptance and implementation by government agencies and non-governmental organizations. These features do not satisfy those who wish to see a predictable and orderly restoration process with specific area-based and time-bound outcomes, as well as having a set of particular tree species in place. Trajectories of natural regeneration vary substantially, even within the same region and following similar previous land uses (Chazdon *et al.* 2007, Feldpausch *et al.* 2007, Mesquita *et al.* 2015, Norden *et al.* 2015, Arroyo-Rodriguez *et al.* 2016). Many circumstances are inimical to natural regeneration, particularly where soils have been highly degraded, native vegetation is lacking, and fires are frequent. When fields are fallowed, persistence of invasive species, lianas, or fire-tolerant grasses and ferns can

lead to a permanently degraded state that will not return to forest without active management interventions (Styger *et al.* 2009, Jakovac *et al.* 2015, Suazo-Ortuño *et al.* 2015, Tymen *et al.* 2015). These factors underscore the urgent need to prioritize natural regeneration in those areas where it is most likely to be successful, and to implement more active restoration interventions where it is not (Holl & Aide 2011a, Chazdon 2013b, Latawiec *et al.* 2015).

Natural regeneration of tropical forests, even with assistance, is a slow process, and may be interpreted by local people as ineffective or inappropriate land use (Zahawi *et al.* 2015). Moreover, in the absence of long-term studies of succession within the region of interest, it can be difficult to determine whether the natural regeneration process is indeed arrested or deflected (Sarmiento 1997). Building a long-lived forest ecosystem from scratch takes multiple human generations. On the surface, waiting around for forests to regrow does not appear to be an attractive financial investment, as the outcomes are highly risky and there is a substantial lag time for returns on investments. For those who are looking for a quick fix to produce timber and non-timber products, increase carbon storage, stabilize soils, or regulate water flows, planting fast growing trees appears to be a much better solution and a wiser business investment. Alternatively, fallow enrichment with crop species or useful tree species is an approach used by many indigenous peoples to enhance and accelerate natural regeneration while also enhancing economic benefits (Hecht 1982, Michon *et al.* 2007, Paquette *et al.* 2009, Ford & Nigh 2015).

Quick fixes will not solve the problems that FLR needs to solve or provide the multiple benefits that will ensure long-term restoration success (Chazdon *et al.* 2015a). Although rates of accumulation of aboveground biomass are initially higher in tree plantations than in naturally regenerating sites (Holl & Zahawi 2014), these differences tend to diminish within 20–40 yr (Jordan & Farnworth 1982, Lugo 1992, Bonner *et al.* 2013, Shoo *et al.* 2016). Considering the high *long-term* benefits and reduced costs, natural regeneration is often a superior option. Comparative analyses based on a 20-yr time frame are too short to provide realistic assessment. Moreover, carefully controlled long-term experiments need to be conducted to evaluate the short- and long-term benefits of natural regeneration compared to multi-species native tree plantations (see Gilman *et al.* 2016).

Another challenge facing large-scale implementation of natural regeneration is the way they are defined and categorized by forestry organizations and government agencies. Forest definitions that directly affect the persistence of naturally regenerating forests in the landscape are often ambiguous and jurisdictionally scale-dependent (Vieira *et al.* 2014, Chazdon *et al.* 2016a). In contrast, for reforestation or ‘plantation forestry’, public policy and detailed legislation are usually straightforward (Kanowski 2010). In spite of international efforts to recognize naturally regenerating forests as a legitimate land use type (ITTO 2002), these have remained ‘under the radar’ in national land-use planning for decades (Davies 1997) and are often governed separately by different

national and subnational agencies with overlapping mandates (Wieland Fernandini & Sousa 2015). Whether a naturally regenerating area is classified as a ‘forest’ or a ‘fallow’ is more often than not, unresolved and riddled with cross sectorial overlaps (Cronkleton *et al.* 2013, Sears *et al.* 2014). The development of specific criteria may help to ensure that natural regeneration plays a formal role in forest restoration. For example, in the state of Pará, Brazil, secondary vegetation can be legally cleared if below 10 m<sup>2</sup>/ha of tree basal area for municipalities with more than 50 percent primary forest or if below 5 m<sup>2</sup>/ha for those with <50 percent primary forest cover (Vieira *et al.* 2014). Yet when structural variables are used to distinguish a forest from a fallow to prevent further conversion, the legal status of young regenerating forests makes them often prone to government overregulation, which restricts traditional forest use by local populations (Román-Dañobeytia *et al.* 2014).

In most regions, there is a lack of institutional support for broad, multi-sectorial efforts to enable restoration and natural regeneration. The Atlantic Forest Restoration Pact is a clear example of the importance of building a broad, multi-sectorial base of support, expertise, and participation so that technical and sectorial dimensions are incorporated into making natural regeneration a viable option for smallholders (Pinto *et al.* 2014). Although the Brazilian Native Vegetation Recovery Plan (MMA 2014), the Colombian Restoration Plan (MADS 2015), and the Ecuadorian Restoration Plan (MA 2014) explicitly consider natural regeneration as an option, no obvious cross-sectorial integration is explicitly proposed in these documents. Other countries, such as Mexico, have made ambitious restoration commitments, but do not yet have a national restoration plan in place (Ceccon *et al.* 2015); hopefully a cross-sectorial approach will be adopted during its development.

From a social and cultural standpoint, early stages of natural regeneration have a bad reputation among many landowners, land managers, and decision makers in tropical countries. It is called ‘pastro sujo’ in Brazil, ‘acahual’ in Mexico, ‘rastrojo’ in Colombia, ‘charral’ in Costa Rica, and is widely labeled as ‘degraded land’ in most tropical countries, regardless of the actual regeneration potential of the site. Agricultural credit programs often require farmers with land titles to clear forest completely and maintain cleared land (*i.e.*, ‘clean pastures’). In this case, natural regeneration can only occur if land is legally abandoned and land tenure and property ownership are both relinquished. Many farmers view land occupied by ‘weedy vegetation’ as the outcome of irresponsible land management (Zahawi *et al.* 2014). It may invite invasion of farmland by squatters, who interpret this form of land use as ‘abandonment’. The early stages of natural regeneration are messy, overgrown, snake- and wasp-infested tangles of vegetation that do not appear to have any conservation or economic value. Allowing their field or pasture to become a ‘scrubland’ is at times undesirable and may not always compensate landowners for income lost from giving up their agricultural land use. Areas that are no longer being farmed are generally ignored, left out of forest resource assessments, or distained by conservation organizations, and viewed as prime areas for clearance and

plantation establishment. They are orphaned lands that need to be adopted and nurtured—but by whom?

### ENABLING FACTORS FOR NATURAL REGENERATION

Harnessing the power of natural processes to restore forests in degraded landscapes is a powerful concept. Making this concept a reality will require overcoming many of the obstacles and challenges mentioned above. Aligning restoration goals and practices with natural processes of ecosystem recovery can achieve the best possible outcomes for recovering ecosystem functions, services, and biodiversity at scale in ways that improve livelihoods and promote strong, local governance and stewardship. Traditional knowledge can provide key information regarding functional and ecological roles of pioneer species during natural regeneration. For example, the Lacandon people in Chiapas, Mexico use pioneer tree species to recover soil properties and prevent infestation of bracken fern (*Pteridium aquilinum*) in degraded croplands (Douterlunge *et al.* 2010).

One critical step is to develop and apply methods to prioritize areas where small to large patches of natural regeneration are most likely to occur if agricultural land use is halted and lands are protected. Diagnostic frameworks have been proposed to assess where and when natural regeneration is the most appropriate and cost-effective restoration option (Holl *et al.* 2011b, Rodrigues *et al.* 2011). On the technical side, there is a need to further develop and validate frameworks for assessing the potential for natural regeneration and methods to prioritize areas suitable for natural regeneration (Holl & Aide 2011a, Shoo & Catterall 2013). The Restoration Opportunities Assessment Methodology includes a protocol for assessing natural regeneration as an option for large-scale forest restoration and is being applied in several countries (available in Spanish, English, Portuguese, French, and Russian; IUCN and WRI 2014). In the

Eastern Amazonian state of Pará, Brazil, the potential for natural regeneration is observed for three years following cessation of prior land use to assess whether active restoration approaches are needed to comply with mandatory legislation (de Pierro 2015). The Atlantic Forest Restoration Pact developed a preliminary diagnostic framework, and modifications are currently being applied to statewide restoration plans (Isernhagen *et al.* 2009, Martins *et al.* 2014). Martins *et al.* (2014) conducted an assessment of natural regeneration potential in the state of Espírito Santo, Brazil, based on proximity of vegetation, rainfall, soil fertility, texture, and rockiness. Based on the proximity of seed sources from surrounding forest fragments determined from aerial photos, an estimated 2,804,431 ha of the state of Espírito Santo have a ‘high potential’ for natural regeneration, composing 60.9 percent of the total area of the state (Martins *et al.* 2014). More advanced spatial modeling studies are currently underway, based on existing geographic coverages of natural regeneration and multiple social and biophysical variables (de Rezende *et al.* 2015). Multi-criteria spatial prioritization models offer a highly promising approach and are being developed in several tropical regions (Orsi *et al.* 2011, Carwardine *et al.* 2015).

Beyond the planning and prioritization stage, other things need to happen within multiple sectors of society to give natural regeneration a chance to contribute to large-scale restoration (Table 3). Interdisciplinary research efforts that identify key drivers of land change through novel integrative frameworks (Uriarte *et al.* 2010) can help to identify areas where the ‘right mix’ of socioecological, demographic, and economic variables could converge for naturally regenerated forests to persist over time. Enabling policies will also need to be put into place that remove disincentives (including eliminating perverse incentives to clear vigorous and diverse young second growth to plant tree plantations), develop or refine legal instruments that encourage and protect regeneration and that secure land tenure and property rights while not excluding livelihood options (Carabias *et al.* 2007,

TABLE 3. *Enabling factors and policies that can promote large-scale natural regeneration as part of landscape-scale restoration efforts. Adapted from Lamb (2014)*

Sector	Enabling factor
National government	Secure land tenure and property rights for smallholders Develop national and state/province-level restoration plan that recognizes active and passive forms of restoration Develop a national plan for economic incentives for landowners who restore forest through natural regeneration and native species planting, or mixed approaches
State, province, or municipality	Develop regional standards for forest regeneration management plans, diagnostic tools, and monitoring protocols Capacitate forestry extension teams to carry out diagnostic assessments of natural regeneration potential on private and public lands Train community leaders and youth to monitor forest restoration, including natural regeneration Popularize natural regeneration as a resilient form of reforestation with multiple benefits for different stakeholders Reward stewards of natural regeneration with prizes, certification, or honors
Business/Industry	Create value chains for timber and non-timber products harvested from certified naturally regenerated forests Promote premium pricing for carbon credits and other ecosystem services from naturally regenerating forests
Higher education	Train reforestation technicians to conduct diagnostic assessments and work with landowners to develop forest restoration management plans and monitoring protocols
Finance	Provide grants to landowners for fencing, fire control, or hunting patrols in areas with high potential for natural regeneration

Román-Dañobeytia *et al.* 2014, Vieira *et al.* 2014). Ownership of regenerating forests is often contested, and governments often view these areas as ‘land banks’ to be used for other purposes, rather than as forest assets that merit conservation (Chazdon *et al.* 2015a). In Brazil, landowners must comply with legal requirements to conserve or restore vegetation on 80 percent of their property if they are in the Amazon, 35 percent in the Cerrado, and 20 percent in other biomes (Soares-Filho *et al.* 2014). But how these lands are to be restored is not yet planned. Following a diagnostic evaluation of their properties, forest restoration management plans could be developed for and by landowners that would qualify them for additional financial incentives and other benefits that they would not otherwise receive (Table 3). Cooperating landowners would then become forest restoration stewards who manage diverse forms of restoration on their land (Raymond *et al.* 2016).

The permanence of secondary forests at large-scales may also be enhanced when governments decide to enlarge a protected area through natural regeneration, as in the expansion of Guanacaste National Park in Costa Rica (Allen 1988). Yet additional control measures may have to be put in place to achieve this goal. For example, during the early stages of forest succession and if the land is not overseen, the probability of fire outbreaks may be high, particularly during dry years, calling for the implementation of fire protection and control practices (Uriarte *et al.* 2012). Environmental and social conditions in the buffer zones of protected areas often favor natural regeneration, particularly when local communities are involved in ecotourism or conservation activities and receive financial or other benefits. In isolated or small reserves, natural regeneration in buffer zones may help to ameliorate cascading edge effects on forest structure and composition (Laurance *et al.* 2011, Arroyo-Rodriguez *et al.* 2016, Martínez-Ramos *et al.* 2016a).

Natural regeneration (as well as other forms of restoration) must become economically competitive with alternative land uses, and benefits need to start flowing to legal landowners before the regenerating forests reach maturity. Existing protected areas that already have infrastructure and a link to the surrounding communities provide rich potential for natural regeneration and development of biological corridors in mixed-used buffer zones (Zambrano *et al.* 2010, Algeet-Abarquero *et al.* 2015). Targeting properties in the buffer zones of protected areas or adjacent to large tracts of natural forest can substantially increase connectivity for animals in the landscape (Tambosi *et al.* 2014, Rappaport *et al.* 2015, Fagan *et al.* 2016).

New management tools will be needed by landowners, forest managers and communities that currently lack technical expertise in this arena. A new class of forest restoration extension agents and technicians could be trained to work with landowners to develop their restoration management plans and to track progress using carefully selected indicators of ecosystem functions, services, biodiversity, and economic benefits (Table 3). These plans should be tailored to particular conditions within the region and the surrounding landscape to prioritize areas where natural regeneration is most likely to persist and prosper. Natural

regeneration stewards would need to be compensated for costs of fencing, fire protection, hunting patrols, or other actions that are needed to promote and sustain naturally regenerating forests on their land. Environmental service payments can also enable active and passive restoration efforts, such as with the Conservador das Águas program in Extrema, Minas Gerais, Brazil, where native forest cover has increased in 60 percent of targeted sub-watersheds through contracts with 53 landowners, and long-term collaborations have been established among government agencies, civil society, and landowners (Richards *et al.* 2015). Costa Rica also offers environmental service payments for protection of naturally regenerating forests (Fig. 2).

To reach ambitious targets for large-scale restoration, we must leverage the potential for forests to replant themselves, and need to track their progress and respond adaptively. Monitoring is the basis for adaptive management and for planning restoration interventions and approaches that are likely to lead to desirable, long-term outcomes (Kanowski *et al.* 2010). Regular monitoring of indicators of forest structure and biodiversity provides critical demographic information that cannot be obtained from chronosequence methods (Chazdon *et al.* 2007, Rozendaal & Chazdon 2015). Understanding the ecological and social drivers of natural regeneration requires long-term monitoring of vegetation structure and composition. This information provides the basis for spatial prioritization of natural regeneration as a restoration approach and for selecting species appropriate for planting when needed (Meli *et al.* 2013). Defining the range of variation in observed trajectories of natural regeneration provides a benchmark for comparing trajectories of active restoration approaches and assessing their relative costs and benefits (Norden *et al.* 2015, Arroyo-Rodriguez *et al.* 2016).



FIGURE 2. Over 180 ha of natural regeneration thrive in the Refugio Lapa Verde in northeastern Costa Rica alongside 300 ha of old growth forest. The regeneration in the foreground is <10 yr old. The landowners receive environmental service payments for protecting over 90 ha of second growth (photograph by Robin Chazdon).

Because natural regeneration often begins in small patches within agricultural mosaic landscapes, high-resolution mapping is needed to detect this process and to track changes over time (Chazdon *et al.* 2016a). Monitoring and mapping of forest regeneration can also be done effectively using participatory approaches (Danielsen *et al.* 2013, Vergara-Asenjo *et al.* 2015). However, participatory monitoring protocols need to be practical enough so not to become a burden on local landholders, while providing the evidence base for gauging the performance of restoration practices and stimulating reflection and adaptive management practice. The international community, donors, investors, non-governmental organizations, national and local governments and their communities will want to know, within the next decades, how the many existing restoration commitments have fared. To this end, those involved in large-scale restoration need to find the appropriate balance of ‘top down’ versus ‘bottom-up’ monitoring approaches so that information imbalances are minimized (Danielsen *et al.* 2009) and management outcomes are both informative and reported in a cost-effective way across different spatial scales.

Ultimately, the key to increasing the role of natural regeneration in large-scale restoration is to elevate these young forests to a new status that removes the stigma of ‘degradation’ and ‘abandonment’. By enabling the new land use of natural regeneration, multiple stakeholders become partners with nature and become directly embedded within an integrated socio-ecological process. Identifying the ecological and economic conditions where natural regeneration is a viable land-use option and developing incentive structures and enabling conditions to promote the stewardship of naturally regenerating forests are major research and policy priorities. Aligning restoration goals and practices with natural processes of forest regeneration can achieve the best possible outcomes for recovering ecosystem functions, services, and biodiversity at scale in ways that improve livelihoods and promote strong, local governance and stewardship.

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