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TOPICAL REVIEW

Fostering natural forest regeneration on former agricultural land through economic and policy interventions

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Abstract

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 km^2 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

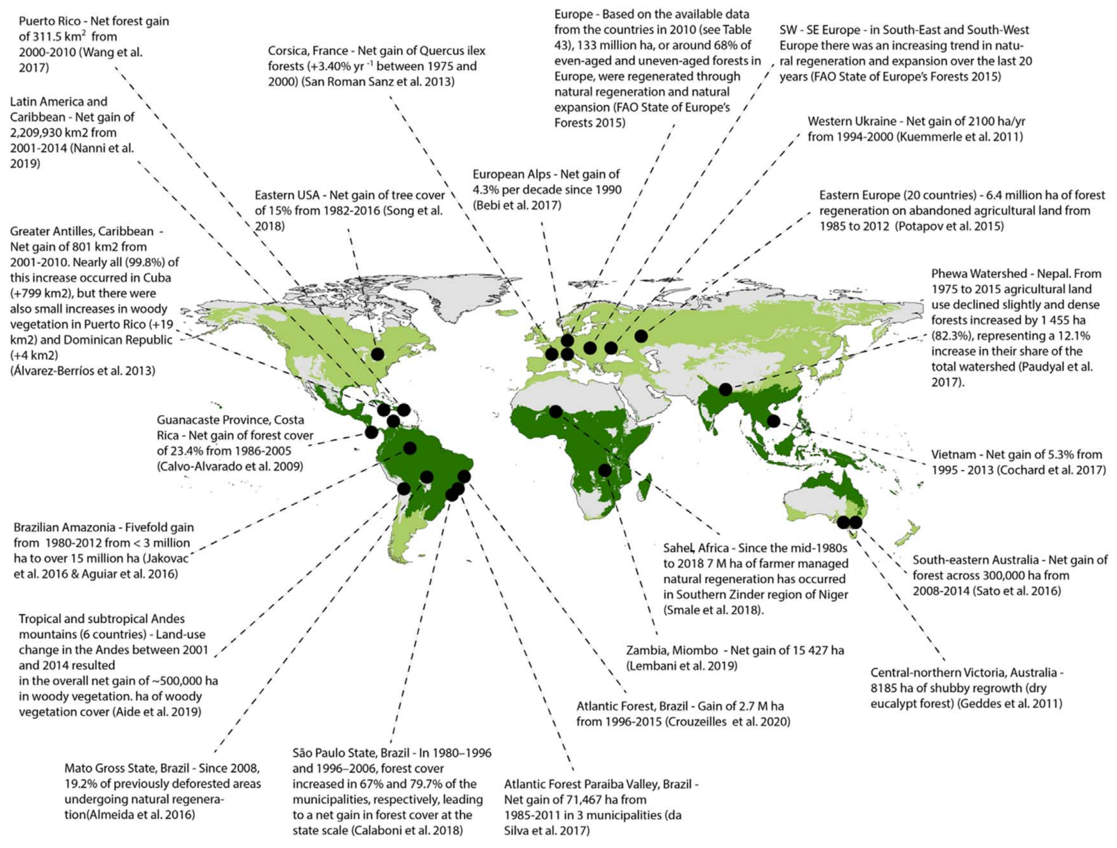

Figure 1. Documented cases of large-scale natural forest regeneration in agricultural landscapes in temperate, tropical, and subtropical forest regions of the world. These illustrative studies vary in the time frames of analysis and in the metrics used to report changes in naturally regenerating forest 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-Rodriguez *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 km^2 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 km^2 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 km^2 of regenerating forests ($<$100 year old) within the lowland Neotropics compared to 4.0 million km^2 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 (Brancalion 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 km^2 of forest over 20 years. Across the entire Atlantic Forest region of Brazil, 210 000 km^2 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 km^2 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 km^2 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 km^2 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 km^2, representing 11% of the region's land area. One of these regions was the tropical Andes, where 5000 km^2 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 Paraiba 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 km^2 of deforested land, 27 000 km^2 of forest regenerated naturally from 1996 to 2015, and a predictive model estimated that another 28 000 km^2 could regrow between 2015 and 2035 without human assistance (Crouzeilles *et al* 2020). Using assisted natural regeneration methods, an additional 188 000 km^2 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 km^2 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 though 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 (Brancalion *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 km^2 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 (Brancalion *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
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 Brancalion 2019). However, policies and mechanisms to empower holistic solutions—including expansion of agroforestry and silvopastoral systems—are underdeveloped (Kremen and Merenlender 2018, Chazdon and Brancalion 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 (Brancalion *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.

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