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Under suitable conditions, deforested land used for agricultural crops or pastures can revert to forest through the assisted or unassisted process of natural regeneration. These naturally regenerating forests conserve biodiversity, provide a wide array of ecosystem goods and services, and support rural economies and livelihoods. Based on studies in tropical and temperate forest ecosystems, we summarize cases where natural regeneration is occurring in agricultural landscapes around the world and identify the socio-ecological factors that favor its development and affect its qualities, outcomes and persistence. We describe how the economic and policy context creates barriers for the development, persistence, and management of naturally regenerating forests, including perverse outcomes of policies intended to enhance protection of native forests. We conclude with recommendations for specific economic and policy interventions at local, national, and global scales to enhance forest natural regeneration and to promote the sustainable management of regrowth forests on former agricultural land while strengthening rural communities and economies.

1. Introduction

When crop fields and pastures that earlier replaced native forests are left unused, the process of natural regeneration—also known as secondary succession, old-field succession, forest regrowth, spontaneous restoration or passive restoration—often leads to the development of a new forest system that gradually regains many properties of the previous forest ecosystem (Cramer *et al* 2008, Chazdon 2014). During this process, native vegetation regenerates in several ways, including by seeds shed in response to burning, from seeds in the soil or newly deposited by wind or by animals, from resprouting rootstocks, or by vegetative propagules (Duncan and Chapman 1999, Pignataro *et al* 2017). In this context, natural regeneration of

forests is both an ecological process as well as a transition from agricultural to forest land use and land cover. The nature of forest regeneration on former agricultural land defines a distinct ecological, social and policy context that contrasts with selective logging and associated silvicultural treatments in natural forests managed for timber production.

A forest undergoing natural regeneration following agricultural land use is a socio-ecological system in transition (Lambin and Meyfroidt 2010). Where socio-economic and biophysical conditions are favorable, this system is likely to recover the structural properties, species composition and socio-ecological functions of the prior forest ecosystem (Filotas *et al* 2014, Ghazoul *et al* 2015, Ghazoul and Chazdon 2017). Unfavorable conditions, however, can push the

system towards an alternate steady state where active interventions are required to restore a forest ecosystem (Suding *et al* 2004). Increasing land-use intensity, weed infestations, and lack of seed dispersal, can strongly modify recovery trajectories, including species composition (Goldsmith *et al* 2011, Jakovac *et al* 2015, 2016).

Naturally regenerating forests on former agricultural land can provide solutions for conservation of biodiversity, mitigation of, and adaptation to, climate change, and multiple ecosystem goods and services (Houghton *et al* 2015, Locatelli *et al* 2015, Wilson *et al* 2017, Jones *et al* 2019, Matos *et al* 2019, Pugh *et al* 2019). Similar benefits can be provided by active forest restoration (e.g. deliberate planting) and diverse forms of reforestation, but at significantly higher costs (Bullock *et al* 2011). For millennia, naturally regenerating forests in shifting cultivation systems were a nexus for food production and forest management (Hernández-X *et al* 1995, Chazdon 2014). Recent expansion of intensified and mechanized agricultural systems, however, has often displaced traditional smallholder agriculture, putting natural regeneration of forests in limbo with regard to land management policies, environmental regulations, and restoration targets (Wood *et al* 2016, Martin *et al* 2018, Rasmussen *et al* 2018).

In preparation for the UN Decade of Ecosystem Restoration (2021–2030), it is timely to consider where and how naturally regenerating forests on land previously used for crops or grazing can contribute to massively up-scaling efforts to restore degraded and lost ecosystems to conserve biodiversity, combat climate change, enhance food security, and protect water supplies in a social, economic, and ecologically effective manner (Chazdon and Brancalion 2019). Bastin *et al* (2019) estimated that 9 million km² of restored woodlands and forests globally could be ecologically suitable areas for reforestation (including natural regeneration). However, the benefits and feasibility of recovering forests to this extent have not been fully evaluated (Chazdon and Brancalion 2019), nor do we have a clear vision of the potential or feasibility of natural regeneration to replenish native forests at this massive scale.

Natural regeneration can occur spontaneously without human intervention after the cessation of previous land use, or the recovery process can be assisted in a variety of ways to overcome existing limitations (hereafter termed assisted natural regeneration). Assisted natural regeneration interventions may not effectively overcome limitations, thus requiring active restoration using site preparation and tree planting (Holl and Aide 2011, Holl *et al* 2018). Continuous plantings, cluster plantings (Saha *et al* 2016), and planting islands or corridors of native trees are effective ways to actively restore forests and to encourage their development through subsequent natural regeneration (Holl 2017, Levy-Tacher *et al* 2019).

Despite many social and ecological obstacles, forests are regenerating in many regions worldwide (Hecht *et al* 2014) (figure 1). Throughout the world, woodlands and forests are returning following abandonment of small-scale agriculture (Li and Li 2017). It is time to recognize the many values of naturally regenerating forests and to place this land-use change firmly within the context of forward-looking environmental policies to create multi-functional landscapes that sustain people and nature. Post-agricultural forest regeneration occurs within the context of multiple-use landscapes, requiring attention to a wide range of social as well as ecological issues, as highlighted by the recent IPBES global assessment (Díaz *et al* 2019). This task is reinforced by the fact that recent global meta-analyses related to forest restoration have found that recovery levels of biodiversity, forest structure and function indicators are similar or greater for passive restoration than for active restoration in the long term, in spite of highly variable results among primary studies (Crouzeilles *et al* 2017, Meli *et al* 2017, Jones *et al* 2018).

Here, we review the social and ecological importance of naturally regenerating forests on former agricultural land in temperate and tropical forest biomes. We summarize available information regarding where forests are regenerating in agricultural landscapes, and explore the conditions that influence their development and persistence. Finally, we examine specific cases where economic and regulatory policies positively or negatively influence natural regeneration. We conclude with recommendations for specific economic and policy interventions to enhance natural regeneration in the context of international, national, and sub-national forest restoration targets.

Our review draws attention to the pervasive economic and policy contexts that currently influence (positively and negatively) natural regeneration of forests around the world. Given the global urgency and ambition for large-scale forest restoration, our synthesis provides a starting point for policy-level discussions and for developing approaches to enhance natural regeneration on former agricultural land in ways that promote long-term recovery while providing economic benefits to rural residents.

2. Search methods

The articles featured in this review were selected largely through thematic literature searches and reference list checking in addition to an extensive bibliography on these topics accumulated from our active research in this field. We searched published, peer-reviewed literature, emphasizing papers published since 2015, using a wide variety of terms including ‘land abandonment,’ ‘farm abandonment,’ ‘forest transition,’ ‘secondary vegetation,’ ‘forest expansion,’ ‘reforestation,’ ‘regrowth,’ ‘rewilding,’ and ‘passive

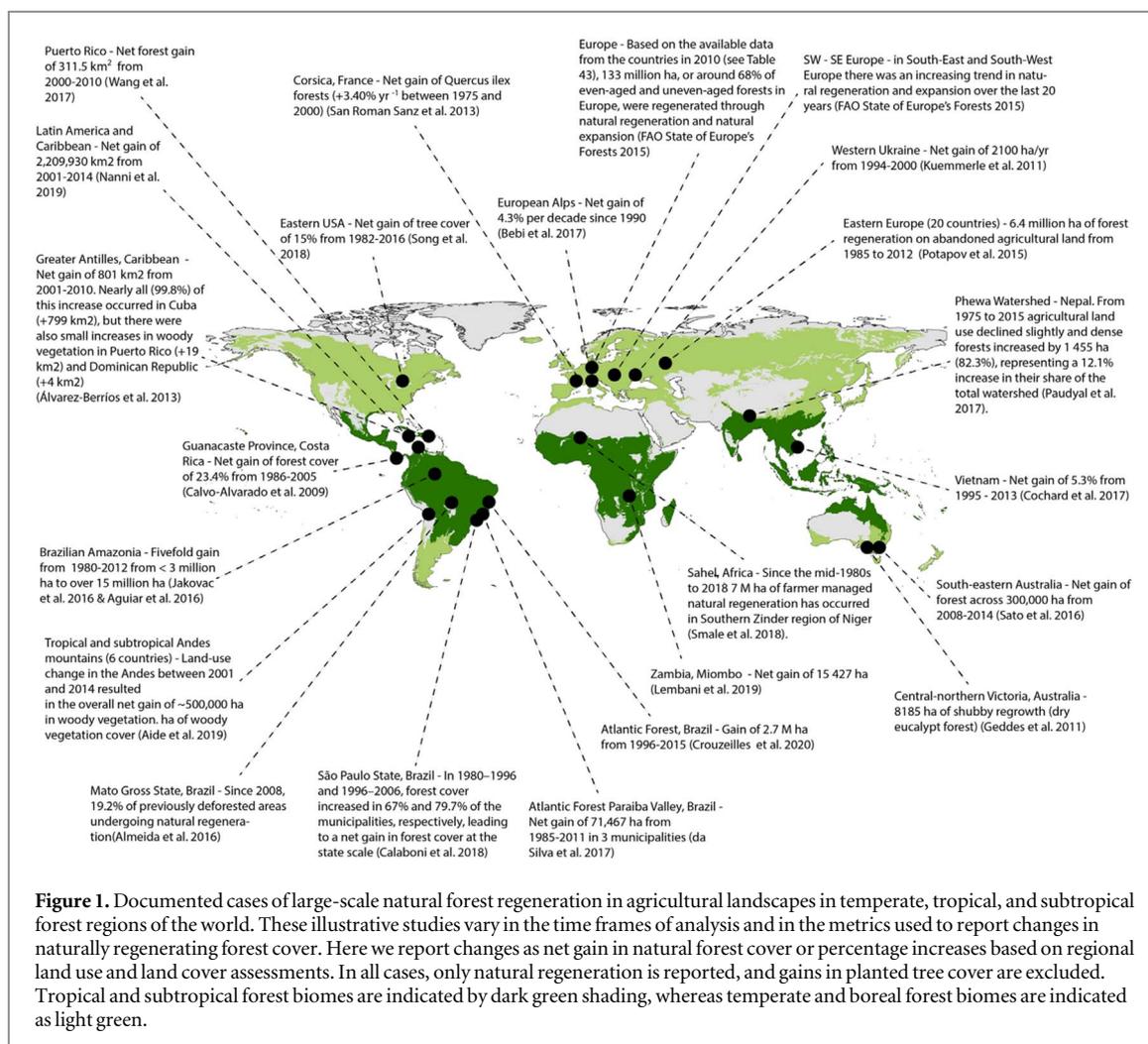


Figure 1. Documented cases of large-scale natural forest regeneration in agricultural landscapes in temperate, tropical, and subtropical forest regions of the world. These illustrative studies vary in the time frames of analysis and in the metrics used to report changes in naturally regenerating forest cover. Here we report changes as net gain in natural forest cover or percentage increases based on regional land use and land cover assessments. In all cases, only natural regeneration is reported, and gains in planted tree cover are excluded. Tropical and subtropical forest biomes are indicated by dark green shading, whereas temperate and boreal forest biomes are indicated as light green.

restoration' in combination with 'temperate' and 'tropical', and additional terms for specific geographic regions to uncover literature from Europe, Asia, Africa, and the Americas. We also used more specialized terms such as 'enrichment planting', 'sustainable management', 'remittances', and 'out-migration' in combination with 'forest regeneration', 'natural regeneration', and 'secondary forests'. We eliminated papers that focused on silvicultural interventions in logged forests or that focused on natural regeneration in the understory of plantations.

3. Environmental and socio-economic importance of naturally regenerating forests

3.1. Biodiversity recovery in naturally regenerating forests and landscapes

Natural regeneration of forests is an intersection point for conservation and restoration goals (Arroyo-Rodríguez *et al.* 2017, Chazdon 2019). Studies of naturally regenerating forests show gradual recovery of native species compared to reference forests, but outcomes vary widely and species composition recovery is significantly slower than species richness

(Chazdon *et al.* 2009, Navarro and Pereira 2015, Acevedo-Charry and Aide 2019, Matos *et al.* 2019, Rozendaal *et al.* 2019). Agricultural land use can have a centuries-long legacy on the biodiversity and productivity of forest ecosystems derived from old-field succession (Isbell *et al.* 2019). During the first 40 years of natural regeneration in temperate areas across the globe, organism abundance and diversity levels attained 133% and 82%, respectively, of reference forest levels (Meli *et al.* 2017). A meta-analysis of 147 studies in tropical regenerating forests found that species richness of amphibians, reptiles, birds, and mammals recovered after approximately 40 years, but recovery of species composition was considerably slower, particularly for forest specialists (Acevedo-Charry and Aide 2019). In Central Spain, Cruz-Alonso *et al.* (2019) reported recovery levels with respect to reference forests of 103% for woody species richness, 45% for tree biomass, 39% for frugivore-dispersed shrub abundance, and 96% for tree functional dispersion for a variety of secondary forests after 50 years of agricultural abandonment. In lowland Latin America, tree species richness showed rapid recovery (mean of 54 years) in naturally regenerating forests, but recovery of species composition may require several centuries

(Rozendaal *et al* 2019). Natural regeneration in Australian subtropical woodlands provides valuable habitat for reptile and bird communities (Bowen *et al* 2009, Bruton *et al* 2013). In tropical regions, recovery of biodiversity and forest structure can be 34%–56% and 19%–56% higher, respectively, in naturally regenerating forests than in actively restored forests (Crouzeilles *et al* 2017).

Biological legacies in the landscape (*sensu* Franklin *et al* 2000), i.e. the living organisms that survive a catastrophic disturbance, contribute to and are created by naturally regenerating forests, with spatial context and prior land use strongly influencing the future trajectory of communities and ecosystems (Bengtsson *et al* 2003, Johnstone *et al* 2016). A meta-analysis based on natural regeneration studies in 135 landscapes in temperate and tropical forest regions showed that the extent of forest cover in the landscape is the most important predictor of landscape variability in recovery of biodiversity, a measure inversely related to ecological restoration success (Crouzeilles *et al* 2019). Restorable areas in landscapes (1 × 1 km pixel) with more than 27% forest cover showed low levels of variation in biodiversity recovery, and encompass a total of 238 M ha, 38% of the temperate and tropical forest regions of the world (Crouzeilles *et al* 2019). These areas present lower risks (higher predictability) for biodiversity recovery through natural regeneration. In contrast, landscapes with less than 6% forest cover showed high levels of variation in recovery, and are better candidates for active restoration or reforestation interventions (Crouzeilles *et al* 2019).

At a landscape scale, naturally regenerating forests can cost-effectively contribute to the conservation and restoration of biodiversity through the creation of buffer zones, establishment of biological corridors and stepping stones in an agricultural matrix, and recovery of disturbed areas within protected areas (Guevara *et al* 2005, Evans *et al* 2017, Newmark *et al* 2017). Forest fragmentation could be reduced by 44% in the Brazilian Atlantic Forest if the 210 000 km² of land with a high capacity for spontaneous and assisted natural regeneration were left to recover (Crouzeilles *et al* 2020). In temperate agricultural southern Australia, shelterbelts composed of natural regeneration can act as critical habitats for a range of native biota while protecting crops from wind and storm damage and reducing erosion (Lindenmayer *et al* 2016). Naturally regenerating forests can support markedly different assemblages compared to planted forests and old growth temperate woodland (Lindenmayer *et al* 2012). Secondary forests in the Brazilian Amazon show high levels of landscape-scale diversity and contribute to habitat heterogeneity (Solar *et al* 2015). In a fragmented landscape in Central Amazonia, natural regeneration of deforested areas between remnant fragments promoted the conservation of birds (Stouffer *et al* 2011), dung beetles (Quintero and Roslin 2005, Bitencourt *et al* 2019), and bats (Rocha *et al* 2018). In

Europe, agricultural land abandonment is the major driver of population expansion of large herbivores and carnivores (Perino *et al* 2019).

Effects of climate change on forest regeneration are a major concern (Bastin *et al* 2019). Because colonizing species are adapted to local conditions, and to other colonizing taxa (Chazdon 2014), naturally regenerating forests are more resilient to drought, disease, windstorms, or heavy rainfall than single-species tree plantations (Jactel *et al* 2017). Droughts and temperature increases associated with climate change can influence rates and quality of vegetation recovery in naturally regenerating forests and in other types of restored forests (Anderson-Teixeira *et al* 2013, Locatelli *et al* 2015, Uriarte *et al* 2016a, 2016b).

3.2. Naturally regenerating forests as sources of ecosystem services

Recovery of ecosystem functions exhibits similar patterns between naturally regenerating and planted forests (Meli *et al* 2017). At a global scale, forests regenerating on land historically cleared for agriculture or timber clear-cuts constitute a significant global carbon sink (Pan *et al* 2011, Griscom *et al* 2017, Houghton and Nassikas 2017). Pugh *et al* (2019) estimated that regenerating forest stands (< 140 year old) encompassed 61.5% of the 42.8 million km² of forests globally in 2010. From 2001 to 2010, the carbon sink from regenerating forests (1.3 Pg yr⁻¹) constituted 60.5% of the global forest carbon sink of 2.15 Pg yr⁻¹. Carbon sinks in regenerating forests are located mostly in deciduous broadleaf and evergreen coniferous forests in temperate zones, whereas most of world's remaining old-growth forest stands are in the moist tropics and boreal Siberia (Pugh *et al* 2019). Chazdon *et al* (2016b) estimated a total of 2.9 million km² of regenerating forests (< 100 year old) within the lowland Neotropics compared to 4.0 million km² of old-growth forest in 2008. If left to continue growing for 40 years, these naturally regenerating forests could accumulate an estimated total aboveground carbon stock of 8.48 Pg C.

Although few comparative studies have been conducted, there is evidence that natural regeneration enhances sediment retention and reduces surface runoff compared to tree plantations (Yang *et al* 2018). Assisted natural regeneration in Fujian, China reduced the export of dissolved organic carbon by 60%–90% compared to plantations of similar age (Yang *et al* 2018). Natural regeneration also can restore year-round flows of streams through increased infiltration of rain into ground water supplies (Filoso *et al* 2017), although effects of prior land use and reforestation approaches on recovery of soil infiltration are complex and poorly studied (Lacombe *et al* 2015, Lozano-Baez *et al* 2019).

In some cases, however, forest regrowth following agricultural abandonment can reduce landscape and habitat diversity, with perceived negative effects on

biodiversity (Queiroz *et al* 2014), alteration of water flows (Bonnesoeur *et al* 2019, Evaristo and McDonnell 2019), and even a loss of cultural landscapes and traditional land management techniques when human migration rates are high (Lasanta *et al* 2017). Natural regeneration also can lead to increase of animal populations that negatively affect agricultural productivity and human health (Byg *et al* 2017). These concerns also apply to active restoration and reforestation interventions, however, and underscore the need for broad stakeholder engagement in decisions regarding management of landscape-scale interventions.

3.3. Economic benefits of naturally regenerating forests

Natural regeneration can bring direct and indirect economic benefits to local residents and communities. Under supportive policies and market development, natural regeneration can enhance, diversify, and increase long-term productivity of agricultural systems (Peltier *et al* 2014), including silvopastoral systems (Hoosbeek *et al* 2016, Kremen and Merenlender 2018). In the temperate woodlands of south-eastern Australia, natural regeneration is a key component of integrating enhanced agricultural production and biodiversity conservation (Lindenmayer *et al* 2018). Naturally regenerating woodlands can act as shelterbelts for protecting livestock and thereby promoting lambing success as well as weight gain in cattle (Cleugh 2003). Areas of naturally regenerated rainforest that occur within oil palm plantations have been shown to support large numbers of native animals and plants (Azhar *et al* 2014).

Over a 20 year period, the economic benefits of natural regeneration can compensate for the opportunity costs of foregoing agricultural use of these lands (Strassburg *et al* 2016). For example, reduction of sediment loads through regeneration of abandoned pastures in the Paraitinga River Basin of São Paulo State in Brazil was estimated to reduce costs of dredging sediments out of the river by US\$1.17 million annually, and would avoid additional costs of water purification (Strassburg *et al* 2016). Natural regeneration also can create income streams from community-based ecotourism, which brings financial returns to local residents in addition to providing conservation benefits for wildlife and provision of ecosystem services (Stem *et al* 2003, Bray 2016).

Compared to natural regeneration, direct economic returns from commercial tree plantations and tree planting are higher and more predictable for timber products in the short-term (Baral *et al* 2016). Indirect economic benefits from natural regeneration can be substantial, however. Through retention of nutrients in buffer strips and hedgerows, which can arise from natural regeneration, crop yields can be enhanced. Hedgerows bordering agricultural croplands in the temperate regions of the world retain 69%

of nitrogen, 67% of phosphorous, and 91% of sediments of run-off (Van Vooren *et al* 2017). In the Humbo community-based natural regeneration project in Ethiopia, assisted natural regeneration brought social and economic benefits to participating communities who collected wild fruits, firewood and fodder (Wolde *et al* 2016).

A major advantage of natural regeneration as an ecological restoration approach is the substantially reduced implementation costs compared to tree planting (Brancaion *et al* 2016, Cruz-Alonso *et al* 2019). In Atlantic Forest landscapes with relatively high forest cover, where natural regeneration is most likely, costs of site preparation and tree planting are reduced by 38% (Molin *et al* 2018). Because of these lower costs, considerably larger areas can be restored using assisted natural regeneration approaches compared to widespread tree planting (Chazdon and Guariguata 2016). In Minas Gerais State, Brazil, Nunes *et al* (2017) projected that spontaneous and assisted natural regeneration could effectively restore 15 000 km² of forest over 20 years. Across the entire Atlantic Forest region of Brazil, 210 000 km² of degraded lands can potentially be restored through assisted natural regeneration, reducing implementation costs by US\$ 90.6 billion (77%) compared to active restoration methods (Crouzeilles *et al* 2020).

4. Where and why forests are growing back

4.1. Global indicators of natural forest regeneration from satellite imagery

Despite many technical advances such as fine-scale satellite imagery (including LIDAR), we still lack an accurate and systematic assessment of where forests are naturally regenerating around the world, largely due to challenges in distinguishing between areas of native forest and tree plantations and to high rates of reclearance of regenerating forests (Rudel 2005, Asner *et al* 2009, Vieira *et al* 2014, Chazdon *et al* 2016a, Reid *et al* 2019). Net increases in tree cover (including planted and unplanted tree cover) detected from satellite imagery in boreal and temperate biomes from 2000 to 2010 can largely be explained by natural regeneration of forests on abandoned agricultural lands (FAO and UNCCD 2015).

Global scale analysis of satellite imagery from 1982 to 2016 revealed that tree cover is changing in dramatic ways across major geographic regions, with tree cover gain attributed to both natural regeneration as well as the establishment of tree plantations (Song *et al* 2018). A tree cover increase of 15% in the Eastern United States was attributed to natural regeneration (Song *et al* 2018). The greatest increases in tree cover were in Eastern Europe (35%), including European Russia and Carpathian montane forests (Song *et al* 2018). In Eastern Europe, tree cover gain was attributed to natural forest regeneration on abandoned

agricultural land following the collapse of the former Soviet Union (Potapov *et al* 2015, Rudel *et al* 2016, Buitenwerf *et al* 2018). Political changes in Eastern Europe and land-use subsidies in the European Union to set aside marginal agricultural areas in regions with steep slopes to limit food production and avoid surpluses (Common Agricultural Policy reforms) led to abandonment of farmland from 1998 to 2008 (Lasanta *et al* 2017).

4.2. Natural forest regeneration in Europe

Abandonment of agriculture in mountainous regions in Europe led to both expansion of plantations and natural regeneration in many countries over the last century, accompanied by rural out-migration and intensification of agriculture in lowland regions (Benayas *et al* 2007, Sitzia *et al* 2010, Cruz-Alonso *et al* 2019). In Italy, forest cover increased by 87% since the end of World War II, with the greatest areas of forest regrowth in lowland areas, where abandonment of farmland and the loss of traditional rural landscapes has occurred as a result of industrialization, urbanization, and agricultural intensification elsewhere (Camarretta *et al* 2018). Within the Basilicata region of southern Italy, approximately 70 154 ha of forest regenerated on abandoned agricultural lands and pastures from 1984 to 2010 (Mancino *et al* 2014). In Spain, natural forest regeneration represented around 2/3 of the increase in tree cover between 2000 and 2010 (Vallejo *et al* 2014). A land-use dynamics model predicted that between 100 000 and 290 000 km² of agricultural land in Europe will be abandoned between 2000 and 2030 (Verburg and Overmars 2009). Much of this new tree cover is expected to result from natural regeneration (Thers *et al* 2019).

4.3. Natural forest regeneration in the tropics and subtropics

Analyses of sequential satellite imagery and ground surveys reveal many areas around the world where tropical and subtropical forests are naturally regenerating following agricultural land use at scales of hundreds of km² or greater (figure 1). In several regions of Africa, farmer managed natural regeneration is occurring on former croplands and grazing lands (Smale *et al* 2018, Lembani *et al* 2019). This approach has transformed an estimated 70 000 km² of denuded dryland forest landscapes into productive agroforestry parklands in Niger alone (Smale *et al* 2018). Nanni *et al* (2019) identified 15 regions of sustained natural regeneration of forests in Latin America and the Caribbean between 2001 and 2014. Combined, these regions covered 2.2 M km², representing 11% of the region's land area. One of these regions was the tropical Andes, where 5000 km² of woody vegetation regrew over this period (Aide *et al* 2019), associated with a decline in rural population and out-migration to urban areas.

Brazil's Atlantic Forest is another region with significant natural regeneration (Nanni *et al* 2019). Forest cover increased by 102% in the Paraíba Valley of São Paulo, Brazil from 1962 to 2011, dominated by natural regeneration on abandoned cattle pastures (Lira *et al* 2012, da Silva *et al* 2017, Calaboni *et al* 2018). These land-use changes appear to be driven by agricultural expansion and intensification on the most suitable agricultural lands, which encouraged abandonment of marginal agricultural lands. Similar trends apply across the entire Atlantic Forest Region of Brazil. In this region with 755 000 km² of deforested land, 27 000 km² of forest regenerated naturally from 1996 to 2015, and a predictive model estimated that another 28 000 km² could regrow between 2015 and 2035 without human assistance (Crouzeilles *et al* 2020). Using assisted natural regeneration methods, an additional 188 000 km² of Atlantic Forest in Brazil has the potential to be restored (Crouzeilles *et al* 2020).

Natural regeneration also occurs in regions that are still undergoing net deforestation. In Brazil's arc of deforestation in Pará State, naturally regenerating forests are increasing dramatically following abandonment of cattle pastures. Across the Brazilian Amazon, natural regeneration increased five-fold over the last three decades, exceeding 150 000 km² in 2012 (Aguiar *et al* 2016). Extensive areas of natural regeneration in Amazonia are often observed in areas close to large remnant patches of forest and low intensity of land use (Jakovac *et al* 2015, Lennox *et al* 2018). Along a 1000 km stretch of the BR-163 highway, natural regeneration adjacent to forests contributed to 85% and 70% in Pará and Mato Grosso, respectively, of all forest regrowth detected between 1985 and 2012 (Müller *et al* 2016). Absolute rates of natural regeneration were strongly dependent on the overall amount of deforested area, with higher rates in Pará (maximum of 50% of deforested area) on former pastures with lower management intensity compared to Mato Grosso (maximum of 25% of deforested area) where capital-intensive cropland and pasture systems dominate (Müller *et al* 2016). In the Brazilian Amazon, Conrado da Cruz *et al* (2020) identified 405 forest restoration projects in 191 municipalities between 1950 and 2017, forest restoration techniques used in descending order of importance were seedling planting, agroforestry systems, assisted natural regeneration, and natural regeneration.

Compared to subtropical and temperate zones, natural regeneration on former agricultural land in the tropics tends to be a more recent phenomenon, where net forest loss is still occurring (Song *et al* 2018). Tropical secondary forests are younger (mean of 18 year) compared to temperate deciduous forests (mean of 52 year) and coniferous evergreen forests (mean of 72 year) (Pugh *et al* 2019). In Latin America, cases of forest gain through natural regeneration from 2001 to 2014 fell into five main clusters that reflect topographic features and related aspects of agro-ecological

Box 1. Management of natural forest regeneration in the American tropics.

Management of naturally regenerated forests on former agricultural land for commercial products is relatively uncommon. Based on studies in the Latin American tropics and subtropics, however, we know that these forests hold much potential for management for timber and non-timber products (Kammesheidt 2002). These young forests are rich sources of a wide variety of products such as medicine, ornamental plants, food, timber, and fuel (Chazdon and Coe 1999, Guariguata 1999, Souza *et al* 2016). Experimental studies in Central Amazonia and Costa Rica show a high potential for enhancing growth and survival of timber species in naturally regenerating tropical forests through creating canopy gaps, removing understory vegetation and manipulating leaf litter (Mesquita 2000, Dupuy and Chazdon 2008). In Puerto Rico, widespread naturally regenerating forests contain high densities of trees suited for timber and non-timber products, although many forests are still too young to support extractive activities (Forero-Montaña *et al* 2019). Managed natural regeneration in coastal areas of Brazil's Atlantic Forest also showed high diversity and abundance of useful species, including two endemic species, and is providing economic benefits to smallholders (Souza *et al* 2016). In a study of two 33 year old naturally regenerating forests in Brazil's Atlantic Forest, one managed through enrichment planting and one unmanaged, Fantini *et al* (2019) found that selective harvesting could produce valuable timber from planted and unplanted species, while permitting growth for future harvests. Small-scale management of secondary forest in this region has the potential to produce sufficient merchantable timber to become an incentive for land owners to maintain and recover forest on their farms. Enrichment of young regenerating forests with native palm species used for commercial fruit production and timber species generated an economically viable production model over a 30 year period in the Atlantic Forest of southeastern São Paulo, Brazil (Maier *et al* 2018).

marginality, climate change, rural population decline, and increased urbanization (Nanni *et al* 2019). Broader analysis of global patterns showed that distinct regional contexts have given rise to significant cases of net reforestation (Li and Li 2017).

4.4. Local, landscape and regional drivers of natural forest regeneration

Natural regeneration reflects myriad drivers and contexts of land-use change. Environmental factors that can influence natural regeneration include soil quality, the presence of weedy or invasive species that arrest the natural regeneration process, or inadequate seed dispersal that restricts colonization of native species (Rey Benayas *et al* 2008). Observational studies have shown that the loss of primates and birds negatively influences forest regeneration (Gardner *et al* 2019). In these cases, interventions are needed to control weeds, enrich natural regeneration, and enhance seed dispersal. Natural regeneration also can be assisted by controlling or eliminating grazing livestock and preventing wildfires (Fischer *et al* 2009, Gardner *et al* 2019). The diversity of local tree regeneration can be supplemented by enrichment planting of important local species or non-invasive commercial species for

later harvesting of timber and non-timber products (Paquette *et al* 2009, Maier *et al* 2018) (Box 1).

In some areas of Australia, natural regeneration is occurring as a result of reduced grazing pressure either through deliberate limiting of grazing pressure or drought-related destocking (Fischer *et al* 2009, Geddes *et al* 2011). In other contexts, deliberate interventions to assist natural regeneration include establishment of protected areas (Von Thaden *et al* 2018), fenced enclosures on farms (Mekuria *et al* 2018), reforestation on private lands in compliance with mandatory restoration policies (Brancaion *et al* 2016), and voluntary actions to enhance conservation values in amenity landscapes (Stelling *et al* 2018).

The ecological determinants of natural regeneration have been investigated in a variety of contexts (Chazdon 2014) and provide the basis for land-use planning within farms, landscapes, and municipalities. Planning the location of naturally regenerated areas relative to other parts of farms such as grazing paddocks, watercourses, and rocky outcrops is critical to effectively integrate agricultural production with areas of natural regeneration (Lindenmayer *et al* 2016). In agricultural landscapes, patches of forest regeneration are more likely to be found adjacent to existing old-growth forest remnants (Sloan *et al* 2016), and natural regeneration is more likely to occur and have better biodiversity outcomes in landscapes with more forest cover (Crouzeilles *et al* 2016, 2020). Deforested areas on steep slopes with less intensive prior land use and close to forest remnants are the most likely to regenerate spontaneously (Rezende *et al* 2015, Molin *et al* 2018). A systematic review of drivers of tropical forest cover expansion through natural regeneration found that proximity to forest remnants, steep slopes, high forest cover at the landscape scale and proximity to watercourses were the most important biophysical factors (Borda-Niño *et al* 2020). Natural regeneration is often associated with poor soil quality or other proxies of agricultural marginality (Arroyo-Mora *et al* 2005), but this trend is not universally observed (Sloan *et al* 2016).

Important socio-economic factors associated with tropical forest cover expansion through natural regeneration were inclusion in protected areas, distance to roads, and distance to population centers (Borda-Niño *et al* 2020). Land tenure regimes also significantly affected recovery of woody natural regeneration in Mexico. Municipalities dominated by communal land tenure showed the largest increases in forest cover from 2001 to 2010 in moist forest, dry forest, and coniferous forest biomes (Bonilla-Moheno *et al* 2013).

In Mesoamerica and South America, agricultural abandonment is associated with the expectation of increasing economic opportunities from jobs in nearby cities, ecotourism operations, or industrial zones, and is often accompanied by out-migration from rural areas (Hecht *et al* 2015). Similar trends occur in Nepal, where levels of international

outmigration are high (Oldekop *et al* 2018). International outmigration in Nepal was associated with substantial increases in local forest cover due to farmland abandonment and subsequent natural regeneration of forest (Oldekop *et al* 2018).

The social and cultural costs of rural migration may be high, including exploitation and increasing poverty (Garcia-Barrios *et al* 2009, Hecht *et al* 2015). In some areas, influx of remittances following outmigration can partially compensate for losses of agricultural labor, sustaining some traditional farming activities in these areas (Ospina *et al* 2019). The influx of remittances varies greatly, however, depending on external economic and political conditions. For instance, remittances accounted for approximately 25% of Nepal's Gross Domestic Product in 2013 (Oldekop *et al* 2018).

5. Economic and policy barriers to natural forest regeneration

Soil degradation (often caused by intensive and long-term land-use), climate harshness, and low levels of neighboring natural forest cover are major impediments to natural regeneration around the world (Jakovac *et al* 2015, Sato *et al* 2019). Aside from these biophysical constraints, natural regeneration faces additional socio-economic and jurisdictional barriers. In the following paragraphs, we focus on barriers to natural regeneration due to regulations, policies and global economic trends that favor intensified modes of commodity production, restrictive forest conservation measures, and large-scale tree monocultures. These barriers also pose challenges to the widespread adoption of active forest restoration approaches involving planting of native tree species. In the tropics, intensive agricultural production systems for palm oil, soybeans, sugarcane, pineapples, and other crops require removal of trees from parts of the landscape that hinder mechanized or intensive production, such as flat areas in lowlands, where young patches of natural regeneration are frequently eliminated (Sayer *et al* 2012, Shaver *et al* 2015).

Additional barriers stem from the 'invisibility' of natural regeneration in the context of reforestation and forest restoration. Decision-makers, resource management agencies, farmers, and restoration practitioners tend to overlook natural restoration-based approaches for at least six reasons. First, large-scale restoration initiatives are often conceived solely through tree planting (Chazdon and Uriarte 2016, Biggs 2018, Hua *et al* 2018). Second, farmers view early stages of natural regeneration as undesirable and messy, or as a sign of poor land management (Zahawi *et al* 2014). Third, limited knowledge is available to guide policies and actions to target where natural regeneration could potentially occur, to estimate how much area could be regenerated, and how long it takes

to deliver specific social and environmental outcomes (Uriarte and Chazdon 2016). Fourth, there is a lack of sound economic projections and business models based on natural regeneration to evaluate socio-economic effectiveness (Ding *et al* 2017). Fifth, natural regeneration has not been considered an activity requiring human agency and therefore cannot be enforced as a policy. And sixth, in some countries, agrarian reform laws obligate farmers to cultivate land, and state authorities can confiscate uncultivated land or declare fallow land as 'unutilized or degraded land' to be used for other purposes (Ferguson 2014, Duangjai *et al* 2015).

In commodity production landscapes, natural regeneration in suitable areas presents high opportunity costs and requires that landowners receive appropriate financial compensation to transform agricultural land into natural forest. Payments for environmental services to landowners in Costa Rica are USD \$125/ha/yr for a 16 year contract to establish a native tree species plantation, but only USD \$39/ha/yr for a 5 year contract for protecting natural regeneration (Porras and Chacón-Cascante 2018). Given the choice, landowners favor clearing young secondary forest to establish tree plantations or for growing commodity crops over regenerating native forest (Shaver *et al* 2015). Naturally regenerating forests can actually support a high abundance of commercial tree species (Box 1), but trees can take several decades to reach commercial size (Forero-Montaña *et al* 2019). The economic value of naturally regenerating forests is often considerably lower than a commercial forestry-style plantation, agroforestry system, or crop field.

Older stages of natural regeneration and primary forests are now legally protected from clearing in many countries, but early growth stages are rarely protected and are commonly (and sometimes legally) cleared to make way for crop or cattle production. Outside of protected areas, young stages of natural regeneration are highly vulnerable to being re-cleared (Schwartz *et al* 2017, Reid *et al* 2019). In the Brazilian Amazon, 42 040 km² of secondary forests derived from natural regeneration of abandoned pastures were converted into other types of land cover between 2010 and 2014 (Carvalho *et al* 2019). From 2008 to 2014, deforestation of secondary forests in Brazilian Amazonia became decoupled from deforestation of primary forests, suggesting a trend toward pasture management based on reclearance of young forests (Wang *et al* 2020). In Costa Rica, recent expansion of pineapple and other crops largely replaced pasture, exotic and native tree plantations, and secondary forests, as 1986 legislation strictly prohibits clearance of primary forest (Shaver *et al* 2015). Environmental legislation tends to look backward rather than forward, emphasizing protection of historical conditions (preventing loss of primary forests) rather than ensuring the future potential for landscape-scale restoration and forest

connectivity, which strongly influence future levels of biodiversity and ecosystem services.

Naturally regenerated forest on former agricultural land is generally poorly mapped for planning and decision-making purposes. Forest gain is rarely disaggregated into its components of natural and planted forests. The importance of natural regeneration is also easily overlooked because often it is not shown on a map (figure 1). Estimates of deforestation in the Brazilian Amazon using the Brazilian national satellite-based deforestation monitoring system PRODES do not include deforestation of secondary forests. Yet, clearing of secondary forests and woodlands for agro-industrial pastures, plantations, and small-scale agricultural activities contributes significantly to forest loss in some areas. One exception is the TerraClass land-use mapping system used in Brazil that classifies secondary forest, pasture with woody regeneration, and regeneration with pasture as distinct categories (Almeida *et al* 2016). This approach revealed that 19.2% of previously deforested areas in Mato Grosso State, Brazil in 2008 were undergoing natural regeneration.

Even when owners of small properties allow natural regeneration and manage native forests on their land, they are often legally prevented from managing the young forest or selectively harvesting timber and non-timber products. For example, once natural regeneration reaches a stage when it is legally defined as forest in Mexico, harvesting restrictions and high transaction costs reduce the economic benefits received by small farmers (Román-Dañobeytia *et al* 2014). Forest law in Bhutan stipulates that planted forests on private and communal property are considered private property, and thus do not require state authorization to harvest. But trees and forests established naturally, either on public or private land, is national forest patrimony and require a management plan and authorization prior to utilization (Sears *et al* 2018a), moreover, timber harvested from natural forests is subject to taxation. In lowland Peru, a local market for the pioneer tree *Guazuma crinita* makes natural regeneration economically profitable. But there are no feasible national regulatory mechanisms for low-income smallholder farmers to harvest timber from fallow forests that are cyclically cleared for agricultural use (Sears *et al* 2018b) and current legislation restricts the sale of timber from these systems.

Sectoral and jurisdictional policies also hamper natural regeneration. For example, land use planning in Peru falls under the mandate of the Ministry of Environment, yet it is the Ministry of Agriculture that governs land use change by issuing titles and permits. As a result, the Ministry of Environment has poor leverage to support conservation of natural regeneration in spite of implementing carbon-based payments and related incentives (Kowler *et al* 2016). Conflicting mandates across government sectors in the context of

who governs forest restoration interventions (which include natural regeneration) are in fact widespread across most Latin American countries (Schweizer *et al* 2020). In southern Australia, large patches of old growth woodland on agricultural land are generally excluded from clearing under legislation, whereas natural regenerating (regrowth) woodland is rarely protected and often subject to widespread clearing (<https://environment.nsw.gov.au/questions/is-land-clearing-permitted>), leading to the loss of key habitats for biodiversity, especially during drought periods (Lindenmayer *et al* 2019).

6. Policy options and management innovations to favor natural forest regeneration

Natural regeneration occurs under specific biophysical, socio-economic and cultural conditions. However, in most cases, it is the result of an unintentional consequence of other processes, such as rural out-migration, changes in commodity prices and export policies, abandonment of agriculture on hilly or steep topography that preclude mechanization and agricultural intensification, land abandonment due to droughts, or government restrictions on agricultural land use on private or common property. Natural regeneration occurs intentionally when previously deforested areas are newly incorporated into state-managed protected areas or partially deforested private land purchased with the intention of conserving and restoring native forests (Algeet-Abarquero *et al* 2015), or when communities decide to promote regeneration to form community-managed forest reserves that provide forest products and other benefits to local livelihoods (Levy-Tacher *et al* 2019). These cases illustrate different socio-economic, cultural, and political drivers and impacts. Compared to temperate and boreal zones, approaches for management of naturally regenerated forests in tropical regions are poorly developed, particularly on former agricultural land. Yet there is much potential for silvicultural interventions in temperate and tropical regenerating forests to promote management for timber, non-timber products, carbon storage, and recreational, cultural and educational activities (Levy-Tacher *et al* 2012, Cojzer *et al* 2014) (Box 1).

Policy changes could be more achievable now, as capabilities have advanced to permit identification of specific areas where natural regeneration of forests is feasible and beneficial to both the environment and livelihoods. Natural regeneration is increasingly recognized as an important natural solution to tackling climate change (Chazdon *et al* 2016b, Griscom *et al* 2017), but its drivers and limitations need to be clearly identified. In cases where the major limitations are socio-economic rather than biophysical, innovations in policies and economic incentives at multiple

Table 1. Suggested interventions at the international, national, and sub-national scales to encourage natural regeneration to meet national and global forest restoration targets.

International scale

Create appropriate land type definitions. The United Nations Strategic Plan for Forests (2017–2020) has a global goal of increasing forest area by 3% worldwide. The FAO definition of forest used does not distinguish between native forests and monoculture plantations composed of exotic species. This goal should be modified to also include an aim to increase native forest area specifically through native tree plantings or assisted natural regeneration

Produce a global map at a 30 m resolution spatial scale of natural regeneration potential. This map should be based on the historical distribution of existing areas of natural regeneration (excluding plantations), environmental (topography, proximity to remnant forests, and river systems) and socio-economic factors (prior land use, land distribution, poverty index, inequity index, commodity production, forestry, shifting cultivation, and human migration dynamics). This map can show also the expected ecological outcomes from natural regeneration to reduce uncertainty and manage risk of low-cost forest restoration

Leverage the 2021–2030 UN Decade on Ecosystem Restoration, the UN Framework Convention on Climate Change agenda and the UN Convention on Biological Diversity to call for actions to enhance the long-term persistence of native forests (including natural regeneration) for biodiversity conservation, climate mitigation and adaptation, and hydrological regulation

National scale

Create a global map and national-scale maps of natural regeneration capacity in assessments of national-level restoration opportunities. Identify restoration opportunities that are suitable for unassisted or assisted natural regeneration

Increase efforts to map and classify naturally regenerated forests that include biophysical and socio-ecological land use dimensions (Boillat *et al* 2017)

Rebalance national forest management policies to emphasize local decision-making and to permit local or regional governance of management policies for harvesting timber and non-timber products from naturally regenerated forests, including harvesting of small diameter timber species and non-timber products while creating new income streams

Develop a national program of enrichment planting of trees with local commercial value or ecological value for wildlife to enhance diversity and management of secondary forest patches on private farms or community-managed land

Train and build capacity for environmental and restoration professionals to become natural regeneration extension agents who advise landowners and communities regarding prioritization of areas, assisted natural regeneration techniques, and sustainable management practices

Develop business models for assisted natural regeneration with input from local communities (Maier *et al* 2018)

Sub-national scale

Encourage landowners in areas suitable for natural regeneration to wait 1–2 years prior to planting trees to assess whether the rate of natural regeneration is sufficient, a policy currently applied in states in Brazil (Brancaion *et al* 2016) as a good predictor of longer term recovery (Holl *et al* 2018)

Stimulate ‘local forest’ movements. Develop ‘adopt a forest’ programs for local communities and schools, supported by NGOs, local government agencies, and local businesses partners. Provide incentives for local stewardship and valuation of regenerating forests and their importance for providing ecosystem services that benefit local communities. Use local regenerating forests for cultural, educational, and capacity building programs

Table 1. (Continued.)

Respect, encourage and foster local community decisions for natural regeneration to achieve sustainable management (Levy-Tacher *et al* 2019)

In areas appropriate for natural regeneration, apply the same value in payments for environmental service programs for natural regeneration as for tree plantations and reduce the minimum area requirement so smallholders can qualify and benefit from these programs

Leverage the UN Sustainable Development goal of healthy rural livelihoods to create attractive options for small farmers to retain land ownership while earning off-farm income and increasing native forest cover on their properties. Provide incentives via tax credits and conservation or restoration easements to protect land ownership while enhancing native forest cover and increasing conservation values

levels will be needed to reach the scale needed to restore native forests around the world.

Holistic land-use planning and spatial prioritization approaches can help ensure that native forests continue to regrow and persist without compromising food, fuel, or fiber production (Chazdon and Brancaion 2019). However, policies and mechanisms to empower holistic solutions—including expansion of agroforestry and silvopastoral systems—are underdeveloped (Kremen and Merenlender 2018, Chazdon and Brancaion 2019). Economic and policy incentives will be needed as economies and markets transition from those driving further degradation of native forests to restoration and enhancement of native forests (Boillat *et al* 2017). We now have the capacity to identify specific target areas where natural regeneration is beneficial and feasible (Brancaion *et al* 2019, Crouzeilles *et al* 2020), which can facilitate policy changes. Further development of these targeted approaches will need to be accompanied by innovative policies at multiple levels to reach the scale needed to restore native forests around the world by harnessing the power of nature (table 1).

Nurturing a forest transition—particularly where natural regeneration is promoted—presents immense policy and institutional challenges (Sloan 2015). These challenges are not insurmountable, but will require further research and innovations in policy and governance. For example, innovative institutional and policy approaches in Costa Rica supporting agricultural intensification, forest protection, and payments for environmental services contributed to a forest transition process that led to overall environmental benefits (Jadin *et al* 2016) including native species plantations and natural regeneration of forests (Calvo-Alvarado *et al* 2019). We encourage a focus on creating multi-functional landscapes where forest regrowth is compatible with agricultural production and sustainable rural livelihoods, by rejecting narrow sectoral mandates that spawned conflicts between conservation, production, and land rights (Kremen and Merenlender 2018). Sustainable intensification of agriculture and land sharing are key goals to

promote food security and wellbeing of smallholders in rural landscapes (Latawiec *et al* 2018, Liao and Brown 2018).

7. Conclusions: toward a sustainable rural resurgence in forest landscapes

This review brings out on an emergent theme regarding the driving forces that operate from regional to global scales to influence natural regeneration: expansion of intensified and mechanized agriculture in lowlands and, in many cases, associated abandonment of agricultural land, primarily in steep or mountainous areas that are poorly suited for this mode of agricultural expansion. In some cases, natural regeneration is associated with rural outmigration or remittance economies.

Reestablishing native forest cover does not have to require mass exodus of families and decline of rural livelihoods or traditions. We urge new ways of thinking about how natural regeneration, coupled with other solutions, may promote a rural resurgence where communities and local economies thrive along with expansion of native forests. One challenge for policy initiatives that promote natural regeneration is to address the social costs and drivers of rural outmigration. Enhancing natural regeneration of native forests is not a viable option for forest restoration if these changes fail to provide benefits for rural residents and forests are short-lived (Chazdon and Brancalion 2019).

In the new era of restoration, rural livelihoods can be re-envisioned through new opportunities created by growing native forests and trees in agricultural landscapes. For example, the Sustainable Rural Development Program of Rio de Janeiro State, Brazil has now become public policy involving community-based rural development in micro-watersheds with the support of rural organizations and decision-makers at local, municipal, and regional levels (Hissa *et al* 2019). Rural communities can become the stewards of community-managed forests that provide local, regional and global benefits. Forests of all kinds can contribute to prosperity (Miller and Hajjar 2020), a healthier society (Colfer 2012), and mitigate climate change (Griscom *et al* 2017). In many regions, youth and employable adults are leaving rural areas and abandoning a future relationship with land and with forests (Paudel *et al* 2014). We still have time to change these trends and promote rural resurgence based on proactive and integrated land management and landscape-scale restoration, where forests and new generations of people have room to grow and prosper together.

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Data availability statement

Any data that support the findings of this study are included within the article.

References

- Acevedo-Charry O and Aide T M 2019 Recovery of amphibian, reptile, bird and mammal diversity during secondary forest succession in the tropics *Oikos* **128** 1065–78
- Aguiar A P *et al* 2016 Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon? *Glob. Change Biol.* **22** 1821–40
- Aide T M, Grau H R, Graesser J, Andrade-Nuñez M J, Araújo E, Barros A P, Campos-Cerqueira M, Chacon-Moreno E, Francisco C C and Espinoza R 2019 Woody vegetation dynamics in the tropical and subtropical andes from 2001 to 2014: satellite image interpretation and expert validation *Glob. Change Biol.* **25** 2112–26
- Algeet-Abarquero N, Sánchez-Azofeifa A, Bonatti J and Marchamalo M 2015 Land cover dynamics in osa region, costa Rica: secondary forest is here to stay *Reg. Environ. Change* **15** 1461–72
- Almeida C A D, Coutinho A C, Esquerdo J C D M, Adami M, Venturieri A, Diniz C G, Dessay N, Durieux L and Gomes A R 2016 High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data *Acta Amazonica* **46** 291–302
- Anderson-Teixeira K J, Miller A D, Mohan J E, Hudiburg T W, Duval B D and Delucia E H 2013 Altered dynamics of forest recovery under a changing climate *Glob. Change Biol.* **19** 2001–21
- Arroyo-Mora J P, Sanchez-Azofeifa G A, Rivard B, Calvo J C and Janzen D H 2005 Dynamics in landscape structure and composition for the Chorotega region, Costa Rica from 1960 to 2000 *Agric. Ecosyst. Environ.* **106** 27–39
- Arroyo-Rodriguez V, Melo F, Martinez-Ramos M, Bongers F, Chazdon R, Meave J, Norden N, Santos B, Leal I and Tabarelli M 2017 Multiple successional pathways in human-modified tropical landscapes: new insights from forest succession, forest fragmentation and landscape ecology research *Biol. Rev.* **92** 326–40
- Asner G P, Rudel T K, Aide T M, Defries R and Emerson R 2009 A contemporary assessment of change in humid tropical forests *Conserv. Biol.* **23** 1386–95
- Azhar B, Lindenmayer D B, Wood J, Fischer J and Zakaria M 2014 Ecological impacts of oil palm agriculture on native mammal richness and feeding guilds in Peninsular Malaysia *Biodiversity Conservation* **23** 1175–91
- Baral H, Guariguata M R and Keenan R J 2016 A proposed framework for assessing ecosystem goods and services from planted forests *Ecosyst. Serv.* **22** 260–8
- Bastin J-F, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner C M and Crowther T W 2019 The global tree restoration potential *Science* **365** 76–9

- Benayas J, Martins A, Nicolau J and Schulz J 2007 Abandonment of agricultural land: an overview of drivers and consequences *CAB Rev.: Perspect. Agric., Veterinary Sci., Nutrition Nat. Resour.* **2** 1–14
- Bengtsson J, Angelstam P, Elmqvist T, Emanuelsson U, Folke C, Ihse M, Moberg F and Nyström M 2003 Reserves, resilience and dynamic landscapes *AMBIO: J. Human Environ.* **32** 389–96
- Biggs D 2018 Clearing, 'wasting,' and regreening: an environmental history of bare hills in central Vietnam *J. Asian Stud.* **77** 1037–58
- Bitencourt B S, Da Silva P G, Morato E F and De Lima Y G 2019 Dung beetle responses to successional stages in the amazon rainforest *Biodiversity Conservation* **28** 2745–61
- Boillat S, Scarpa F M, Robson J P, Gasparri I, Aide T M, Aguiar A P D, Anderson L O, Batistella M, Fonseca M G and Fudemma C 2017 Land system science in Latin America: challenges and perspectives *Curr. Opin. Environ. Sustain.* **26** 37–46
- Bonilla-Moheno M, Redo D J, Aide T M, Clark M L and Grau H R 2013 Vegetation change and land tenure in Mexico: a country-wide analysis *Land Use Policy* **30** 355–64
- Bonnesoeur V, Locatelli B, Guariguata M R, Ochoa-Tocachi B F, Vanacker V, Mao Z, Stokes A and Mathez-Stiefel S-L 2019 Impacts of forests and forestation on hydrological services in the andes: a systematic review *Forest Ecol. Manage.* **433** 569–84
- Borda-Niño M, Meli P and Brancalion P H S 2020 Drivers of tropical forest cover increase: a systematic review *Land Degrad. Dev.* Accepted (<https://doi.org/10.1002/ldr.3534>)
- Bowen M E, Mcalpine C A, Seabrook L M, House A P N and Smith G C 2009 The age and amount of regrowth forest in fragmented brigalow landscapes are both important for woodland dependent birds *Biol. Conservation* **142** 3051–9
- Brancalion P H, Schweizer D, Gaudare U, Manguera J R, Lamonato F, Farah F T, Nave A G and Rodrigues R R 2016 Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: the case of Brazil *Biotropica* **48** 856–67
- Brancalion P H et al 2019 Global restoration opportunities in tropical rainforest landscapes *Sci. Adv.* **5** eaav3223
- Bray D B 2016 Muir and pinchot in the sierra norte of oaxaca: governance of forest management and forest recovery in pueblos mancomunados *World Dev. Perspect.* **4** 8–10
- Bruton M J, Mcalpine C A and Maron M 2013 Regrowth woodlands are valuable habitat for reptile communities *Biol. Conservation* **165** 95–103
- Buitenwerf R, Sandel B, Normand S, Mimet A and Svenning J C 2018 Land surface greening suggests vigorous woody regrowth throughout European semi-natural vegetation *Glob. Change Biol.* **24** 5789–801
- Bullock J M, Aronson J, Newton A C, Pywell R F and Rey-Benayas J M 2011 Restoration of ecosystem services and biodiversity: conflicts and opportunities *Trends Ecol. Evol.* **26** 541–9
- Byg A, Novo P, Dinato M, Moges A, Tefera T, Balana B, Woldeamanuel T and Black H 2017 Trees, soils, and warthogs—distribution of services and disservices from reforestation areas in southern Ethiopia *Forest Policy Econ.* **84** 112–9
- Calaboni A, Tambosi L, Igari A, Farinaci J, Metzger J P and Uriarte M 2018 The forest transition in São Paulo, Brazil: historical patterns and potential drivers *Ecol. Soc.* **23**
- Calvo-Alvarado J, Jiménez V, Calvo-Obando A and Castillo M 2019 Current perspectives on forest recovery trends in Guanacaste, Costa Rica *Int. Forestry Rev.* **21** 425–31
- Camarretta N, Puletti N, Chiavetta U and Corona P 2018 Quantitative changes of forest landscapes over the last century across Italy *Plant Biosyst.—Int. J. Dealing Asp. Plant Biol.* **152** 1011–9
- Carvalho R, Adami M, Amaral S, Bezerra F G and De Aguiar A P D 2019 Changes in secondary vegetation dynamics in a context of decreasing deforestation rates in Pará, Brazilian Amazon *Appl. Geogr.* **106** 40–9
- Chazdon R and Brancalion P 2019 Restoring forests as a means to many ends *Science* **365** 24–5
- Chazdon R L 2014 *Second Growth: The Promise of Tropical Forest Regeneration in An Age of Deforestation* (Chicago, IL: University of Chicago Press)
- Chazdon R L 2019 Towards more effective integration of tropical forest restoration and conservation *Biotropica* **51** 463–72 Accepted
- Chazdon R L, Brancalion P H, Laestadius L, Bennett-Curry A, Buckingham K, Kumar C, Moll-Rocck J, Vieira I C G and Wilson S J 2016a When is a forest a forest ? Forest concepts and definitions in the era of forest and landscape restoration *Ambio* **45** 538–50
- Chazdon R L and Coe F G 1999 Ethnobotany of woody species in second-growth, old-growth, and selectively logged forests of northeastern Costa Rica *Conserv. Biol.* **13** 1312–22
- Chazdon R L and Guariguata M R 2016 Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges *Biotropica* **48** 716–30
- Chazdon R L, Peres C A, Dent D, Sheil D, Lugo A E, Lamb D, Stork N E and Miller S E 2009 The potential for species conservation in tropical secondary forests *Conserv. Biol.* **23** 1406–17
- Chazdon R L and Uriarte M 2016 Natural regeneration in the context of large-scale forest and landscape restoration in the tropics *Biotropica* **48** 709–15
- Chazdon R L et al 2016b Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics *Sci. Adv.* **2** e1501639
- Cleugh H 2003 *Trees for Shelter—A Guide to Using Windbreaks on Australian Farms* (Canberra: Rural Industries Research and Development Corporation)
- Cojzer M, Diaci J and Brus R 2014 Tending of young forests in secondary succession on abandoned agricultural lands: an experimental study *Forests* **5** 2658–78
- Colfer C J P 2012 *Human Health and Forests: A Global Overview of Issues, Practice, and Policy*. (London: Earthscan)
- Cramer V A, Hobbs R J and Standish R J 2008 What's new about old fields ? Land abandonment and ecosystem assembly *Trends Ecol. Evol.* **23** 104–12
- Crouzeilles R, Barros F S, Molin P G, Ferreira M S, Junqueira A B, Chazdon R L, Lindenmayer D B, Tymus J R C, Strassburg B B N and Brancalion P H S 2019 A new approach to map landscape variation in forest restoration success at the global scale *J. Appl. Ecol.* **56** 2675–86
- Crouzeilles R, Curran M, Ferreira M S, Lindenmayer D B, Grelle C E and Benayas J M R 2016 A global meta-analysis on the ecological drivers of forest restoration success *Nat. Commun.* **7**
- Crouzeilles R, Ferreira M S, Chazdon R L, Lindenmayer D, Sansevero J B B, Monteiro L, Iribarrem A, Latawiec A and Strassburg B B N 2017 Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests *Sci. Adv.* **3** e1701345
- Crouzeilles R et al 2020 Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration *Conservation Lett.* Accepted (<https://doi.org/10.1111/conl.12709>)
- Cruz-Alonso V, Ruiz-Benito P, Villar-Salvador P and Rey-Benayas J M 2019 Long-term recovery of multifunctionality in mediterranean forests depends on restoration strategy and forest type *J. Appl. Ecol.* **56** 745–57
- Da Cruz D C, Rey Benayas J M, Ferreira G C, Santos S R and Schwartz G 2020 An overview of forest loss and restoration in the Brazilian Amazon *New Forests* (<https://doi.org/10.1007/s11056-020-09777-3>)
- Da Silva R F B, Batistella M, Moran E F and Lu D 2017 Land changes fostering Atlantic Forest transition in Brazil: evidence from the Paraíba Valley *Prof. Geogr.* **69** 80–93
- Díaz S et al 2019 Summary for policymakers of the global assessment report of the Intergovernmental science-policy platform on biodiversity and ecosystem services, Bonn, IPBES Secretariat, p 39 (https://ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf)

- Ding H, Altamirano J C, Anchondo A, Faruqi S, Verdone M, Wu A, Zamora R, Chazdon R and Vergara W 2017 *Roots of Prosperity: The Economics and Finance of Restoring Land* (Washington, DC: World Resources Institute)
- Duangjai W, Schmidt-Vogt D and Shrestha R P 2015 Farmers' land use decision-making in the context of changing land and conservation policies: a case study of doi mae salong in Chiang Rai province, Northern Thailand *Land Use Policy* **48** 179–89
- Duncan R S and Chapman C A 1999 Seed dispersal and potential forest succession in abandoned agriculture in tropical Africa *Ecol. Appl.* **9** 998–1008
- Dupuy J M and Chazdon R L 2008 Interacting effects of canopy gap, understory vegetation and leaf litter on tree seedling recruitment and composition in tropical secondary forests *Forest Ecol. Manage.* **255** 3716–25
- Evans L J, Goossens B and Asner G P 2017 Underproductive agriculture aids connectivity in tropical forests *Forest Ecol. Manage.* **401** 159–65
- Evaristo J and McDonnell J J 2019 Global analysis of streamflow response to forest management *Nature* **570** 455–61
- Fantini A C, Schuch C, Siminski A and Siddique I 2019 Small-scale management of secondary forests in the Brazilian Atlantic forest *Floresta e Ambiente* **26**
- FAO & Global Mechanism Of The UNCCD 2015 Sustainable financing for forest and landscape restoration: opportunities, challenges and the way forward *Discussion Paper* (Rome: FAO and UNCCD)
- Ferguson J M 2014 The scramble for the waste lands: tracking colonial legacies, counterinsurgency and international investment through the lens of land laws in Burma/Myanmar *Singap. J. Tropical Geogr.* **35** 295–311
- Filoso S, Bezerra M O, Weiss K C and Palmer M A 2017 Impacts of forest restoration on water yield: a systematic review *PLoS One* **12** e0183210
- Filotas E et al 2014 Viewing forests through the lens of complex systems science *Ecosphere* **5** art1
- Fischer J, Stott J, Zerger A, Warren G, Sherren K and Forrester R I 2009 Reversing a tree regeneration crisis in an endangered ecoregion *Proc. Natl Acad. Sci.* **106** 10386–91
- Forero-Montaña J, Marcano-Vega H, Zimmerman J K and Brandeis T J 2019 Potential of second-growth Neotropical forests for forestry: the example of Puerto Rico *Forests, Trees Livelihoods* **28** 1–16
- Franklin J F, Lindenmayer D B, Macmahon J A, Mckee A, Magnuson J, Perry D A, Waide R and Foster D R 2000 Threads of continuity *Conservation Biol. Pract.* **1** 8–16.
- García-Barrios L, Galvan-Miyoshi Y M, Valdivieso-Perez I A, Masera O R, Bocco G and Vandermeer J 2009 Neotropical forest conservation, agricultural intensification, and rural out-migration: the Mexican experience *Bioscience* **59** 863–73
- Gardner C J, Bicknell J E, Baldwin-Cantello W, Streubig M J and Davies Z G 2019 Quantifying the impacts of defaunation on natural forest regeneration in a global meta-analysis *Nat. Commun.* **10** 4590
- Geddes L S, Lunt I D, Smallbone L T and Morgan J W 2011 Old field colonization by native trees and shrubs following land use change: could this be Victoria's largest example of landscape recovery? *Ecol. Manage. Restor.* **12** 31–6
- Ghazoul J, Burivalova Z, García-Ulloa J and King L A 2015 Conceptualizing forest degradation *Trends Ecol. Evol.* **30** 622–32
- Ghazoul J and Chazdon R L 2017 Degradation and recovery in changing forest landscapes: a multiscale conceptual framework *Annu. Rev. Environ. Resour.* **42** 161–88
- Goldsmith G R, Comita L S and Chua S C 2011 Evidence for arrested succession within a tropical forest fragment in Singapore *J. Tropical Ecol.* **27** 323–6
- Griscom B W, Adams J, Ellis P W, Houghton R A, Lomax G, Miteva D A, Schlesinger W H, Shoch D, Siikamäki J V and Smith P 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
- Guariguata M R 1999 Early response of selected tree species to liberation thinning in a young secondary forest in Northeastern Costa Rica *Forest Ecol. Manage.* **124** 255–61
- Guevara S, Laborde J and Sanchez-Rios G 2005 The trees the forest left behind *Interciencia* **30** 595
- Hecht S, Yang A L, Basnett B S, Padoch C and Peluso N L 2015 *People in Motion, Forests in Transition: Trends in Migration, Urbanization, and Remittances and their Effects on Tropical Forests* (Bogor, Indonesia: CIFOR) (<https://doi.org/10.17528/cifor/005762>)
- Hecht S B, Morrison K D and Padoch C 2014 *The Social Lives of Forests: Past, Present, and Future of Woodland Resurgence* (Chicago, IL: University of Chicago Press)
- Hernández-X E, Levy-Tacher S I and Bello-Baltazar Y E 1995 La roza-tumba-quema en Yucatán ed E Hernández-X et al *La milpa en Yucatán: un sistema de producción agrícola tradicional* (México: Colegio de)
- Hissa H R, Alves Filho N T, Costa M, Strauch G, Bassi L and Assis, R. L. D E 2019 Sustainable rural development in Rio de Janeiro state: the Rio rural program *Strategies and Tools for a Sustainable Rural Rio de Janeiro* (Berlin: Springer)
- Holl K D 2017 Restoring tropical forests from the bottom up *Science* **355** 455–6
- Holl K D and Aide T M 2011 When and where to actively restore ecosystems? *Forest Ecol. Manage.* **261** 1558–63
- Holl K D, Reid J L, Oviedo-Brenes F, Kulikowski A J and Zahawi R A 2018 Rules of thumb for predicting tropical forest recovery *Appl. Veg. Sci.* **21** 669–77
- Hoosbeek M R, Remme R P and Rusch G M 2016 Trees enhance soil carbon sequestration and nutrient cycling in a silvopastoral system in south-western Nicaragua *Agroforestry Syst.* **92** 1–11
- Houghton R, Byers B and Nassikas A A 2015 A role for tropical forests in stabilizing atmospheric CO₂ *Nat. Clim. Change* **5** 1022–3
- Houghton R and Nassikas A A 2017 Global and regional fluxes of carbon from land use and land cover change 1850–2015 *Glob. Biogeochem. Cycles* **31** 456–72
- Hua F, Wang L, Fisher B, Zheng X, Wang X, Douglas W Y, Tang Y, Zhu J and Wilcove D S 2018 Tree plantations displacing native forests: the nature and drivers of apparent forest recovery on former croplands in Southwestern China from 2000 to 2015 *Biol. Conservation* **222** 113–24
- Isbell F, Tilman D, Reich P B and Clark A T 2019 Deficits of biodiversity and productivity linger a century after agricultural abandonment *Nat. Ecol. Evol.* **3** 1533–8
- Jactel H, Bauhus J, Boberg J, Bonal D, Castagnèrol B, Gardiner B, Gonzalez-Olabarria J R, Koricheva J, Meurisse N and Brockerhoff E G 2017 Tree diversity drives forest stand resistance to natural disturbances *Curr. Forestry Rep.* **3** 223–43
- Jadin I, Meyfroidt P and Lambin E 2016 International trade, and land use intensification and spatial reorganization explain Costa Rica's forest transition *Environ. Res. Lett.* **11** 035005
- Jakovac C C, Bongers F, Kuypers T W, Mesquita R C and Peña-Claros M 2016 Land use as a filter for species composition in Amazonian secondary forests *J. Vegetation Sci.* **27** 1104–16
- Jakovac C C, Peña-Claros M, Kuypers T W and Bongers F 2015 Loss of secondary-forest resilience by land-use intensification in the Amazon *J. Ecol.* **103** 67–77
- Johnstone J F, Allen C D, Franklin J F, Frelich L E, Harvey B J, Higuera P E, Mack M C, Meentemeyer R K, Metz M R and Perry G L 2016 Changing disturbance regimes, ecological memory, and forest resilience *Frontiers Ecol. Environ.* **14** 369–78
- Jones H P, Jones P C, Barbier E B, Blackburn R C, Benayas J M R, Holl K D, Mccrackin M, Meli P, Montoya D and Mateos D M 2018 Restoration and repair of Earth's damaged ecosystems *Proc. R. Soc. B* **285** 20172577
- Jones I L, Dewalt S J, Lopez O R, Bunnefeld L, Pattison Z and Dent D H 2019 Above- and belowground carbon stocks are decoupled in secondary tropical forests and are positively

- related to forest age and soil nutrients respectively *Sci. Total Environ.* **697** 133987
- Kammesheidt L 2002 Perspectives on secondary forest management in tropical humid lowland America *Ambio* **31** 243–50
- Kowler L F, Ravikumar A, Larson A M, Rodriguez-Ward D, Burga C and Gonzales Tovar J 2016 Analyzing multilevel governance in Peru *Working Paper 203* (Bogor, Indonesia: CIFOR) (http://www.cifor.org/publications/pdf_files/WPapers/WP203Kowler.pdf)
- Kremen C and Merenlender A M 2018 Landscapes that work for biodiversity and people *Science* **362** eaau6020
- Lacombe G, Ribolzi O, De Rouw A, Pierret A, Latschak K, Silvera N, Pham Dinh R, Orange D, Janeau J and Soullieuth B 2015 Afforestation by natural regeneration or by tree planting: examples of opposite hydrological impacts evidenced by long-term field monitoring in the humid tropics *Hydrol. Earth Syst. Sci. Discuss.* **12** 12615–48
- Lambin E F and Meyfroidt P 2010 Land use transitions: Socio-ecological feedback versus socio-economic change *Land Use Policy* **27** 108–18
- Lasanta T, Arnáez J, Pascual N, Ruiz-Flaño P, Errea M P and Lana-Renault N 2017 Space-time process and drivers of land abandonment in Europe *Catena* **149** 810–23
- Latawiec A E, Dos Santos J S, Maioli V, Junqueira A B, Crouzeilles R, Jakovac C C, Tubenchlak F and Strassburg B N 2018 Forest landscape restoration and land sparing—sharing: shifting the focus towards nature’s contributions to people ed S Mansourian and J Parrotta *Forest Landscape Restoration* (London: Routledge) pp 116–34
- Lembani R L, Knight J and Adam E 2019 Use of Landsat multi-temporal imagery to assess secondary growth Miombo woodlands in Luanshya, Zambia *Sothern Forests* **81** 129–40
- Lennox G D *et al* 2018 Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests *Glob. Change Biol.* **24** 5680–94
- Levy-Tacher S, Ramírez-Marcial N, González-Espinosa M and Román-Dañobeytia F 2012 Rehabilitación ecológica de áreas agropecuarias degradadas en la selva lacandona: una alternativa fincada en el conocimiento ecológico tradicional maya *La otra innovación para el ambiente y la sociedad en la frontera sur de México* ed E Bello Baltazar *et al* (San Cristóbal de Las Casas, Chiapas: ECOSUR) pp 248–58
- Levy-Tacher S I, Ramírez-Marcial N, Navarrete-Gutiérrez D A and Rodríguez-Sánchez P V 2019 Are Mayan community forest reserves effective in fulfilling people’s needs and preserving tree species? *J. Environ. Manage.* **245** 16–27
- Li S and Li X 2017 Global understanding of farmland abandonment: a review and prospects *J. Geog. Sci.* **27** 1123–50
- Liao C and Brown D G 2018 Assessments of synergistic outcomes from sustainable intensification of agriculture need to include smallholder livelihoods with food production and ecosystem services *Curr. Opin. Environ. Sustain.* **32** 53–9
- Lindenmayer D, Michael D, Crane M and Florance D 2018 Ten lessons in 20 years: insights from monitoring fauna and temperate woodland revegetation *Ecol. Manage. Restor.* **19** 36–43
- Lindenmayer D, Michael D, Crane M, Okada S, Ikin K, Barton P and Florance D 2016 *Wildlife Conservation in Farm Landscapes* (Melbourne: CSIRO Publishing)
- Lindenmayer D B, Lane P, Crane M, Florance D, Foster C N, Kin K, Michael D, Sato C F, Scheele B C and Westgate M J 2019 Weather effects on birds of different size are mediated by long-term climate and vegetation type in endangered temperate woodlands *Glob. Change Biol.* **25** 675–85
- Lindenmayer D B, Northrop-Mackie A R, Montague-Drake R, Crane M, Michael D, Okada S and Gibbons P 2012 Not all kinds of revegetation are created equal: revegetation type influences bird assemblages in threatened Australian woodland ecosystems *PLoS One* **7** e34527
- Lira P K, Tambosi L R, Ewers R M and Metzger J P 2012 Land-use and land-cover change in atlantic forest landscapes *Forest Ecol. Manage.* **278** 80–9
- Locatelli B, Catterall C P, Imbach P, Kumar C, Lasco R, Marin-Spiotta E, Mercer B, Powers J S, Schwartz N and Uriarte M 2015 Tropical reforestation and climate change: beyond carbon *Restor. Ecol.* **23** 337–43
- Lozano-Baez S, Cooper M, Frosini De Barros Ferraz S, Ribeiro Rodrigues R, Castellini M and Di Prima S 2019 Recovery of soil hydraulic properties for assisted passive and active restoration: assessing historical land use and forest structure *Water* **11** 86
- Maier T F, Benini R D M, Fachini C, Alves D E and Santana P J 2018 Financial analysis of enrichment model using timber and non-timber products of secondary remnants in the atlantic forest *Rev. Árvore* **42** e420602
- Mancino G, Nolè A, Ripullone F and Ferrara A 2014 Landsat TM imagery and NDVI differencing to detect vegetation change: assessing natural forest expansion in Basilicata, southern Italy *iForest-Biogeosci. Forestry* **7** 75
- Martin A, Coolsaet B, Corbera E, Dawson N, Fisher J, Franks P, Mertz O, Pascual U, Rasmussen L V and Ryan C 2018 Land use intensification: the promise of sustainability and the reality of trade-offs *Ecosystem Services and Poverty Alleviation (OPEN ACCESS)* ed K Schreckenberg, G Mace and M Poudyal (London: Routledge) pp 94–110
- Matos F A, Magnago L F S, Aquila Chan Miranda C, De Menezes L F T, Gastauer M, Safar N V, Schaefer C E G R, Da Silva M P, Simonelli M and Edwards F A 2019 Secondary forest fragments offer important carbon-biodiversity co-benefits *Glob. Change Biol.* (<https://doi.org/10.1111/gcb.14824>)
- Mekuria W, Wondie M, Amare T, Wubet A, Feyisa T and Yitafaru B 2018 Restoration of degraded landscapes for ecosystem services in North-Western Ethiopia *Heliyon* **4** e00764
- Meli P, Holl K D, Benayas J M R, Jones H P, Jones P C, Montoya D and Mateos D M 2017 A global review of past land use, climate, and active vs. passive restoration effects on forest recovery *PLoS One* **12** e0171368
- Mesquita R D C G 2000 Management of advanced regeneration in secondary forests of the Brazilian Amazon *Forest Ecol. Manage.* **130** 131–40
- Miller D C and Hajjar R 2020 Forests as pathways to prosperity: empirical insights and conceptual advances *World Dev.* **15** 104647
- Molin P G, Chazdon R L, Ferraz S F and Brancalion P H S 2018 A landscape approach for cost-effective large-scale forest restoration *J. Appl. Ecol.* **55** 2767–78
- Müller H, Rufin P, Griffiths P, Hissa L D B V and Hostert P 2016 Beyond deforestation: differences in long-term regrowth dynamics across land use regimes in southern Amazonia *Remote Sens. Environ.* **186** 652–62
- Nanni A S, Sloan S, Aide T M, Graesser J, Edwards D and Grau H R 2019 The neotropical reforestation hotspots: a biophysical and socioeconomic typology of contemporary forest expansion *Glob. Environ. Change* **54** 148–59
- Navarro L M and Pereira H M 2015 Rewilding abandoned landscapes in Europe *Rewilding European Landscapes* (Berlin: Springer)
- Newmark W D, Jenkins C N, Pimm S L, Mcneally P B and Halley J M 2017 Targeted habitat restoration can reduce extinction rates in fragmented forests *Proc. Natl Acad. Sci.* **114** 9635–40
- Nunes F S, Soares-Filho B S, Rajão R and Merry F 2017 Enabling large-scale forest restoration in minas gerais state, Brazil *Environ. Res. Lett.* **12** 044022
- Oldekop J A, Sims K R, Whittingham M J and Agrawal A 2018 An upside to globalization: international outmigration drives reforestation in Nepal *Glob. Environ. Change* **52** 66–74
- Ospina D, Peterson G and Crépin A-S 2019 Migrant remittances can reduce the potential of local forest transitions—a social-ecological regime shift analysis *Environ. Res. Lett.* **14** 024017
- Pan Y D *et al* 2011 A large and persistent carbon sink in the world’s forests *Science* **333** 988–93
- Paquette A, Hawryshyn J, Senikas A V and Potvin C 2009 Enrichment planting in secondary forests: a promising clean

- development mechanism to increase terrestrial carbon sinks *Ecol. Soc.* **14** 31
- Paudel K P, Tamang S and Shrestha K K 2014 Transforming land and livelihood: analysis of agricultural land abandonment in the mid hills of Nepal *J. Forest Livelihood* **12** 11–9
- Peltier R, Dubiez É, Diowo S, Gigaud M, Marien J N, Marquant B, Peroches A, Proce P and Vermeulen C 2014 Assisted natural regeneration in slash-and-burn agriculture: results in the democratic republic of the congo *Bois Forets Tropiques* **68** 67–79
- Perino A et al 2019 Rewilding complex ecosystems *Science* **364** eaav5570
- Pignataro A G, Levy-Tacher S I, Aguirre-Rivera J R, Nahed-Toral J, González-Espinosa M, González-Arzac A and Biganzoli F 2017 Natural regeneration of tree species in pastures on peasant land in Chiapas, Mexico *Agricul., Ecosyst. Environ.* **249** 137–43
- Porras I and Chacón-Cascante A 2018 Costa Rica's payments for ecosystem services programme. Case study Module 2 ed I Porras and N Asquith *Ecosystems, Poverty Alleviation and Conditional Transfers*. (London: International Institute for Environment and Development)
- Potapov P V, Turubanova S, Tyukavina A, Krylov A, Mccarty J, Radeloff V and Hansen M 2015 Eastern Europe's forest cover dynamics from 1985 to 2012 quantified from the full Landsat archive *Remote Sens. Environ.* **159** 28–43
- Pugh T A, Lindeskog M, Smith B, Poulter B, Arneeth A, Haverd V and Calle L 2019 Role of forest regrowth in global carbon sink dynamics *Proc. Natl Acad. Sci.* **116** 4382–7
- Queiroz C, Beilin R, Folke C and Lindborg R 2014 Farmland abandonment: threat or opportunity for biodiversity conservation? A global review *Frontiers Ecol. Environ.* **12** 288–96
- Quintero I and Roslin T 2005 Rapid recovery of dung beetle communities following habitat fragmentation in Central Amazonia *Ecology* **86** 3303–11
- Rasmussen L V, Coolsaet B, Martin A, Mertz O, Pascual U, Corbera E, Dawson N, Fisher J A, Franks P and Ryan C M 2018 Social-ecological outcomes of agricultural intensification *Nat. Sustain.* **1** 275
- Reid J L, Fagan M E, Lucas J, Slaughter J and Zahawi R A 2019 The ephemerality of secondary forests in southern Costa Rica *Conservation Lett.* **12** e12607
- Rey Benayas J M, Bullock J M and Newton A C 2008 Creating woodland islets to reconcile ecological restoration, conservation, and agricultural land use *Frontiers Ecol. Environ.* **6** 329–36
- Rezende C L, Uezu A, Scarano F R and Araujo D S D 2015 Atlantic forest spontaneous regeneration at landscape scale *Biodiversity Conservation* **24** 2255–72
- Rocha R, Ovaskainen O, López-Baucells A, Farneda F Z, Sampaio E M, Bobrowiec P E, Cabeza M, Palmeirim J M and Meyer C F 2018 Secondary forest regeneration benefits old-growth specialist bats in a fragmented tropical landscape *Sci. Rep.* **8** 3819
- Román-Dañobeytia F J, Levy-Tacher S I, Macario-Mendoza P and Zúñiga-Morales J 2014 Redefining secondary forests in the Mexican Forest Code: implications for management, restoration, and conservation *Forests* **5** 978–91
- Rozendaal D M A et al 2019 Biodiversity recovery of neotropical secondary forests *Sci. Adv.* **5** eaau3114
- Rudel T K 2005 *Tropical Forests: Regional Paths of Destruction and Regeneration in the late Twentieth Century* (New York: Columbia University Press)
- Rudel T K, Sloan S, Chazdon R and Grau R 2016 The drivers of tree cover expansion: Global, temperate, and tropical zone analyses *Land Use Policy* **58** 502–13
- Saha S, Kuehne C and Bauhus J 2016 Lessons learned from oak cluster planting trials in central Europe *Can. J. For. Res.* **47** 139–48
- Sato C F, Florance D and Lindenmayer D B 2019 Drivers of temperate woodland condition through time in an agricultural landscape *Land Degrad. Dev.* **30** 1357–67
- Sayer J, Ghazoul J, Nelson P and Boedihartono A K 2012 Oil palm expansion transforms tropical landscapes and livelihoods *Glob. Food Secur.* **1** 114–9
- Schwartz N B, Uriarte M, Defries R, Gutierrez-Velez V and Pinedo-Vasquez M 2017 Land-use dynamics influence estimates of carbon sequestration potential in tropical second-growth forest *Environ. Res. Lett.* **12** 074023
- Schweizer D, Meli P, Brancalion P H S and Guariguata M R 2020 Implementing forest landscape restoration in Latin America: stakeholder perceptions on legal frameworks *Land Use Policy* (<https://doi.org/10.1016/j.landusepol.2019.104244>)
- Sears R, Choden K, Dorji T, Dukpa D, Phuntsho S, Rai P, Wangchuk J and Baral H 2018a Bhutan's forests through the framework of ecosystem services: rapid assessment in three forest types *Forests* **9** 675
- Sears R R, Cronkleton P, Villanueva F P, Ruiz M M and Del Arco M P-O 2018b Farm-forestry in the peruvian amazon and the feasibility of its regulation through forest policy reform *Forest Policy Econ.* **87** 49–58
- Shaver I, Chain-Guadarrama A, Cleary K A, Sanfiorenzo A, Santiago-García R J, Finegan B, Hormel L, Sibelet N, Vierling L A and Bosque-Pérez N A 2015 Coupled social and ecological outcomes of agricultural intensification in Costa Rica and the future of biodiversity conservation in tropical agricultural regions *Glob. Environ. Change* **32** 74–86
- Sitzia T, Semenzato P and Trentanovi G 2010 Natural reforestation is changing spatial patterns of rural mountain and hill landscapes: a global overview *Forest Ecol. Manage.* **259** 1354–62
- Sloan S 2015 The development-driven forest transition and its utility for REDD *Ecol. Econ.* **116** 1–11
- Sloan S, Goosem M and Laurance S G 2016 Tropical forest regeneration following land abandonment is driven by primary rainforest distribution in an old pastoral region *Landscape Ecol.* **31** 601–18
- Smale M, Tappan G and Reij C 2018 Farmer-managed restoration of agroforestry parklands in Niger *Fostering Transformation and Growth in Niger's Agricultural Sector* (Wageningen: Academic Publishers) ch 1
- Solar R R D C et al 2015 How pervasive is biotic homogenization in human-modified tropical forest landscapes? *Ecol. Lett.* **18** 1108–18
- Song X-P, Hansen M C, Stehman S V, Potapov P V, Tyukavina A, Vermote E F and Townshend J R 2018 Global land change from 1982 to 2016 *Nature* **560** 639
- Souza S E, Vidal E, Chagas G D F, Elgar A T and Brancalion P H 2016 Ecological outcomes and livelihood benefits of community-managed agroforests and second growth forests in Southeast Brazil *Biotropica* **48** 868–81
- Stelling F, Allan C and Thwaites R 2018 An ambivalent landscape: the return of nature to post-agricultural land in South-eastern Australia *Landscape Res.* **43** 329–44
- Stem C J, Lassoe J P, Lee D R, Deshler D D and Schelhas J W 2003 Community participation in ecotourism benefits: the link to conservation practices and perspectives *Soc. Nat. Resour.* **16** 387–413
- Stouffer P C, Johnson E I, Bierregaard R O and Lovejoy T E 2011 Understorey bird communities in Amazonian rainforest fragments: species turnover through 25 years post-isolation in recovering landscapes *PLoS One* **6** e20543
- Strassburg B N, Barros F S M, Couzeilles R, Iribarrem A, Santos J S, Silva D, Sansevero J B B, Alves-Pinto H, Feltran-Barbieri R and Latawiec A 2016 The role of natural regeneration to ecosystem services provision and habitat availability: a case study in the Brazilian Atlantic Forest *Biotropica* **48** 890–9
- Suding K N, Gross K L and Houseman G R 2004 Alternative states and positive feedbacks in restoration ecology *Trends Ecol. Evol.* **19** 46–53
- Thers H, Bøcher P K and Svenning J C 2019 Using lidar to assess the development of structural diversity in forests undergoing passive rewilding in temperate Northern Europe *Peer J.* **6** e6219

- Uriarte M and Chazdon R L 2016 Incorporating natural regeneration in forest landscape restoration in tropical regions: synthesis and key research gaps *Biotropica* **48** 915–24
- Uriarte M, Lasky J R, Boukili V K and Chazdon R L 2016a A trait-mediated, neighbourhood approach to quantify climate impacts on successional dynamics of tropical rainforests *Funct. Ecol.* **30** 157–67
- Uriarte M, Schwartz N B, Powers J S, Marin-Spiotta E, Liao W and Werden L 2016b Impacts of climate variability on tree demography in second-growth tropical forests: the importance of regional context for forest landscape restoration outcomes *Biotropica* **48** 780–97
- Vallejo R, Torres-Quevedo M, Robla E and Viejo C 2014 *Evaluación de los recursos forestales mundiales* (España: Informe nacional)
- Van Vooren L, Bertb R, Broeckx S, De Frenne P, Nelissen V, Pardon P and Verheyen K 2017 Ecosystem service delivery of agri-environment measures: a synthesis for hedgerows and grass strips on arable land *Agric., Ecosyst. Environ.* **244** 32–51
- Verburg P H and Overmars K P 2009 Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model *Landscape Ecol.* **24** 1167–81
- Vieira I C G, Gardner T, Ferreira J, Lees A C and Barlow J 2014 Challenges of governing second-growth forests: a case study from the Brazilian Amazonian State of Pará *Forests* **5** 1737–52
- Von Thaden J J, Laborde J, Guevara S and Venegas-Barrera C S 2018 Forest cover change in the los tuxtlas biosphere reserve and its future: the contribution of the 1998 protected natural area decree *Land Use Policy* **72** 443–50
- Wang Y, Ziv G, Adami M, Almeida C. A. d., Antunes J F G, Coutinho A C, Esquerdo J C D M, Gomes A R and Galbraith D 2020 Upturn in secondary forest clearing buffers primary forest loss in the Brazilian Amazon *Nat. Sustain.* (<https://doi.org/10.1038/s41893-019-0470-4>)
- Wilson S J, Schelhas J, Grau R, Nanni A S and Sloan S 2017 Forest ecosystem-service transitions: the ecological dimensions of the forest transition *Ecol. Soc.* **22** 38
- Wolde A, Amsalu T and Mekonnen M 2016 Social and economic impacts of community managed reforestation and natural regeneration of forestry development, the case of Humbo District, Ethiopia *Environ. Nat. Resour. Res.* **6** 36
- Wood S L, Rhemtulla J M and Coomes O T 2016 Intensification of tropical fallow-based agriculture: trading-off ecosystem services for economic gain in shifting cultivation landscapes? *Agric. Ecosyst. Environ.* **215** 47–56
- Yang Y, Wang L, Yang Z, Xu C, Xie J, Chen G, Lin C, Guo J, Liu X and Xiong D 2018 Large ecosystem service benefits of assisted natural regeneration *J. Geophys. Res.: Biogeosci.* **123** 676–87
- Zahawi R A, Reid J L and Holl K D 2014 Hidden costs of passive restoration *Restor. Ecol.* **22** 284–7