LANDSCAPE RESTORATION, NATURAL REGENERATION, AND THE FORESTS OF THE FUTURE[1]

Robin L. Chazdon[2]

Abstract

Reversing large-scale degradation and deforestation goes beyond what can be achieved by site-level ecological restoration. Forest and landscape restoration focuses on spatial scales beyond the "site" level, where multiple land uses and forms of land ownership coexist, and where management decisions are usually made by different sets of stakeholders. In this context, natural regeneration can be a cost-effective approach to expand buffer zones of protected areas or forest reserves, create new forest patches and riparian zones, and create biological corridors to link existing protected areas. Here, I describe different modalities of natural regeneration, describe their benefits and features, and present several case studies of large-scale natural regeneration. Regrowing forests are often ignored, and their ecological and economic value remains largely unrecognized. Effective incentives for landowners and local communities are needed to encourage and protect naturally regenerating forests on farms. Predicting and mapping areas with a high capacity for natural regeneration will lower the overall costs of implementing restoration at local, regional, and national levels and may permit larger areas to be restored. Regrowing tropical forests will play an increasingly important role in climate change mitigation and biodiversity conservation in our future uncertain world.

Key words: Assisted natural regeneration, farmer-managed natural regeneration, landscape restoration, large-scale restoration, spatial prioritization, succession.

We face an unprecedented opportunity to transform degraded and unproductive lands into functional landscapes that offer multiple benefits to society and future generations. Over 2 billion ha of (7.7 million square miles) of deforested and degraded land (formerly forest and mixed woodland) provide opportunities for forest landscape restoration around the world; roughly 1 billion ha are within tropical regions (Laestadius et al., 2011). The massive scale of this opportunity creates an enormous implementation challenge that requires engagement, mobilization, and commitment of all sectors of society across all regions of the planet. Most of the opportunities for restoration, particularly in tropical regions, lie within mosaic landscapes, where people live, work, and depend upon forest resources for their livelihoods (Chazdon & Uriarte, 2016).

This is a tall order. The effort needed to reverse large-scale degradation and deforestation goes beyond what can be achieved by site-level ecological restoration. Ecological restoration is the act of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2004). Although early restoration practice is generally focused at a site scale, global restoration initiatives focus increasingly on new approaches implemented at the landscape and regional scale (Maginnis & Jackson, 2007; Doyle & Drew, 2012). 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 (Sabogal et al., 2015). This process focuses on spatial scales beyond the "site" level, where multiple land uses and forms of land ownership coexist, and where management decisions are usually made by different sets of stakeholders. Within a landscape, tree cover can be reestablished in a variety of ways, including agroforestry or silvopastoral systems, ecological restoration plantations, commercial forest plantations, or natural regeneration. Each of these modalities brings different types of benefits for local, regional, and global stakeholders. FLR is a forward-looking approach that aims to reconfigure and reconstruct landscapes in sustainable ways through increasing tree cover and enhancing native biodiversity; the goal is not necessarily to reestablish complete forest cover or to return to prior forest composition.

In the context of FLR, a *landscape* can be regarded as a heterogeneous mosaic of different land uses

[1] I thank Leighton Reid and James Aronson for the invitation to participate in the 63rd Annual Systematics Symposium of the Missouri Botanical Garden, "Ecological Restoration in a Changing Biosphere." I also thank Don Falk, Leighton Reid, and James Aronson for their constructive comments on a previous version of the manuscript. This paper benefited greatly from discussions with Manuel Guariguata, Pedro Brancalion, Renato Crouzeilles, and many colleagues involved in People and Reforestation in the Tropics Network for Education, Research, and Synthesis (PARTNERS). Research was supported by U.S. National Science Foundation Grants DEB-0639393, DEB-1147429, and DEB-1313788.

[2] Department of Ecology and Evolutionary Biology, University of Connecticut, 75 North Eagleville Road, Storrs, Connecticut 06268-3043, U.S.A. chazdon@uconn.edu

doi: 10.3417/2016035

(agriculture, forestry, soil protection, water supply and distribution, biodiversity conservation, pasture provision, etc.) across a large area of land or a watershed (Sabogal et al., 2015). In this context, a landscape is not defined by a particular extent or size, but by the configuration of landforms and the activities and governance of local actors. As stated by Sayer et al. (2013: 8350), "Landscapes provide the setting over which wicked problems unfold, and the landscape approach provides the social-ecological systems' framework by which we can grapple with them." Approaches to restoring landscapes focus as much on the social and economic aspects as on the biophysical aspects. The key to implementing FLR is reaching a balance of social and ecological benefits based on a spectrum of land uses and an active process of planning and decision making among multiple stakeholders. FLR requires spatial planning to maximize effective long-term outcomes and benefits to multiple stakeholders, engage diverse groups of stakeholders, and minimize overall costs.

Natural Regeneration as a Key Component of Forest and Landscape Restoration

We can get some help in this endeavor by joining forces with nature. Natural regeneration is nature's way of restoring ecosystems after disturbances. Under the proper circumstances, natural regeneration of forests is the least expensive and most ecologically effective approach to large-scale forest restoration (Chazdon & Guariguata, 2016). Forest regeneration is a long-term successional process that occurs in stages defined by vegetation structure, species composition, and functional attributes (Walker et al., 2007; Chazdon, 2014). The process unfolds in stages, based on the available source pool of species, dispersal events, and the history and nature of disturbance. Despite the cost-effectiveness of natural regeneration, it is underutilized as a means of achieving restoration at the scale of forest ecosystems or landscapes. Active ecological restoration interventions, such as native tree plantations, aim to accelerate natural regeneration and stand development processes when spontaneous establishment of trees or assisted regeneration is insufficient to create conditions for successful native tree regeneration and forest development (Holl & Aide, 2011; Chazdon, 2014).

In many cases, natural regeneration follows natural or anthropogenic disturbance without the need for any human intervention. After all, this process was well established long before *Homo sapiens* arrived on the scene. Although secondary succession is a passive process, certain conditions need to be in place to allow this process to proceed and to reach a relatively stable state of structure and native species composition. Natural regeneration can be enhanced or assisted in a variety of ways. Assisted regeneration techniques include: fire protection, weed control, herbivore control (fencing), and targeted enrichment planting. Even when regeneration is assisted, the costs are substantially lower than those with large-scale tree-planting approaches (Brancalion et al., 2016; Chazdon & Uriarte, 2016). Natural forest regrowth is promoted by high local resource availability and high propagule (i.e., seeds and sprouts) availability and where suitability of land for agricultural land use is low. If colonization of native tree species is limited, particular species of local ecological and economic importance can be planted and tended. Natural regeneration can be a cost-effective approach to expand buffer zones of protected areas or forest reserves, to create new forest patches and riparian zones, as well as to create biological corridors that link existing protected areas.

Natural regeneration has many benefits compared to other restoration approaches, including enhancement and conservation of local biodiversity, genetic diversity, and local species interactions; increased resilience to climate shocks due to heterogeneous forest structure and composition; and production of diverse and locally sourced timber and non-timber products (Chazdon & Guariguata, 2016). Initially, tree plantings may yield more rapid recovery of a range of community and ecosystem properties, but natural regeneration can match and even exceed these benefits over time (Bechara et al., 2016; Shoo et al., 2016). Rigorous comparisons of costs, benefits, and outcomes of passive versus active approaches to restoration are just beginning to be conducted, however (Gilman et al., 2016; Shoo et al., 2016).

Because it is a natural process subject to multiple site and landscape effects, natural regeneration often unfolds in unpredictable ways (Chazdon, 2014). Trajectories of forest structure and species composition during spontaneous natural regeneration can vary widely across sites within the same region (Chazdon et al., 2007; Chazdon, 2008; Norden et al., 2015). Successional trajectories can be shaped by different forms of management to enhance colonization and growth of species of high economic, cultural, or ecological value, as demonstrated by millennia of successional fallow management approaches by indigenous farmers (Wangpakapattanawong et al., 2010; Chazdon, 2014). From the perspective of FLR, the multiple trajectories of natural regeneration provide low-cost opportunities for management and for creating heterogeneous patches of native forest cover within a landscape mosaic. Species composition in regenerating forests differs from pre-disturbance or "reference" forests and may take many decades or even centuries to reach similar states.

The Potential for Unassisted and Assisted Natural Regeneration

Case studies around the world have demonstrated the potential for recovery of woody vegetation via natural and assisted regeneration (Chazdon & Guariguata, 2016). In Latin America and the Caribbean, woody vegetation regrew on over 36 million ha (nearly 140,000 square miles) between 2001 and 2010 (Aide et al., 2013). Spontaneous natural regeneration tended to occur in regions that were too dry or too steep for mechanized agriculture. Economic changes affecting farmers are often the major trigger of land-use change favoring forest regeneration. On the island of Puerto Rico, forest cover increased from 9% to 37% due to natural regeneration between 1950 and 1990. Most of the regeneration was concentrated in the upland regions in coffee-growing municipalities. Widespread abandonment of these coffee plantations followed labor shortages when workers migrated to new jobs in urban factories (Rudel et al., 2000). In Guanacaste Province, Costa Rica, most of the region's dry forests had been eliminated by 1970 to create cattle pasture, and by 1979 forest cover was only 23.6%. By 2005 forest cover doubled to 47% due to natural regeneration, with 90% of the forest regrowth on private lands. In this region, the main driver of forest regeneration was large-scale abandonment of farms by smallholders after a dramatic decline in international beef prices (Calvo-Alvarado et al., 2009).

In other cases, revegetation and increases in tree cover through assisted natural regeneration (ANR) are enhancing farmer livelihoods, incomes, and agricultural production, leading to forest regeneration in protected areas. In the semi-arid Tigray Region of northern Ethiopia, the use of livestock exclosures has led to significant increases in the tree regeneration and forest cover. Over 3 million ha of degraded forestland in Ethiopia are under area exclosure (Lemenih & Kassa, 2014). The Humbo Community–based Natural Regeneration Project, a partnership with the World Bank, led to the ANR of 2720 ha of degraded native forests and is bringing social, economic, and ecological benefits to participating local communities (Brown et al., 2011; Francis et al., 2015). Tree regeneration occurs by releasing dormant tree stumps and roots, which are abundant in degraded forestlands. Resprouts are actively managed by pruning.

Farmer-managed natural regeneration promotes the resprouting of living tree stumps and roots that remain below the ground, which can be abundant in croplands and grazing lands. In drylands of Niger and Mali, ANR of trees and shrubs has created 5 million ha of agroforestry parklands. Tree densities on farms have increased an order of magnitude, providing additional sources of income, improvement of environmental conditions, and economic resilience for farmers (Reij et al., 2009; Reij & Garrity, 2016).

Another approach to ANR is being practiced in the Philippines and other countries in Asia in formerly forested areas now dominated by highly flammable *Imperata cylindrica* (L.) Cirillo grasslands (Shono et al., 2007; Durst et al., 2011). ANR is a method for enhancing the establishment of secondary forest on degraded grasslands and shrublands by protecting and nurturing naturally colonized trees and seedlings. Without interventions, these individuals have a poor chance of survival due to competition from grass and recurrent fires. Enrichment planting with nursery-grown seedlings supplements natural regeneration, further protecting soils, reducing weed cover, reducing fire risk, and increasing local tree diversity.

Once natural regeneration becomes established, these areas are highly vulnerable to reclearance. Although secondary forests in Costa Rica are legally protected beyond a certain stage of development, laws are poorly enforced and clearance rates for young secondary forests are high (Fagan et al., 2013). Deforestation bans can provide a perverse disincentive to clear early stages of forest regrowth to prevent regeneration beyond the stage where vegetation regrowth becomes legally classified as forest and is protected by law (Román-Dañobeytia et al., 2014; Vieira et al., 2014). To maintain areas undergoing long-term forest regeneration, additional measures need to be taken to protect existing areas and to provide incentives for keeping these areas forested or with high tree cover as part of FLR programs. Sustainable management of young second-growth forests is also discouraged by protective legislation due to high transaction costs for obtaining legally approved forest management plans (Román-Daobeytia et al., 2014). Naturally regenerating forests can and do persist in areas where landowners have strong motivations to restore and maintain forest cover. In Osa County, Costa Rica, nearly half of the area that became reforested from 1987 to 2009 persisted as second-growth forest. These regenerating forests are helping to decrease forest fragmentation and form biological corridors that are strengthening regional conservation efforts (Algeet-Abarquero et al., 2015). They are also encouraging the flow of tourists to the region and creating new sources of employment aligned with restoration and conservation agendas (Kull et al., 2007; Zambrano et al., 2010).

Finding the right incentives for landowners to encourage and protect naturally regenerating forests on private farms remains a major challenge. In Brazil, the Forest Code legally mandates forest restoration on deforested land, and the landowner is financially responsible for these costs. The registered landowner can take two to four years to evaluate which restoration method (or combination of methods) to adopt, with large implications for their cost (Brancalion et al., 2016). By observing the initial stages of colonization on the land over this period, farmers can better determine whether natural regeneration (which is far less costly than tree planting) is likely to be a successful method for restoration on their farm (Holl & Aide, 2011). Among 42 recently initiated restoration projects covering 698,398 ha in the Atlantic Forest and Amazon biomes of Brazil, 14.2% of the land is being restored through natural regeneration, 7.4% through ANR (partial tree planting), and 78.4% is being restored using total tree-planting approaches (Brancalion et al., 2016). The use of natural regeneration was more extensive in Amazonia than in the Atlantic Forest Biome and in areas with greater than 50% forest cover, which are more frequent in Amazonia (Brancalion et al., 2016).

Predicting and Mapping Natural Regeneration Potential

Prioritization of natural regeneration as a restoration approach will lower the overall costs of restoration at local, regional, and national levels and may permit larger areas to undergo restoration. Within the context of FLR, natural regeneration should be prioritized first in areas that show the greatest likelihood of successful natural colonization and diverse forest development. Areas with an inherently low capacity for natural regeneration would become priorities for active restoration approaches involving commercial tree planting, agroforestry, or ecological restoration plantings of diverse native species. Ultimately, a combination of biophysical and socio-economic factors will dictate the potential for natural regeneration and its persistence over time.

Spatial analyses within areas that have undergone natural regeneration provide essential information to begin developing prioritization schemes for restoration planning. Just as prior land use influences the rate and nature of forest succession within a site, the spatial template of landscape features influences the distribution of spontaneously regenerating forests across a landscape. In a region of São Paulo State, Brazil, with little primary forest remaining, Teixeira et al. (2009) found higher probabilities of regrowth near rivers, on steep slopes, and far from dirt roads. Sloan et al. (2016) assessed the spatial dynamics of forest regeneration on former agropastoral land within a 3000-km^2 region of northern tropical Queensland. Although many factors were considered, the overwhelmingly important factor underlying the spatial distribution of regenerating forests was the size and proximity of forest fragments in the surrounding landscape; 85% of regrowth forests occurred within 1 km of primary forest fragments and 70% occurred within 500 m of primary forest (Sloan et al., 2016). These results highlight the importance of existing forest fragments and their distribution in the landscape as a spatial template for naturally regenerating forests.

Topography plays an important role in determining areas undergoing natural regeneration, largely through its effect on the opportunity costs of land abandonment (Chazdon, 2014). Within the Atlantic Forest municipality of Trajano de Moraes in Rio de Janeiro State, forest cover increased by 3020 ha (15.3%) from 1978 to 2014 due to natural regeneration (de Rezende et al., 2015). The main factors that predicted where natural regeneration occurred were topographic position, slope, solar radiation, soil type, and distance to forest, urban areas, and roads. Natural regeneration was more likely to occur in topographic depressions with higher slopes, which are marginal for agricultural production. And similar to the findings of other studies, forest regrowth was concentrated in areas within 180 m from older forest fragments (de Rezende et al., 2015). In the Paraíba do Sul watershed in São Paulo state, Brazil, 205,690 ha of second-growth forest regenerated spontaneously between 1985 and 2015, an increase in forest cover of 83%. Most of this regrowth occurred on former pasturelands in areas with slopes above 20% (Ronquim et al., 2016).

These trends suggest that natural regeneration should be prioritized in the buffer zones of protected areas, forest reserves, or large forest fragments and on steep slopes where agricultural production is low, access is difficult, and tree planting is difficult and expensive. Buffer zones around the periphery of protected areas can also capitalize from ongoing fire and hunting protection. Natural regeneration can also be favored in riparian zones, if there are suitable seed sources in the vicinity. Studies are now using predictive models to map the probability of natural regeneration across landscape units within Brazil's Atlantic Forest biome. These maps can be used to estimate costs of restoration and can also provide input for multi-criteria spatial prioritization approaches for planning and implementation of large-scale restoration initiatives. Harnessing the potential for natural regeneration can greatly reduce the costs of large-scale restoration while offering additional benefits to multiple stakeholders.

What Will Future Regenerating Forests Be Like?

Despite much uncertainty, current trends suggest that areas of regenerating forests will increase in the future, particularly in the tropics. The world has witnessed forest regrowth in many temperate regions (Foster, 1992; Mather, 1992), and forest transitions are now occurring in tropical regions due to emergence of both planted and unplanted forests (Aide et al., 2013; Rudel et al., 2016; Sloan et al., 2016). Many future forests will grow up in predominantly deforested landscapes where only fragments of primary or secondary forests remain.

Regrowing forests are likely to play an increasingly important role in the conservation of native flora and fauna in human-managed landscapes with intermediate levels of forest cover, from 10% to 40% (Chazdon et al., 2009; Arroyo-Rodriguez et al., 2015). They may not contain all of the species that were present in the forests they replaced, but they are likely to have more tree species than found in most types of plantations. Particularly in mosaic landscapes, regrowth forests will show heavy influences of human activities in the surrounding landscapes and will be managed to produce a variety of environmental services, including timber and non-timber products. The human footprint is increasing globally, with 75% of the planet experiencing measurable human impact (Venter et al., 2016). Forest dynamics and composition in generating forests will also be affected by climate change and by interacting climatic and anthropogenic stressors (Uriarte et al., 2016). Based on long-term studies in wet forests of Costa Rica, simulated multi-annual drought stress will significantly alter structure, composition, and dynamics of second-growth forests by favoring functional traits of old-growth tree species, potentially accelerating successional species turnover (Uriarte et al., 2016).

Forest regeneration and restoration will not completely reverse effects of deforestation, but will increase habitat availability for many forest-requiring species and will permit greater movement of plants and animals around the landscape, enabling critical species interactions such as pollination, herbivory, and seed dispersal. Regrowing tropical forests will also play an increasingly important role in climate change mitigation due to their rapid gain in woody biomass and high potential for carbon storage (Poorter et al., 2016). Chazdon et al. (2016a) simulated carbon storage of regenerating forests (≤ 60 years) of lowland Latin America, under a scenario of continued protection and regeneration. From 2008 to 2048, these forests were estimated to store 31.09 Pg of CO_2 in tree biomass, equivalent to the CO_2 emissions from fossil fuel use and industrial processes from all countries of Latin America and the Caribbean from 1993 to 2014.

In many parts of the world, regrowing forests are invisible and unrecognized because they are too young or too small to be seen in remote sensing surveys of forest cover or they otherwise fail to conform to legal definitions of forest applied by countries or international organizations (Chazdon et al., 2016b). As a consequence, they are poorly mapped, monitored, and valued. In many cases, they are viewed as wastelands (Kinhal & Parthasarathy, 2008; Knoke et al., 2009). New approaches will be needed to track and assess both quantitative and qualitative changes in naturally regenerating areas as well as other types of forest restoration within landscapes. All of these changes that define the new era of restoration (Suding, 2011; Palmer et al., 2016) will have impacts and be impacted by people at the local, regional, and national scales. With proper stewardship and planning, regenerating and restored forests will provide a new nexus for people and nature where lives, livelihoods, and culture are interwoven with the forest regeneration cycle.

Literature Cited

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

Algeet-Abarquero, N., A. Sánchez-Azofeifa, J. Bonatti & M. Marchamalo. 2015. Land cover dynamics in Osa Region, Costa Rica: Secondary forest is here to stay. Regional Environm. Change 15: 1461–1472.

Arroyo-Rodriguez, V., F. Melo, M. Martinez-Ramos, F. Bongers, R. Chazdon, J. Meave, N. Norden, B. Santos, I. Leal & M. Tabarelli. 2015. Multiple successional pathways in human-modified tropical landscapes: New insights from forest succession, forest fragmentation and landscape ecology research. Biol. Rev. 92(1): 326–340.

Bechara, F. C., S. J. Dickens, E. C. Farrer, L. Larios, E. N. Spotswood, P. Mariotte & K. N. Suding. 2016. Neotropical rainforest restoration: Comparing passive, plantation and nucleation approaches. Biodivers. & Conservation 25: 2021–2034.

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

Brown, D. R., P. Dettmann, T. Rinaudo, H. Tefera & A. Tofu. 2011. Poverty alleviation and environmental restoration using the clean development mechanism: A case study from Humbo, Ethiopia. Environm. Managem. 48: 322–333.

Calvo-Alvarado, J., B. McLennan, A. Sanchez-Azofeifa & T. Garvin. 2009. Deforestation and forest restoration in Guanacaste, Costa Rica: Putting conservation policies in context. Forest Ecol. Managem. 258: 931–940.

Chazdon, R. L. 2008. Chance and determinism in tropical forest succession. Pp. 384–408 *in* W. Carson & S. A. Schnitzer (editors), Tropical Forest Community Ecology. Wiley-Blackwell Publishing, Oxford.

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

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

Chazdon, R. L. & M. Uriarte. 2016. Natural regeneration in the context of large-scale forest and landscape restoration in the tropics. Biotropica 48: 709–715.

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

Chazdon, R. L., C. A. Harvey, O. Komar, D. M. Griffith, B. G. Ferguson, M. Martínez-Ramos, H. Morales, R. Nigh, L. Soto-Pinto, M. van Breugel & S. M. Philpott. 2009. Beyond reserves: A research agenda for conserving biodiversity in human-modified tropical landscapes. Biotropica 41: 142–153.

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

Chazdon, R. L., E. N. Broadbent, D. M. A. Rozendaal, F. Bongers, A. M. A. Zambrano, T. M. Aide, P. Balvanera, J. M. Becknell, V. Boukili, P. H. S. Brancalion, D. Craven, J. S. Almeida-Cortez, G. A. L. Cabral, B. de Jong, J. S. Denslow, D. H. Dent, S. J. DeWalt, J. M. Dupuy, S. M. Durán, M. M. Espírito-Santo, M. C. Fandino, R. G. César, J. S. Hall, J. Luis Hernández-Stefanoni, C. C. Jakovac, A. B. Junqueira, D. Kennard, S. G. Letcher, M. Lohbeck, M. Martínez-Ramos, P. Massoca, J. A. Meave, R. Mesquita, F. Mora, R. Muñoz, R. Muscarella, Y. R. F. Nunes, S. Ochoa-Gaona, E. Orihuela-Belmonte, M. Peña-Claros, E. A. Pérez-García, D. Piotto, J. S. Powers, J. Rodríguez-Velazquez, I. E. Romero-Pérez, J. Ruíz, J. G. Saldarriaga, A. Sanchez-Azofeifa, N. B. Schwartz, M. K. Steininger, N. G. Swenson, M. Uriarte, M. van Breugel, H. van der Wal, M. D. M. Veloso, H. Vester, I. C. G. Vieira, T. Vizcarra Bentos, G. Bruce Williamson & L. Poorter. 2016b. Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. Sci. Advances 2: e1501639.

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

Doyle, M. & C. Drew (editors). 2012. Large-Scale Ecosystem Restoration: Five Case Studies from the United States. Island Press, Washington, D.C.

Durst, P. B., P. Sajise & R. N. Leslie (editors). 2011. Forests Beneath the Grass. Proceedings of the Regional Workshop on Advancing the Application of Assisted Natural Regeneration for Effective Low-Cost Restoration. Food and Agriculture Organization of the United Nations, Bangkok.

Fagan, M., R. DeFries, S. Sesnie, J. Arroyo, W. Walker, C. Soto, R. Chazdon & A. Sanchun. 2013. Land cover dynamics following a deforestation ban in northern Costa Rica. Environm. Res. Lett. 8: 034017.

Foster, D. R. 1992. Land-use history (1730–1990) and vegetation dynamics in central New England, U.S.A. J. Ecol. 80: 753–772.

Francis, R., P. Weston & J. Birch. 2015. The Social, Environmental and Economic Benefits of Farmer Managed Natural Regeneration. World Vision Australia, Melbourne.

Gilman, A., S. Letcher, R. M. Fincher, A. Perez, T. Madell, A. Finkelstein & F. Corrales-Araya. 2016. Recovery of floristic diversity and basal area in natural forest regeneration and planted plots in a Costa Rican wet forest. Biotropica 48: 798–808.

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

Kinhal, V. & N. Parthasarathy. 2008. Secondary succession and resource use in tropical fallows: A case study from the Coromandel Coast of South India. Land Degradation Developm. 19: 649–662.

Knoke, T., B. Calvas, N. Aguirre, R. M. Roman-Cuesta, S. Gunter, B. Stimm, M. Weber & R. Mosandl. 2009. Can tropical farmers reconcile subsistence needs with forest conservation? Frontiers Ecol. Environm. 7: 548–554.

Kull, C. A., C. K. Ibrahim & T. C. Meredith. 2007. Tropical forest transitions and globalization: Neo-liberalism, migration, tourism, and international conservation agendas. Soc. & Nat. Resources 20: 723–737.

Laestadius, L., S. Maginnis, S. Minnemeyer, P. Potapov, C. Saint-Laurent & N. Sizer. 2011. Mapping opportunities for forest landscape restoration. Unasylva 238, 62: 47–48.

Lemenih, M. & H. Kassa. 2014. Re-greening Ethiopia: History, challenges and lessons. Forests 5: 1896–1909.

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

Mather, A. S. 1992. The forest transition. Area 24: 367–379.

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

Palmer M. A., D. A. Falk & J. B. Zedler (editors). 2016. Foundations of Restoration Ecology, 2nd ed. Island Press, Washington, D.C.

Poorter, L., F. Bongers, T. M. Aide, A. M. A. Zambrano, P. Balvanera, J. M. Becknell, V. Boukili, P. H. Brancalion, E. N. Broadbent, R. L. Chazdon, D. Craven, J. S. de

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

Reij, C. & D. Garrity. 2016. Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. Biotropica 48: 834–843.

Reij, C., G. Tappan & M. Smale. 2009. Agroenvironmental transformation in the Sahel: Another kind of "Green Revolution." International Food Policy Research Institute Discussion Paper 00914, Washington, D.C.

Román-Dañobeytia, F. J., S. I. Levy-Tacher, P. Macario-Mendoza & J. Zúñiga-Morales. 2014. Redefining secondary forests in the Mexican Forest Code: Implications for management, restoration, and conservation. Forests 5: 978–991.

Ronquim, C. C., R. F. B. Silva, E. B. de Figuiredo, R. O. Bordonal, A. H. de C. Teixeira, T. C. D. Cochasrki & J. F. Leivas. 2016. Carbon sequestration associated to the land-use and land-cover changes in the forestry sector in Southern Brazil *in* Proceedings of SPIE 2016 Remote Sensing and Security + Defense International Symposia, Edinburgh. doi: 10.1117/12.2242094.

Rudel, T. K., M. Perez-Lugo & H. Zichal. 2000. When fields revert to forest: Development and spontaneous reforestation in post-war Puerto Rico. Professional Geographer 52: 386–397.

Rudel, T. K., S. Sloan, R. Chazdon & R. Grau. 2016. The drivers of tree cover expansion: Global, temperate, and tropical zone analyses. Land Use Policy 58: 502–513.

Sabogal, C., C. Besacier & D. McGuire. 2015. Forest and landscape restoration: Concepts, approaches and challenges for implementation. Unasylva 245, 66: 3–10.

Sayer, J., T. Sunderland, J. Ghazoul, J.-L. Pfund, D. Sheil, E. Meijaard, M. Venter, A. K. Boedhihartono, M. Day & C. Garcia. 2013. Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proc. Nat. Acad. Sci. U.S.A. 110: 8349–8356.

SER. 2004. Society for Ecological Restoration. <http://www.ser.org>, accessed 23 October 2016.

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

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

Sloan, S. 2015. The development-driven forest transition and its utility for REDD+. Ecol. Econ. 116: 1–11.

Sloan, S., M. Goosem & S. G. Laurance. 2016. Tropical forest regeneration following land abandonment is driven by primary rainforest distribution in an old pastoral region. Landscape Ecol. 31: 601–618.

Suding, K. N. 2011. Toward an era of restoration in ecology: Successes, failures, and opportunities ahead. Annual Rev. Ecol. Evol. Syst. 42: 465–487.

Teixeira, A. M. G., B. S. Soares, S. R. Freitas & J. P. Metzger. 2009. Modeling landscape dynamics in an Atlantic Rainforest region: Implications for conservation. Forest Ecol. Managem. 257: 1219–1230.

Uriarte, M., J. R. Lasky, V. Boukili & R. L. Chazdon. 2016. A trait-mediated, neighbourhood approach to quantify climate impacts on successional dynamics of tropical rainforests. Funct. Ecol. 30: 157–167.

Venter, O., E. W. Sanderson, A. Magrach, J. R. Allan, J. Beher, K. R. Jones, H. P. Possingham, W. F. Laurance, P. Wood & B. M. Fekete. 2016. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat. Commun. doi: 10.1038/ncomms12558.

Vieira, I. C. G., T. Gardner, J. Ferreira, A. C. Lees & J. Barlow. 2014. Challenges of governing second-growth forests: A case study from the Brazilian Amazonian State of Pará. Forests 5: 1737–1752.

Walker, L. R., J. Walker & R. J. Hobbs (editors). 2007. Linking Restoration and Ecological Succession. Springer, New York.

Wangpakapattanawong, P., N. Kavinchan, C. Vaidhayakarn, D. Schmidt-Vogt & S. Elliott. 2010. Fallow to forest: Applying indigenous and scientific knowledge of swidden cultivation to tropical forest restoration. Forest Ecol. Managem. 260: 1399–1406.

Zambrano, A. M. A., E. N. Broadbent & W. H. Durham. 2010. Social and environmental effects of ecotourism in the Osa Peninsula of Costa Rica: The Lapa Rios case. J. Ecotourism 9: 62–83.