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Incorporating natural regeneration in forest landscape restoration in tropical regions: synthesis and key research gaps

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ABSTRACT

Extensive tropical forest loss and degradation have stimulated increasing awareness at the international policy level of the need to undertake large-scale forest landscape restoration (FLR). Natural regeneration offers a cost-effective way to achieve large-scale FLR, but is often overlooked in favor of tree plantations. The studies presented in this special issue show how natural regeneration can become an important part of FLR and highlight the ecological, environmental, and social factors that must be considered to effectively do so. They also identify major knowledge gaps and outline a research agenda to support the use of natural regeneration in FLR. Six central questions emerge from these studies: (1) What are the ecological, economic, and livelihood outcomes of active and passive restoration interventions?; (2) What are the tradeoffs and synergies among ecological, economic, and livelihood outcomes of natural regeneration, restoration and productive land uses, and how do they evolve in the face of market and climate shocks?; (3) What diagnostic tools are needed to identify and map target areas for natural regeneration?; (4) How should spatial prioritization frameworks incorporate natural regeneration into FLR?; (5) What legal frameworks and governance structures are best suited to encourage natural regeneration and how do they change across regions and landscapes?; (6) What financial mechanisms can foster low-cost natural regeneration? Natural regeneration is not a panacea to solve tensions and conflicts over land use, but it can be advantageous under some circumstances. Identifying under what conditions this is the case is an important avenue for future research.

Abstract in Portuguese and Spanish are available with online material.

Key words: ecosystem services; forest landscape restoration; land governance; mosaic restoration; natural regeneration; spatial prioritization; spontaneous sustainable land use; trade-offs.

The world's tropical forests harbor the majority of Earth's biodiversity, regulate global climate, provide key ecosystem services, and form the basis for the livelihoods of more than 500 million forest-dependent people worldwide. The extent, structure, and composition of these forests are changing dramatically under the influence of human activities (Lambin & Geist 2006, FAO 2010, Hansen *et al.* 2013). Over 50 percent of the original extent of tropical forests has been cleared (Lewis *et al.* 2015) and the area of degraded old growth and second growth forests in the tropics is estimated at 850 million hectares (Food and Agriculture Organization 2010). Within this area 350 million ha of land have reached such a state of degradation that they no longer can be classified as forest (ITTO 2002). Land degradation leads to food insecurity, high pest pressure, biodiversity loss, reduced availability of clean water, depleted soils, and increased vulnerability to climate and market shocks for the human populations that inhabit and depend on forested landscapes for their livelihood (Sutton *et al.* 2016, Turner *et al.* 2016).

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The magnitude and pervasiveness of these changes—and the realization that the pressures that have led to forest loss and degradation are likely to persist in the future—have led to increasing awareness at the international policy level of the need to undertake large-scale forest landscape restoration (FLR). The Bonn Challenge aims to restore 150 million hectares of deforested and degraded lands by 2020. This ambitious goal was reinforced during the UN Climate Summit 2014 in New York when more than 130 governments, private companies, civil society and indigenous people endorsed the restoration of more than 350 million hectares of forests and croplands globally by 2030. In light of these ambitious targets and emerging national commitments, it is imperative to develop cost-effective methods and techniques for FLR that are also socially inclusive (Laestadius *et al.* 2012). FLR is the long-term process of regaining ecological functionality and enhancing human well-being across deforested and degraded landscape (WRI 2011). The most widely used methods of restoration, such as planting with native or introduced tree species, are costly and scale limited. FAO and UNCCD (2015) estimate the cost of restoring 350 million ha of forest over

15 years at US$ 837 billion. A dire need for low-cost techniques and approaches is evident.

A growing number of studies document cases of large-scale forest restoration through spontaneous and assisted natural regeneration (Rietbergen-McCracken *et al.* 2007, Brancalion *et al.* 2016, Chazdon & Guariguata 2016). These approaches offer cost-effective ways to achieve large-scale FLR (Holl & Aide 2011, Lamb 2014). Native species reassemble on their own or with some assistance, and rapid biomass growth is achieved by local species adapted to the site. Restoration methods based on natural regeneration also provide low-cost opportunities for conserving biodiversity and species interactions (Latawiec *et al.* 2016), sequestering carbon (Mukul *et al.* 2016, Poorter *et al.* 2016, Strassburg *et al.* 2016), and protecting soils and watersheds (Uriarte *et al.* 2011, Locatelli *et al.* 2015). Despite those economic and environmental benefits, natural regeneration is often overlooked when restoration policies and programs are designed (Brancalion *et al.* 2016). Incorporating natural regeneration in FLR will require an efficient manner to identify formerly forested areas with a high potential for self-recovery and a clear understanding of the social and ecological costs and benefits of natural regeneration (Fig. 1). Governance structures, legal frameworks, and policies that foster human capacities to create, manage, monitor, and benefit from FLR activities and outcomes must also be developed.

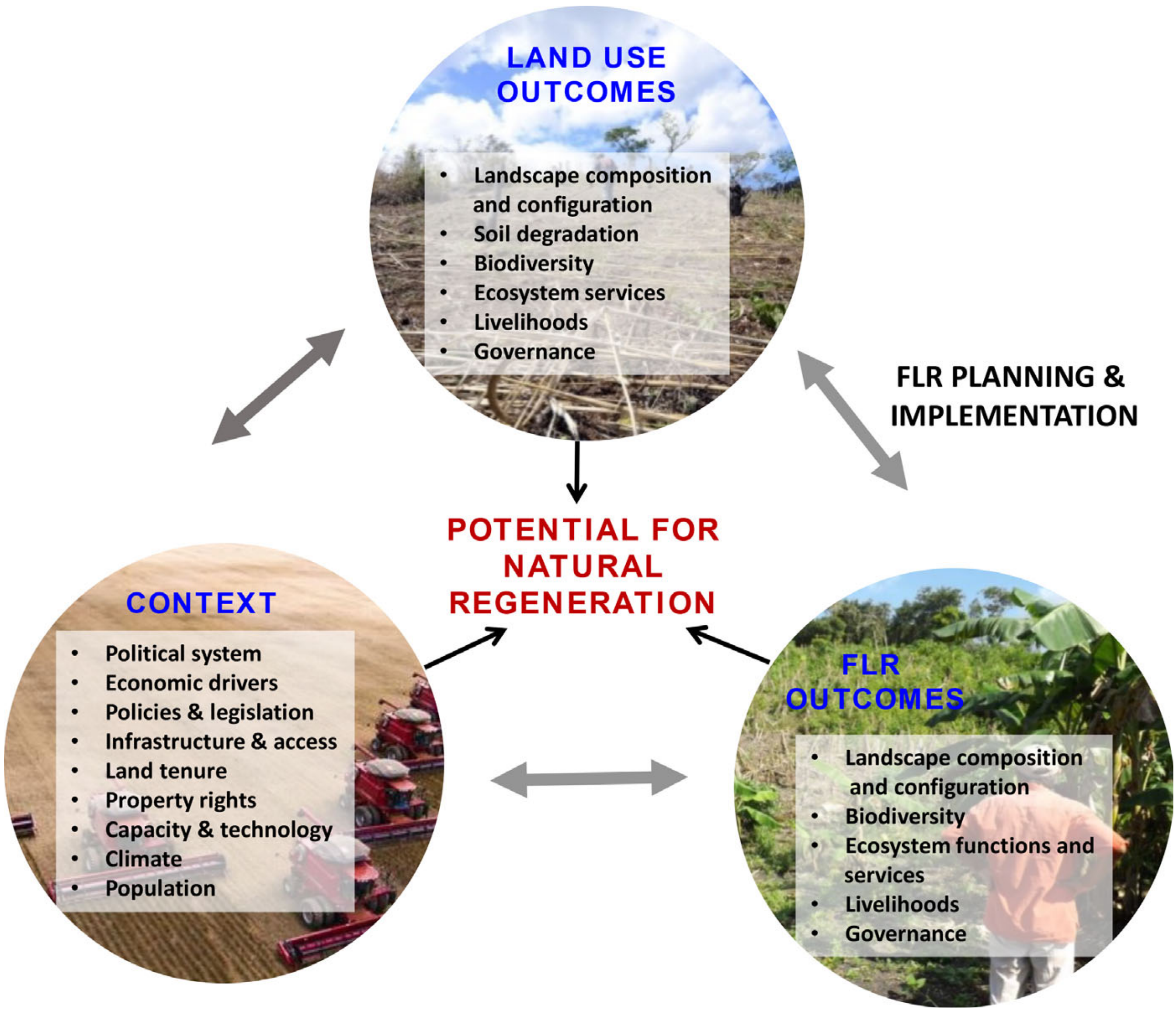

FIGURE 1. The potential for adopting and incorporating natural regeneration into FLR interventions in tropical human-modified landscapes depends on three inter-linked sets of factors. The socioeconomic, biophysical, political, and regulatory Context leads to Land use outcomes for ecosystems and people. Together, these context and land use outcomes motivate FLR planning. Implementation of FLR plans leads to FLR outcomes, which feedback into context and land use outcomes.

The 16 papers included in this special issue identify challenges and opportunities that we must confront in order to achieve large-scale natural forest regeneration in tropical regions. Working from different disciplinary and sectoral backgrounds, the authors address the following questions: (1) What is the scale of the challenge and opportunity for including natural regeneration in FLR?; (2) What local and landscape factors influence the ecological dynamics of natural regeneration?; (3) How can we link the pattern and process of natural regeneration into the practice of landscape restoration?; (4) How can large-scale natural regeneration be managed in the context of multifunctional landscapes and regional planning?; and (5) How does natural regeneration contribute to the provision of forest-based ecosystem services and livelihoods? Below we summarize the most salient findings for each question and identify key research needs for harnessing the potential of natural regeneration in FLR.

THE SCALE OF THE CHALLENGE AND OPPORTUNITY

Across the tropics, over 1 billion hectares of degraded forest and woodlands provide opportunities for various forms of restoration (Laestadius *et al.* 2012). The majority of this area is suited for mosaic landscape restoration in which primary and second growth forests and on-farm trees are combined with other land uses, including agroforestry, plantations, smallholder agriculture, and human settlements (WRI 2011, Chazdon & Uriarte 2016). Given that restoration opportunities exist primarily within these multifunctional landscapes, implementing low-cost natural regeneration will require planning instruments and policy reforms and initiatives that allow scaling-up to the national and regional level. Furthermore, this implementation will require the participation of the multiple stakeholders who stand to benefit from managing natural forest regeneration processes (Adams *et al.* 2016, Lazos *et al.* 2016). Some of these benefits include jobs and income, food security, secure land tenure, carbon sequestration, and improved soil and water resources.

FLR initiatives can learn from case studies where large-scale natural regeneration—whether assisted or not—has already been documented over large geographic scales (*i.e.*, forest transition) (Mather 1992, Rudel *et al.* 2005, 2016, Perz 2007, Aide *et al.* 2013). Such studies can help identify enabling factors and barriers to wide-scale adoption of FLR, as well as arguments and methods to promote enabling factors or overcome barriers (Chazdon & Guariguata 2016). Historically, large-scale natural regeneration was largely determined by context, be it cultural, institutional, or macro- versus micro-economic conditions (Perz 2007). Case studies tell us that adoption and implementation of natural regeneration programs may be most effective in areas where the opportunity cost of land is low (*e.g.*, on steep slopes and remote areas, Asner *et al.* 2009, Yackulic *et al.* 2011), after the collapse of agricultural commodity prices (as in Puerto Rico with coffee, Grau *et al.* 2003), under conditions of wood scarcity (South Korea, Bae *et al.* 2012), or where programs to promote migration of rural population to manufacturing (*e.g.*, Puerto Rico) or service jobs (*e.g.*, Costa Rica) are promoted (Calvo-Alvarado *et al.* 2009). One important caveat is that unassisted forest transitions have typically occurred over a much longer time (*e.g.,* 30–50 year) than those to which global restoration goals aspire (*e.g.,* 15–20 year).

Governments were not passive actors in these examples of forest transitions; they played an important role in jumpstarting and enabling reforestation. In China, severe erosion motivated an ambitious government-finance reforestation program (Weimin *et al.* 2014). Scarcity of wood for construction and heating prompted the adoption of a government-financed reforestation program in South Korea (Bae *et al.* 2012). Motivated by an external debt crisis and increasing concern over deforestation, the Costa Rican government ended subsidies for livestock, which had encouraged extensive cattle ranching, and in the 1990s adopted a series of policies to promote reforestation in small and medium sized rural properties (Campos *et al.* 2005) (Fig. 2). In Puerto Rico, a government-sponsored industrialization program fostered an economic shift from agriculture to manufacturing, which led to abandonment of agriculture and increases in forest cover (Grau *et al.* 2003). Finding the right mix of government versus civil society interventions will be key in determining the success of FLR initiatives (Guariguata & Brancalion 2014).

Large-scale natural restoration programs can also inform FLR initiatives by highlighting the factors and policies that regulate human behavior and that cause the transitions from deforestation to reforestation (Adams *et al.* 2016). Although FLR has clear benefits for climate mitigation at the global scale (Stanturf *et al.* 2015, Chazdon *et al.* 2016) and for production of goods and services at the landscape scale (Stanturf *et al.* 2012, Locatelli *et al.* 2015), the impact of FLR on local livelihoods is poorly understood (Aronson *et al.* 2010, Le *et al.* 2012, Adams *et al.*

FIGURE 2. A Payment for Environmental Services program in Costa Rica supports 90.4 ha of natural regeneration.

2016). Adams *et al.* (2016) identify some of the key issues that must be considered if national FLR initiatives are to bring a broad range of livelihood benefits to stakeholders. Participatory, farmer-managed, bottom-up programs have more positive impacts on livelihoods, especially for ecosystem services and food security, than centralized, top-down approaches. FLR initiatives should avoid a sole focus on income (or Payment for Ecosystem Services programs) because increases in incomes that accompany such programs are sometimes driven by an increase in remittances from off-farm employment opportunities in distant areas and only secondarily by PES payments. Although remittances may diversify household's livelihoods in such cases, they may increase household vulnerability in the long-term (Adams *et al.* 2016). Finally, FLR is a long-term process that requires development of institutional, governance, and communication systems that empower stakeholders by addressing land tenure security and building participatory management schemes (Chazdon *et al.* 2015).

LOCAL AND LANDSCAPE FACTORS INFLUENCE THE ECOLOGICAL DYNAMICS OF NATURAL REGENERATION

Natural forest regeneration is driven by emergent processes at both local and landscape scales (Arroyo-Rodriguez *et al.* 2016). Natural regeneration potential increases with proximity to forest remnants, rainfall, and soil fertility (Martins *et al.* 2014, Poorter *et al.* 2016) and is reduced after intensive land uses (*e.g.,* cattle pastures and conventional monocultures). Weed invasion, repeated fire cycles, grazing, and depleted soils can arrest succession (*e.g.,* Schneider & Fernando 2009, Suazo-Ortuño *et al.* 2015, Jakovac *et al.* 2016) and dramatically increase restoration costs. Effective and affordable FLR will require consideration of multiple management practices together with landscape and local environmental factors that determine successional trajectories and the extent and persistence of natural regeneration.

From a landscape perspective, preservation of remnant forest is key (Chazdon & Guariguata 2016, Lu *et al.* 2016, Martínez-Ramos *et al.* 2016). Tree populations in forest remnants act as sources of propagules, particularly during the early stages of succession (Lu *et al.* 2016) and for late successional species (Aide & Cavelier 1994, Thomlinson *et al.* 1996, Holl 1999). Since the majority of seeds from tropical forest trees are dispersed by animals (Howe & Smallwood 1982) and tree pollination is predominantly insect-mediated (Bawa *et al.* 1985), forest remnants are critical as habitat for pollinators, seed dispersers, and predators of pests and pathogens (Banks-Leite *et al.* 2014, Omeja *et al.* 2016). Remnant forest patches do not need to be pristine to host many important generalist seed dispersers (Wills *et al.* 2016). For example, in large regenerating areas in Kibale National Park, Uganda, mammal communities, including a number of primate species, recovered within 20 years of agricultural abandonment. However, regenerating forests can also host predators and pathogens so the effects of animal communities on FLR may vary with context (Omeja *et al.* 2016). Nevertheless, preservation of old growth forests or well-developed second growth forests at the landscape scale is likely to improve the quality and extent of regenerating forests in their vicinity (Sloan *et al.* 2015).

At the local scale, FLR must consider the legacies of prior agriculture land uses on natural regeneration potential because they influence the structural, compositional, functional, and dynamical attributes of regenerating forests (Guariguata & Ostertag 2001, Chazdon 2014, Mesquita *et al.* 2015, Jakovac *et al.* 2016). Factors to consider include size of the agricultural field, presence of remnant trees, the number of years of use, harvest frequency, type of machinery and tools used, fire frequency and intensity, amount and frequency of agrochemicals, biomass and aggressiveness of non-native species, and density of livestock (Zermeno-Hernandez *et al.* 2015). Incorporating all of these metrics into a single measure of land use intensity and scaling up to the landscape can be challenging. However, Martínez-Ramos *et al.* (2016) demonstrate that a simple metric of local land use intensity constructed with input from land owners is a good predictor of natural regeneration potential in southern Mexico.

Depending on the degree of prior disturbance, FLR will require different approaches. A first step is determining the inherent capacity of the system to regenerate. If human intervention is required, removing barriers to seed dispersal and seedling establishment at the local level may include seeding, providing perches for dispersers, transplanting seedlings, protecting seedlings and small trees from fire and grazers, removing weeds, and intensive monitoring (Holl & Aide 2011). These interventions, however, can be costly so it is important to identify native or introduced tree species with high potential for natural regeneration (Fuentealba & Martínez-Ramos 2014, Martínez-Ramos *et al.* 2016). Species selected for regeneration should also provide desirable timber or non-timber forest products if farmers are to invest the resources necessary to ensure success (Meli *et al.* 2013, Lamb 2014). Training farmers and agricultural extension agents on natural regeneration and assisted restoration techniques and approaches, and making seedlings available, can go a long way towards improving FLR outcomes.

LINKING NATURAL REGENERATION AND LANDSCAPE RESTORATION IN PRACTICE

Although natural forest regeneration and forest succession can proceed very rapidly in minimally degraded landscapes and in areas conserving high levels of remnant old growth forests (Sloan *et al.* 2015, Martínez-Ramos *et al.* 2016), restoration of biodiversity and ecosystem services in highly degraded areas may require active restoration interventions (Holl & Aide 2011, Brancalion *et al.* 2016, Latawiec *et al.* 2016). The most common intervention is large-scale tree monoculture plantations (Gerber 2011), which are highly vulnerable to pests and pathogens, provide limited resources for wildlife, require fertilizer or soil improvements to sustain productivity (FAO 2001), and are costly. We believe that aligning restoration goals and practices with natural forest regeneration can achieve the best possible outcomes for recovering ecosystem functions, services, and biodiversity in ways that improve livelihoods and promote strong, local governance and stewardship. However, there is still much to learn.

Surprisingly little experimental evidence provides guidance for identifying effective strategies for restoring biodiversity and ecosystem services in heavily degraded lands where spontaneous natural regeneration is unlikely to succeed. Mixed-species plantations, especially if they include native species, may provide a way forward that combines rapid biomass increase and high timber yields and biodiversity conservation (Lugo 1992, Kanowski & Catterall 2010, Gilman *et al.* 2016). Recruitment of native tree species to the seedling layer in these mixed plantations may hinge on proximity to forest remnants (Thomlinson *et al.* 1996). Native tree species, however, are not the only way to move forward with FLR. Decades of restoration work has shown that introduced species can be helpful in initiating the process of succession process in degraded areas, which have become dominated by weeds and invasive grasses (Catterall 2016). Existing restoration projects provide excellent research opportunities to deepen our understanding of FLR options via natural regeneration but they seem to remain underutilized.

Upscaling natural regeneration to meet ambitious regional and global restoration goals will need to balance passive and active restoration approaches (Brancalion *et al.* 2016) and can benefit from novel approaches to automate forest monitoring and restoration via the deployment of low cost drones and new imaging systems (Elliott 2016). Drones can collect data for site assessment and quickly and cheaply identify barriers to natural regeneration. Such information can inform restoration plans. Metrics of forest restoration effectiveness (*e.g.,* canopy closure, biomass, presence of weeds, biodiversity) can also be collected remotely. Automated methods have also been successful in carrying out maintenance activities in restored forest such as aerial seeding and selective herbicide application (Elliott 2016). Although still in their infancy, these technologies offer tremendous promise.

SCALING NATURAL REGENERATION IN THE CONTEXT OF MULTIFUNCTIONAL LANDSCAPES AND REGIONAL PLANNING

Natural regeneration can be a relevant component of integrated landscape management and sustainable rural livelihoods (Brancalion *et al.* 2016, Chazdon & Guariguata 2016, Latawiec *et al.* 2016). Because the vast majority of FLR opportunities in the tropics lie within mosaic landscapes, achieving restoration goals is only feasible if agencies, institutions, and organizations at the national and subnational level commit to working collaboratively towards common goals (Chazdon & Laestadius 2016, Morães 2016). Specifically, environmental and agricultural policies must be aligned; new scientific knowledge must inform capacity building, technical extension and rural extension efforts; legal, financial, and institutional provisions must work together to coherently promote FLR and avoid perverse incentives; and communication, dialogue, and governance structures must be built in a deliberate, participatory, and pragmatic fashion (Morães 2016). This is a tall order.

Linking natural regeneration and FLR to legal frameworks is a key issue. A large proportion of restoration interventions in mosaic landscapes are implemented to comply with environmental laws (Ruiz-jaen & Aide 2005, Brancalion *et al.* 2016). In such cases, land owners who fail to meet restoration goals face fines or loss of environmental certification and access to credit (Rodrigues *et al.* 2011). Because at least for some biophysical metrics, natural regeneration has unpredictable outcomes and can be slower to achieve restoration goals (Chazdon & Guariguata 2016), punitive legal frameworks can act as a disincentive for natural regeneration (Brancalion *et al.* 2016). Yet, Brancalion *et al.* (2016) demonstrate that the ecological outcomes of active restoration can be as variable and unpredictable as natural regeneration, directly challenging the assumption that underlies the choice of active restoration methods over passive ones. Although problems with species selection, inadequate maintenance and monitoring, unexpected outcomes and high failure rates are ubiquitous in active restoration projects, legal and technical instruments still focus on active restoration. Incorporating natural regeneration into FLR will require development of more flexible and adaptive legal and financial instruments (Palmer & Ruhl 2015). For example, rather than investing in massive seedling plantation programs, governments may choose to offer financial incentives and technical assistance for farmers and landowners to promote natural regeneration (Chazdon & Guariguata 2016). In Brazil, a new program leaves farmers to decide which restoration approach is most appropriate given their particular situation (Brancalion *et al.* 2016).

The integration of productive land uses with different forms of forest restoration at the landscape scale will also require reorganization of agriculture, environment, and forestry sectors within national and regional governments to align land-use policies in ways that promote biodiversity conservation and ecosystem service provision while addressing the needs of stakeholders who live on these landscapes (Sayer *et al.* 2013). Often, government policies hinder restoration goals, sometimes at the expense of livelihoods. For example, an economic crisis and the state's inability to support rural development and forestry extension programs in Niger led to a change in perception of tree ownership- which before the crisis were perceived to belong to the State—increasing protection and management of woody regeneration, and large-scale re-greening (Reij & Garrity 2016). These new agroforestry parklands increased crop yields and made farmers' incomes more resilient to drought. This and other examples from Africa, Brazil, and SE Asia demonstrate that recognition of farmers' rights to own, manage and harvest the trees that establish on their land is an essential step in harnessing the power of natural regeneration. Therefore, governmental and non-governmental organization should also aim to identify and analyze policies and regulations that foster natural regeneration success (Chaves *et al.* 2015), nurture grassroots movements to promote natural regeneration, and implement communication and extension strategies that reinforce and expand restoration successes.

Effective approaches to integrated landscape management will have to be tailored to each region and country; there is no single solution. Tropical forests in Neotropical, Afrotropical, and Indo-Malau-Australasian regions differ in the evolutionary history of regional species pools, geology, natural disturbance regimes, and climate (Malhi *et al.* 2014). Such differences are likely to modulate successional trajectories and the effectiveness and outcomes of different restoration approaches (Uriarte *et al.* 2016). For example, Latawiec *et al.* (2016) found that biodiversity levels in second growth Afrotropical and Australian forests are close to old growth values whereas this is not the case in the more diverse Neotropical and Indo-Malay realms that host larger species pools. Regional and national histories of economic development and land use will also influence FLR outcomes. Extensive cattle pastures are common in the Neotropics (Strassburg *et al.* 2016) whereas shifting cultivation is an important agent of deforestation and degradation in Southeast Asia (Ziegler *et al.* 2011, Mukul *et al.* 2016). Natural regeneration may be most effective in countries and landscapes with less intensive land use history, recent deforestation, and overall more highly forested landscapes since all of these factors facilitate natural regeneration (Chazdon *et al.* 2007, Sloan *et al.* 2015, Latawiec *et al.* 2016, Martínez-Ramos *et al.* 2016). Higher sensitivity of the population to environmental degradation, greater financial resources, and stronger institutions in regions and countries with a history of successful economic development can also offer opportunities for embedding natural regeneration into FLR planning (Latawiec *et al.* 2016).

NATURAL REGENERATION, LIVELIHOODS AND ECOSYSTEM SERVICES

Natural forest regeneration can provide a number of ecosystem services including timber and non-timber products, carbon sequestration, protection of soil and water resource, pest mitigation, and cultural services that support local livelihoods of inhabitants of mosaic landscapes (Locatelli *et al.* 2015, Chazdon & Guariguata 2016). Natural regeneration, however, is just one landscape component along with agriculture, forestry, and conservation areas (Sayer *et al.* 2010, Brancalion *et al.* 2016). Balancing different ecosystem services in a way that minimizes tradeoffs among services at relevant scales is key to the success of FLR initiatives (Lazos *et al.* 2016, Mukul *et al.* 2016, Strassburg *et al.* 2016).

From a landscape perspective, the benefits and costs of natural regeneration are context and location specific, and influenced by biophysical and socioeconomic heterogeneity (Latawiec *et al.* 2015). For example, focusing regeneration on riparian areas will influence water quality more directly than reforesting areas distant from streams (Uriarte *et al.* 2011) and restoration interventions that reconnect isolated remnant forest patches can maximize biodiversity conservation (Chazdon *et al.* 2009, Fagan *et al.* 2016). From a socioeconomic perspective, natural regeneration is best suited to areas with low opportunity costs for other land uses (*e.g.,* agriculture in steep slopes or areas with low fertility soils) or in remote areas where access to resources and technical support for active restoration may be lacking (Mukul *et al.* 2016). New spatial planning frameworks can aid in devising restoration schemes that maximize benefits and minimize costs (*e.g.*, Tambosi *et al.* 2014, Crouzeilles *et al.* 2015).

Any FLR intervention will involve tradeoffs, particularly in the mosaic landscapes that offer the majority of restoration opportunities (Laestadius *et al.* 2012). Tradeoffs are likely to occur between environmental and social benefits (*e.g.*, biodiversity conservation vs. agriculture), individual and community benefits (*e.g.*, agriculture vs. watershed protection), conflicting mandates across different government agencies over the same resource, and burdens and gains borne by different stakeholders (*e.g.*, local vs. distant parties). The degree to which different stakeholders bear the costs and benefits from FLR interventions depends on myriad socioeconomic and biophysical factors. Although tradeoffs and synergies in ecosystem services are increasingly incorporated into landscape planning, the fact that these tradeoffs change over time has been ignored (Lazos *et al.* 2016). The tradeoffs faced by stakeholders will vary depending on restoration strategy and over time as succession proceeds and landscapes, political and socioeconomic and cultural conditions change (Lazos *et al.* 2016). The age, identity, power, and interests of stakeholders themselves may also evolve, especially if local people have greater empowering opportunities (*e.g.*, access to health, education). Robust and sustainable FLR planning will require identification of tradeoffs and synergies, an adaptive strategy to stakeholder engagement, continuous evaluation of outcomes, and collectively devised governance structures that account for this dynamism (Lazos *et al.* 2016).

KEY RESEARCH QUESTIONS

The studies presented in this special issue show how natural regeneration can become an important part of FLR and highlight the ecological, environmental, economic, and social factors that must be considered to effectively implement it as a cost effective action (Fig. 1). At the same time, the studies identify major gaps in our knowledge and provide clear directions for new lines of research within and across traditional disciplines. Six general research questions emerge from these studies (Table 1).

1. How does the choice of restoration strategy influence ecological and socio-economic outcomes for stakeholders and ecosystems? Restoration strategies may range from natural regeneration to active restoration (reforestation) interventions, including agroforestry and mixed-species plantations. This question should be addressed at a variety of spatial and temporal scales and also identify key bottlenecks while moving across scales. Different spatial scales —global, biome, regional, landscape, and local—will uncover enabling factors and barriers to implementation. Given the different and evolving time horizons of stakeholders, outcomes should also be evaluated over a range of temporal scales.
2. What are the tradeoffs and synergies among ecological and socioeconomic outcomes of restoration via natural regeneration versus currently productive land uses, and how are these affected by fluctuations in external markets and climate shocks? Landscapes, people, and institutions are always

TABLE 1. *A proposed research agenda to harness the potential of natural regeneration in FLR.*

Six key research questions
What are the ecological, socioeconomic, and livelihood outcomes of natural regeneration and active restoration interventions?
What are the tradeoffs and synergies among ecological, socioeconomic, and livelihood outcomes of natural regeneration, restoration, and productive land uses, and how do they evolve in the face of external market shocks and under climate extremes?
What diagnostic tools are needed to identify and map areas that can support natural regeneration?
What multi-criteria spatial prioritization frameworks are needed to take into account natural regeneration potential?
What legal frameworks and governance structures are best suited to encourage natural regeneration and how do they change across regions and landscapes?
What financial mechanisms can increase returns from low-cost natural regeneration?

changing, yet our understanding of the dynamics of these tradeoffs and synergies in multifunctional landscapes is extremely limited. Given the overwhelming evidence that the climate and its extremes are shifting (IPCC 2013), and the effects such changes are likely to have on agricultural commodity markets, this information is needed to develop landscape policies that can mitigate risks to society and ecosystems.

3. What are the most effective diagnostic tools for identifying land that can support natural regeneration and what spatial prioritization frameworks can be used to implement this approach? Locally, there is a need for engaging with landowners to develop efficient indicators that capture history of land use and the potential for regeneration. At larger regional scales, multi-criteria spatial prioritization tools offer a promising approach. Such tools should also have the capability to engage local stakeholders in the planning process and to evaluate tradeoffs and synergies.
4. How can natural regeneration be linked with regulatory and legal frameworks at different hierarchical levels (*e.g.*, municipality, state, national) and across government levels (*e.g.,* forestry, environment, agriculture), while identifying overlaps and gaps in policy? A systematic evaluation of past restoration and reforestation programs offers a point of departure. Mandatory restoration programs have often focused on active restoration efforts while development of effective legal and regulatory frameworks for passive restoration has remained challenging. Since restoration—both active and passive– is a long-term process, which requires constant monitoring and corrective actions, policies and legal instruments to support the use of natural regeneration in FLR should be flexible. They should also engage multiple government sectors that influence land use choices.
5. What are effective governance structures for embedding (or mainstreaming) natural regeneration into FLR planning and under which ecological, socioeconomic, and legal circumstances do these effective governance structure emerge? Historically, participatory, bottom-up approaches to governance have generated better outcomes than centralized, command-and-control structures but this may depend on the state of degradation of the target area, existing political structures, and level of economic development. Finding the right mix of top-down and community-driven approaches and the degree of government engagement that is likely to lead to effective use of natural regeneration in FLR remains a challenge.
6. How can financial mechanisms foster the use of natural regeneration into FLR planning? Restoration is often perceived as a high cost, low return activity. We can overcome this perception if we can devise financial mechanisms that increase returns from low-cost natural regeneration. A number of pilot programs to market goods and services (*e.g.,* carbon, water) provided by natural regeneration are already underway. Another emerging approach is to develop standards for verification or certification of restoration programs that incorporate economic, social, and ecological outcomes assessed at the landscape scale. These accountability-based approaches will serve to highlight successful projects, promote best practices for FLR, and reduce the risk of financial investments in restoration.

In closing, global FLR initiatives provide an opportunity for restoring degraded areas and recovering biodiversity, functions, and services of forest ecosystems over large-scales. Achieving large-scale restoration will require long-lasting and sustained changes in land use allocation and human behavior. Assisted and spontaneous natural regeneration can significantly reduce the costs of FLR and at the same time, offer substantial benefits for biodiversity conservation, ecosystem service provision, and human livelihoods. Natural regeneration, however, is not a panacea to solve tensions and conflicts over land use management, but it can bring be advantageous under some circumstances. Identifying the conditions under which natural regeneration makes sense is an important avenue for future research.

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