Amazon Assessment Report 2021

Chapter 29

Restoration priorities and benefits within landscapes and catchments and across the Amazon basin in the Amazon

Rio Parima na Terra Indígena Yanomami (Foto: Bruno Kelly/Amazônia Real)

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Graphical Abstract

Figure 29.A Graphical Abstract

Restoration Priorities and Benefits within Landscapes and Catchments and Across the Amazon Basin

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Key Messages

- Identifying priority locations for restoration across the Amazon Basin is highly dependent on the objectives (e.g., increasing carbon stocks or conserving threatened species). These priority regions must be identified through participatory approaches involving local peoples and governments, supported by up-to-date scientific evidence.
- Considering where and how to restore at the catchment or landscape scale can help return much higher social and ecological benefits than simple site-based approaches.
- Implementing restoration at the landscape and catchment scale must consider a broad range of restoration options, from encouraging the natural regeneration of secondary forests to restoring economic activities in degraded lands. This will help ensure restoration delivers the greatest benefits to the broadest range of stakeholders.
- Restoring ecosystems in the context of climate change requires rebuilding ecosystems that are resilient to higher temperatures, droughts, and climate extremes.
- Restoration strategies will be more effective if they involve complementary conservation measures, such as the protection of remaining natural forests and free flowing rivers (see Chapter 27).
- For long-term success, restoration policies and programs must generate socioeconomic benefits for local populations (e.g., food security, employment, and income opportunities) and raise awareness of the benefits that forests and other natural systems provide

Abstract

Restoration can be applied in many different Amazonian contexts but will be most effective at leveraging environmental and social benefits when it is prioritized across the Amazon Basin and within landscapes and catchments. Here we outline the considerations that are most relevant for planning and scaling restoration.

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29.1. Introduction

When restoration has been identified as an important action to achieve a particular target (e.g. Chapter 28), the first tier of prioritization involves identifying which areas to restore. Across ecosystems, systematic conservation planning aims to support decision making regarding the allocation of resources (Margules and Pressey 2000). These approaches have been widely used to help identify priority areas for conservation or restoration across the world (e.g. Strassburg *et al.,* 2020) and within catchments (e.g. Beechie *et al.,* 2008; McIntosh *et al.,* 2017). In this chapter, we go beyond the specific restoration options outlined in Chapter 28 to examine benefits of planning conservation across the basin, in catchments, and in landscapes. We then outline how restoration can be used to encourage a favorable forest cover transition in the Amazon, before outlining some of the crucial societal benefits. Finally, we explore the resilience of restoration to climate change, and examine measures which could help encourage large-scale restoration across the Amazon.

29.2. Prioritizing restoration actions across the Amazon Basin

Despite a growing number of global and ecosystem level prioritization exercises (Crouzeilles *et al.,* 2020; Strassburg *et al.,* 2020), very few formal analyses exist prioritizing restoration actions across the Amazon Basin or identifying optimal scenarios to realize multiple aims. Here we outline some of the key ecological and societal benefits that could be attained from a large-scale, basin-wide restoration program.

29.2.1. Conservation of the Amazon's threatened species and unique ecosystems

Habitat loss is the main cause of biodiversity loss globally and it is not surprising that the most threatened forest-dependent birds in the Amazon have distributions coinciding with the most deforested and degraded regions such as Andean slopes and the "Arc of Deforestation" (Bird *et al.,* 2010). In these regions, restoration could play a key role in supporting the conservation of forest-dependent species (Figure 29.1), including the recently rediscovered Belem Curassow *Crax [fasciolata] pinima* (Alteff *et al.,* 2019), Black-winged Trumpeter *Psophia obscura*, and the Kaapori capuchin *Cebus kaapori*, which was only described in 1992. All of these species are Critically Endangered according to the IUCN's Red List of Threatened Species. However, the first priority in these regions is avoiding further deforestation and degradation by protecting existing forests from logging and forest fires (Chapter 27; Silva Junior *et al.,* 2020). This needs to be accompanied by measures that reduce hunting pressure, by tackling commercial hunting and illegal trade, providing alternative livelihoods to communities dependent on bushmeat, changing cultural attitudes, encouraging community-based management with local benefits such as from ecotourism (Bragagnolo *et al.,* 2019) or even incentivizing alternative hunting practices such as using dogs that are less likely to affect the rarest arboreal species (Constantino 2019).

While the Critically Endangered and/or range-restricted Amazonian species are an urgent conservation priority, some widely distributed species of conservation concern could also be supported by large-scale restoration. These include large and charismatic vertebrates such as the Near-Threatened Harpy eagle *Harpia harpyja* and Jaguar *Panthera onca* and the Vulnerable White-lipped peccary *Tayassu pecari* (BirdLife International 2021, IUCN Red List for birds, IUCN Red list 2020). While these species also require alternative interventions across the basin to reduce hunting pressure and persecution (Chapter 27), their populations would also benefit from restoration actions that help reconnect remaining forests and important habitat areas such as flooded forests. Actions that allow degraded forests to recover will also be key, as they will improve keystone resources such as fruiting trees that are vital for wide ranging species such as

Figure 29.1 Six of Amazonia's Red Listed vertebrates. The Critically Endangered (1) Belem Curassow Crax [fasciolata] pinima, (2) Black-winged Trumpeter Psophia [viridis] obscura, (3) and Kaapori Capuchin Cebus kaapori, the Vulnerable (4) White-lipped peccary Tayassu pecari and the Near Threatened (5) Harpy Eagle Harpia harpyja and (6) Jaguar Panthera onca. Photo credits: 1. Surama Pereira, 2. Pablo Cerqueira, 3. Pablo Cerqueira, 4. André Ravetta, 5. Sidnei Dantas, 6. Fernanda Santos

the White-lipped peccary, or a viable prey base for apex predators such as the Harpy eagle and Jaguar.

Species-based restoration actions in the Amazon also needs to consider the different habitat types within the biome. Some of these hold distinct biota, most notably white sand forests (Guilherme *et al.,* 2018), bamboo-dominated forests of the southwestern Amazon (Kratter 1997), *várzea* and *igapó* forests (Haugaasen and Peres 2007), and savanna enclaves (De Carvalho and Mustin 2017) (see Figure 29.2). These ecosystems are both diverse and unique in their own right, and can hold high levels of endemicity. Some of these ecosystems are even yielding new species discoveries; the Near Threatened Campina Jay (*Cyanocorax hafferi*) was only discovered in 2002 and is endemic to *campina* enclaves in and around the Madeira-Purus interfluve. It is well known that afforestation of open habitats, including oil palm expansion in savannas, can have negative consequences for biodiversity (Fernandes *et al.,* 2016) and it is vital that conservation and restoration efforts protect the integrity of Amazonian savannas and other unique habitat types (Lees *et al.,* 2014).

29.2.2. Improved functional connectivity of river systems

One vital advantage of a basin-wide approach is that the integrity of river systems relies on a high degree of spatial connectivity that operates in multiple dimensions; that is, longitudinally (upstream-downstream), laterally (river channels-riparian zones-floodplains), and vertically (surface-subsurface-groundwater) (Ward, 1989; Castello and Macedo, 2016). Further, seasonal and interannual flows represent a temporal fourth dimension of connectivity. The river continuum concept (Vannote *et al.,* 1980) and the flood pulse concept (Junk *et al,.* 1989), two foundational paradigms describing riverine and floodplain structure and function, are premised on the importance of longitudinal and lateral connectivity as central organizing features of energy flows, food web structure, and nutrient dynamics of running water systems.

Freshwater ecosystems display an acute dependency on subsidies of materials, nutrients, and organisms that originate from elsewhere in the riverscape and landscape, and restoration efforts need to ensure these material and organismal transfers are not disrupted by barriers (Freeman *et al,.* 2003; Flecker *et al.,* 2010). Likewise, maintenance of natural flow (Poff *et al.,* 1997) and sediment regimes (Wohl *et al.,* 2015) are fundamental for the functioning of rivers and floodplains. For example, sediments that build Amazon floodplains are transported long distances from their source of origin in the Andes (McClain and Naiman, 2008). Thus, restoring aquatic ecosystems to more natural states involve supporting the vital multi-dimensional linkages that are found throughout river basins, as well as sustaining the organisms embedded in these systems. Such restoration needs to focus on the full hydrological network, from headwaters through to the main channels.

29.2.3 Global and biome-wide climate benefits

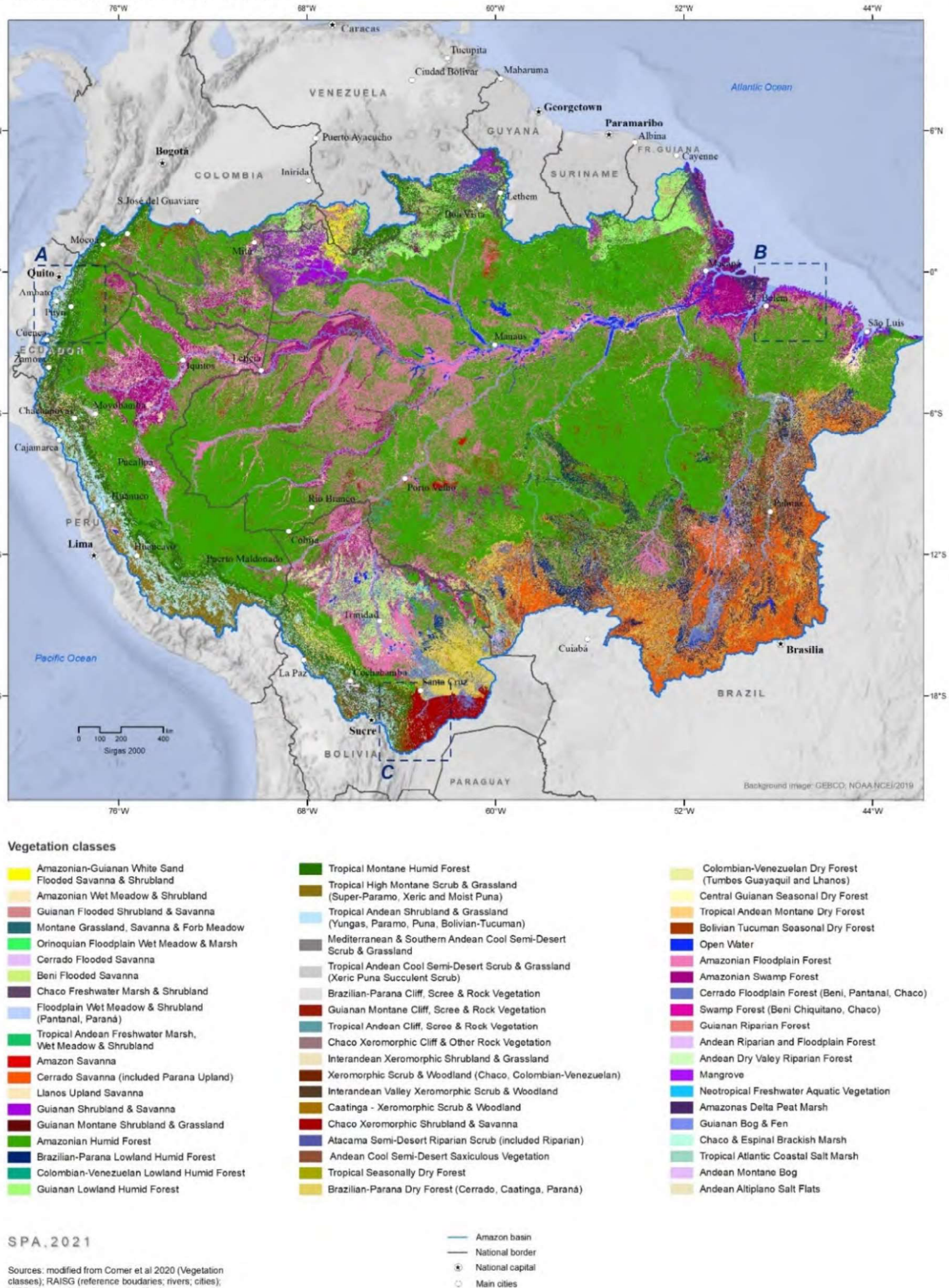
Adding up to 24 million ha of forest across the world every year until 2030 could store around one-quarter of the atmospheric carbon necessary to limit global warming to 1.5°C above pre-industrial levels (Hoegh-Guldberg *et al.,* 2018). Natural forest regrowth following complete or nearly complete removal of forest vegetation can therefore play a significant role in climate change mitigation (Chazdon *et al.,* 2016a; Lewis *et al.,* 2019; Cook-Patton *et al.,* 2020). For example, the 2.4 Mha of secondary forests in tropical Latin America could accumulate a total aboveground carbon stock of 8.48 Pg C (petagrams of carbon) in 40 years (Chazdon *et al.,* 2016b). This is equivalent to all the carbon emissions from fossil fuel use and industrial processes across all Latin America and the Caribbean from 1993 to 2014 (Chazdon *et al.,* 2016).

Where climate change mitigation is a priority, restoration will be most effective on a per hectare basis if it occurs where growth rates are fastest – which is generally in the less seasonal regions and in the western Amazon where soils are more productive (Heinrich *et al.,* 2021), and where the previous land-use intensity was low (Jakovac *et al.,* 2015). However, to date most deforestation has occurred in seasonally-dry regions of the Amazon, and, as a result, most secondary forests (and also most opportunities for large-scale restoration) are in regions that are more seasonal, have suffered higher land use intensities, and have low levels of remaining forests cover (Smith *et al.,* 2020). For example, secondary forests in the Brazilian Amazon have a mean annual precipitation of 1,945 mm, compared to the regional average of 2,224 mm, while their average maximum climatic water deficit is −375.5 mm compared to a regional average of −259 mm (Smith *et al.,* 2020). In the drier and most deforested regions, carbon accumulation rates of secondary forests are some of the lowest in the Amazon (Elias *et al.,* 2020; Heinrich *et al.,* 2021) with rates of just 1.08 $Mg{\cdot}ha^{-1}{\cdot}yr^{-1}$ compared to rates of 2.2 to >4 $Mg{\cdot}ha^{-1}{\cdot}yr^{-1}$ for studies in other regions (Elias *et al.,* 2020).

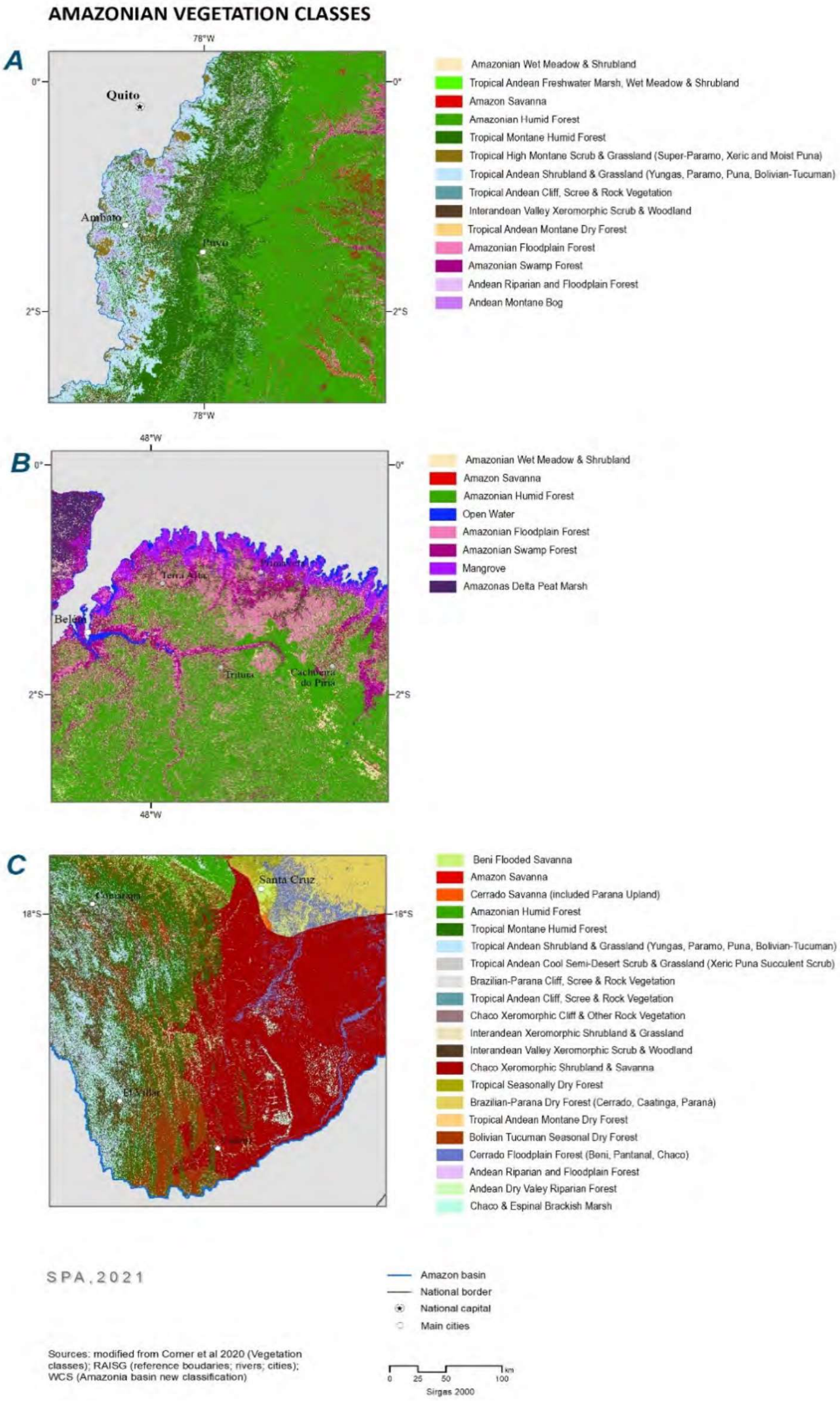
However, this does not mean that these regions should not be a priority for restoration, as the slow growth is offset by the higher availability of land for restoration, and the lower opportunity costs of conducting restoration on degraded farmland that is often unprofitable (Garrett *et al.,* 2017). Furthermore, forest restoration in highly deforested areas may be more important for biodiversity and climatic benefits; new forest fragments may act as important habitat for threatened species, facilitate their dispersal, or buffer remaining primary forests, and the increase in forest cover can potentially increase local rainfall (see section 3.3). The importance of these opportunities for restoration are recognized within climate change targets – for example, the Brazilian state of Pará aims to restore up to 7 million hectares of forest as part of its "Plano Estadual de Amazonia Agora", helping it achieve carbon neutrality by 2035 (Pará State Decree 941/2020).

Crucially, restoration may support the integrity of the biome itself, enhancing its resilience to climate change by reducing the influence of climatic extre-

AMAZONIAN VEGETATION CLASSES



Sources: modified from Comer et al 2020 (Vegetation classes); RAISG (reference boudaries; rivers; cities); WCS (Amazonia basin new classification)



Sources: modified from Comer et al 2020 (Vegetation classes); RAISG (reference boudaries; rivers; cities); WCS (Amazonia basin new classification)

Figure 29.2 Amazonia's diverse array of ecosystems need to be considered when deciding how and where to restore. The vast extent of the Amazon means that many of these are only apparent when taking a closer look (boxes A-C) . Sources: Comer et al (2020), RAISG (2020), and WCS – Venticinque et at (2016).

mes and avoiding dangerous tipping points resulting from climate and land-use change (Chapter 23). This is because forest restoration could help the Amazon maintain its hydrological integrity, with evapotranspiration from restored forests contributing to the east-west transfer of moisture. This, in turn, could help support aquatic ecosystems, ensuring the maintenance of river discharge dynamics across the basin, and even the nutrient transfer from freshwater to floodplains and beyond. Restoring the basin's hydrological functioning could also help prevent forest fires, which are one of the main determinants of any sudden tipping point (Nobre *et al.,* 2016). However, care must be taken to ensure that restoration itself does not make landscapes more flammable; for example, secondary forest understories tend to be hotter and drier in the day than primary forests (Ray *et al.,* 2005), and, depending on what systems they replace, have the potential to aid the spread of fire across landscapes. Forest restoration will therefore require additional measures to reduce risks from fires.

29.2.4. Societal benefits

Restoration of forests and sustainable economic activities are a high priority for some of the most deforested regions of the Amazon, as these older deforestation frontiers include some municipalities with the lowest Human Development Index values (HDI) (Rodrigues *et al.,* 2009). The transformation of unproductive lands into productive and sustainable agricultural or agroforestry systems could yield many direct economic and social benefits (Chapter 28), but there are also many indirect effects of restoration that could provide benefits for society beyond the producers. For example, the climatic benefits of increasing forest cover (e.g. Alkama and Cescatti, 2016) could mitigate some of the higher temperatures associated with climate change, thereby improving other economic activities across the landscape and supporting well-being. Some of these benefits could be of considerable economic importance, as maintaining dry season length could enable the continuation of 'double cropping' systems which are vulnerable to climate change (e.g. Andrea *et al.,* 2020). Landscape restoration could also be a very efficient tool for fire prevention and control, preventing the many negative social costs of fire (Chapter 19). The restoration of aquatic systems will not only improve access to clean water but could also support new fisheries.

Restoration could also have important political consequences, although these remain understudied, especially in developing countries (Blignaut *et al.,* 2013). Many Amazonian countries have included restoration as part of their NDC commitment to the Paris Agreement, and several Amazonian countries (Peru, Bolivia, Ecuador, and Brazil) have made commitments for restoration through programs such as Initiative 20x20. Ecological restoration, like all political initiatives, needs to be placed within the context of policies and the inherent tradeoffs between competing objectives (e.g. Baker and Eckerberg 2013) (). Within this context, governance and institutional frameworks become significant (Mansourian, 2017). Viewed from such a perspective, negotiations can then develop around what types of restoration projects are to be implemented and where, and who manages the land afterwards (see Chazdon *et al.,* 2020; Mansourian, 2021). Restoration is likely to be important in this context as it influences many aspects of well-being targeted by political decision makers; these include the products harvested from restored ecosystems, health benefits such as water quality or changes in exposure to air pollution or high temperatures, reduced exposure to natural disasters such as flooding, or improvements in well-being from increased access to natural systems.

Restoring landscapes also generates additional value such as soil and water protection, microclimate regulation, and provision of goods. This change in political and economic value of the landscape may generate new interests, which could potentially shift the balance of power, impacting conflicts and the use of natural resources, as well as improving inequalities and land tenure rights (Mansourian, 2016; Ding *et al.,* 2017). Expanding restoration beyond the site or project level to the landscape scale inevitably involves more stakeholders and adds further complexity to governance. Overcoming this will require identifying new institutional domains for stakeholders to meet, negotiate, and co-create the necessary conditions for restoration (van Oosten *et al.,* 2021). Achieving it helps ensure that governments uphold important constitutional responsibilities related to environmental protection and accessibility (see the Atrato River legal case in Colombia). Incorporating these benefits into political decision-making could help garner support for the implementation of restoration across the basin.

29.3. Landscape and catchment approaches to restoration and conservation

Once a region has been identified as a priority for restoration, landscape and catchment approaches can help ensure that restoration actions are effective and deliver the greatest benefits to the broadest range of stakeholders.

Within the region of interest, landscape approaches aim to "*provide tools and concepts for allocating and managing land to achieve social, economic, and environmental objectives in areas where agriculture, mining, and other productive land uses compete with environmental and biodiversity goal*" (Sayer *et al.,* 2013). They have been redefined as "*integrated landscape approaches*", reflecting the need to reconcile multiple and conflicting land-use claims and help establish multi-functional landscapes (Reed *et al.,* 2016a). The term now encompasses a wide-range of approaches (Reed *et al.,* 2016), including aquatic approaches such as integrated watershed management (e.g. Shiferaw *et al.,* 2008). Restoration specific approaches include Forest Landscape Restoration (Ianni, 2010) which is now promoted by many leading environmental NGOs and international institutions such as FAO, or initiatives such as the Bonn Challenge (Mansourian and Vallauri, 2005; Lamb *et al.,* 2012; Maginnis and Jackson, 2012). According to FAO, the Forest and Landscape Restoration Mechanism (FLRM) aims to "*restore degraded landscapes by identifying and implementing practices that restore a balance of the ecological, social and economic benefits of forests and trees within a broader pattern of land uses*". The broad approach of the FLRM enables decision makers to consider all components of a landscape, from agriculture to restoration and forestry, and support long-term sustainability decisions through economic zoning (Celentano *et al.,* 2017). They also call for a consideration of all ecosystems within a region, supporting restoration that goes beyond *terra firme* forests, to include restoration of other systems like savanna enclaves and flooded forests (Chazdon *et al.,* 2020b; Ota *et al.,* 2020; César *et al.,* 2021). What these all recognize is that considering where and how to restore at the catchment or landscape scale can help return much higher benefits than simple site-based approaches. We outline some of the key benefits of planning Amazonian restoration within landscapes and catchments below.

29.3.1. Integrating aquatic and terrestrial systems

Terrestrial and aquatic systems are often considered separately but are inextricably linked. Moreover, considering them together can provide large benefits for aquatic biodiversity at no cost to terrestrial biodiversity (Leal *et al.,* 2020). It has long been established that riparian zones can act as buffers for sediment and nutrient retention (Peterjohn and Correll, 1984; Allan, 2004; Saad *et al.,* 2018; Luke *et al.,* 2019), can moderate extremes in stream water temperatures (Macedo *et al.,* 2013a), and are important for biodiversity in both streams and floodplain systems (Arantes *et al.,* 2019; Dala-Corte *et al.,* 2020). For example, in southeast Brazil, modeling efforts using InVEST have explored different riparian restoration strategies that can reduce soil loss and river sediment export by filtering sediments before they reach streams (Saad *et al.,* 2018). Even in highly modified agricultural landscapes, the condition of riparian zones can strongly influence stream water quality via nutrient retention. For example, research in the Amazon-Cerrado frontier in the Brazilian state of Mato Grosso highlights the capacity of functionally-diverse riparian vegetation to capture and sequester nutrients (Nóbrega *et al.,* 2020). Concentrations of nutrients (organic carbon, total nitrogen, phosphorus, calcium, and potassium) in overland flow from croplands are substantially greater than from nearby riparian gallery forest. Moreover, soils from intact gallery forest, especially those with biodiverse plant assemblages with varied root systems, display properties that better enable nutrient uptake, as well as the degradation of nutrients and pollutants as compounds travel through hyporheic zones. Terrestrial systems can also affect stream temperature; a study of 12 catchments in the upper Xingu watershed reported warmer water temperatures in streams from pasture and soya-dominated catchments, with daily maxima 3-4°C higher than in forested catchments (Macedo *et al.,* 2013b). Collectively, these studies provide rationale for placing a premium on gallery forest and riparian zone restoration to mitigate land-use change's impacts on sediment export, water chemistry, and thermal regimes.

Source water protection involves a suite of management practices to protect water quality and quantity, especially in the context of water supplies for urban areas (Abell *et al.,* 2019). When coupled with strategic land protection in targeted catchments, restoration can play an important role in source water protection, via activities such as forest restoration, riparian restoration, livestock exclusion, and wetland restoration. Source water protection is an actively promoted restoration strategy in parts of the Amazonian Andes to improve water quality and preserve biodiversity (Bottazzi *et al.,* 2018). In the Bolivian Andes, a payment for ecosystem services effort known as *Watershared* pays farmers and cattle owners to prevent forest conversion and exclude livestock from riparian forest, all predicated on the notion that improving the condition of riparian zones translates into tangible outcomes for water quality and quantity. Contamination of drinking water by the bacterium *E. coli* is of particular concern where livestock graze freely in streams. Fencing has been shown to be a successful strategy for reducing per capita human cases of diarrhea by preventing livestock intrusion (Abell *et al.,* 2017). Similar practices of livestock removal coupled with riparian revegetation have been implemented elsewhere in the highlands of the tropical Andes to improve water quality and supply for urban areas (Goldman *et al.,* 2010; Higgins and Zimmerling, 2013). *Paramo* and wetland restoration is also a key priority in the Andes given the benefits for water quality and flow regulation (Buytaert *et al.,* 2006; Ochoa-Tocachi *et al.,* 2016) and carbon emissions (Schneider *et al.,* 2020).

In addition to water quality, land use modifies the magnitude and variability of river flows. Although studies have evaluated changes in river discharge due to deforestation and the conversion of land to intensive agriculture in Amazon catchments (Hayhoe *et al.,* 2011; Davidson *et al.,* 2012; Dias *et al.,* 2015; Farinosi *et al.,* 2019), there have been few attempts to track stream flow responses to terrestrial restoration and afforestation. A systematic review of more than 300 case studies worldwide examining impacts of forest restoration on stream flows revealed a deficit of information from the humid tropics (Filoso *et al.,* 2017). However, the studies that do exist from the tropics suggest forest restoration can be beneficial. For example, a study in Madagascar shows how forest restoration can reduce erosion and flooding related to overland flow (van Meerveld *et al.,* 2021). In a study in the Philippines, forest restoration increased infiltration enough to offset reductions in water balance from additional evapotranspiration, leading to a net positive water balance that could help maintain dry season streamflows (Zhang *et al.,* 2019). In an experimental study of hydrological response to land use and afforestation in the Ecuadorian *páramo* highlands, water balance and flow duration curves were compared among four small headwater catchments (Buytaert *et al.,* 2007), including one afforested with pine (*Pinus patula*), a catchment with intensive livestock grazing and potato cultivation, and two catchments with intact *páramo* vegetation. Flow regimes were dramatically modified in the afforested catchment, with severe reductions in base and peak flows. Although the cultivated catchment also displayed altered flows, they were less drastic than observed in the catchment with planted pines. These results suggest that in the Andean highlands, afforestation by non-native tree species used to reduce hillside erosion could result in significant decreases in base flows and compromise water supply. Finally, although untested, it seems plausible that forest restoration could support streamflow if it reduces landscape temperatures and increases rainfall (see Section 29.3.3).

29.3.2. Improving landscape and catchment connectivity for biodiversity

Island biogeography theory has underpinned the discipline of landscape ecology, guiding much of the theoretical and empirical evidence on the outcomes of habitat fragmentation. There are long-running debates about the relative importance of habitat extent versus habitat fragmentation (or changes in landscape configuration without changing habitat extent) (e.g. Fletcher *et al.,* 2018; Fahrig *et al.,* 2019), but a growing consensus recognizes that while habitat extent is the most important factor, configuration also matters for species across the world (Arroyo-Rodríguez *et al.,* 2020). Crucially, a global assessment of species' responses to anthropogenic edges suggests that tropical species are inherently more sensitive to fragmentation than temperate species (Betts *et al.,* 2019). For example, many Neotropical understory birds have a limited capacity to fly more than a few tens of meters (Moore *et al.,* 2008) and are reluctant to cross even small roads (Lees and Peres, 2009), making them highly susceptible to human activities that fragment habitat into discrete patches (Ferraz *et al.,* 2003; Lees and Peres, 2006). Low dispersal ability is evident over evolutionary time scales, as rivers have played a major role in determining the evolution of the Amazon's terrestrial diversity (Chapter 3). Freshwater species are also susceptible to changes in connectivity (Hurd *et al.,* 2016), and the Amazon's migratory catfish have the most spatially expansive metapopulations of freshwater fish across the world (Hurd *et al.,* 2016).

Given the high sensitivity of many Amazonian species to habitat fragmentation, restoration will be most effective if is deployed in a way that both increases habitat *and* maintains or enhances connectivity between remnant forest patches or rivers to ensure migration can take place and gene flow is permitted between populations. Mixed suites of restoration strategies can help improve connectivity between higher quality patches. For example, forest restoration efforts can create corridors that encourage movement between the last remaining habitat patches, and have proven successful at increasing population size and reducing threat status for species such as the black lion tamarin (*Leontopithecus chrysopygus*) in the Atlantic Forest. Similar approaches would support conservation efforts for some of the Critically Endangered species in the most deforested regions of the Amazon (Figure 29.1), including in the Maranhão-Pará border (Figure 29.1), Rondônia, and the Andean regions. However, enhancing connectivity in these regions will only be effective if carried out in conjunction with complementary conservation measures that protect the last remaining populations and habitats for these species (Chapter 27).

For some species, connectivity can be enhanced without physically connecting disjunct patches. For example, high quality habitat will be functionally connected if species are able to cross the non-habitat "matrix" in between (e.g. Lees and Peres, 2009). The permeability of an agricultural matrix composed of cattle pastures and mechanized agriculture is normally very low, but is likely to be enhanced by restoration that encourages occasional trees (e.g. Rossi *et al.,* 2016), plantations (Barlow *et al.,* 2007), or more diverse stands used in agroforestry (Zanetti *et al.,* 2019). Connectivity across the landscape – and benefits for aquatic systems – could also be enhanced by restoring a full network of riparian vegetation (Rossi, Jacques Garcia Alain Roques, and Rousselet, 2016; Kremen and Merenlender, 2018).

29.3.3. Local climate benefits

Forest cover influences Amazonian climates by reducing regional temperatures and maintaining rainfall (see Chapter 6). Restoration in deforested regions could therefore provide important benefits for local and regional climate (Mendes and

Prevedello, 2020). For example, studies across the world show that forest restoration can help reduce the urban heat island effect if conducted around cities (Bhagwat *et al.,* 2008), and can reduce the occurrence of excessive stream temperatures (Hall *et al.,* 2020). There is also some evidence that the configuration of forest cover in a landscape could influence climatic benefits of restoration, with more fragmented patterns actually increasing rainfall and maximizing reductions in land surface temperature (Mendes and Prevedello, 2020). However, there is uncertainty about how this occurs at scale; one modelling study suggests that rainfall increases on agricultural land and decreases on the forests themselves (Garcia-Carreras and Parker, 2011), which could increase forest flammability and enhance drought sensitivity. Furthermore, while a fragmented configuration may reduce the temperature of the deforested area, it is also likely to increase understory temperatures in the remaining forests, contributing to faster drying and increasing flammability. The local climatic benefits of restoring forests in a particular configuration is important, but requires further research.

29.3.4. Reducing the risk of socio-environmental disasters

Landscape or catchment level restoration can reduce the risk of events that are detrimental to the Amazon's people and nature. Forest fires are a growing threat to the Amazon (see Chapter 24), and, unlike deforestation and agricultural fires, benefit almost no-one (Barlow *et al.,* 2020). It is possible that targeted restoration could help reduce the occurrence of these forest fires by influencing landscape temperature and humidity (see Section 2.3), which in turn would make fuels on the forest floor less flammable by increasing humidity and reducing temperatures. Restoration could also be used to 'buffer' primary forest edges; although we are not aware of any research into this, we believe such restored forest buffers could have two complementary roles. First, primary forest edges are drier and hotter than forest interiors, which contributes to them being frequently degraded by fire incursion (Silva Junior *et al.,*2020); the restoration of closed canopy vegetation alongside primary forests would help buffer those forests edges from the hot microclimate of the agricultural matrix, making them less flammable, and could also help suppress pyrophytic grasses that help spread fires. Second, restoration alongside primary forests would help isolate those forests from the wider landscapes where ignition sources are most prevalent. While the use of 'green firebreaks' remains untested in an Amazonian context, the 'Green Hug' project (*Abraço Verde*) in the Atlantic forest provides insight into the long-term viability of projects using agroforestry buffers to project forest edges (Chazdon *et al.,* 2020a). Research is needed to evaluate the effectiveness of green firebreaks in the Amazon, including understanding the ideal widths and what active restoration measures (tree planting or enrichment) are required to maximize other benefits (e.g. economic returns). It will also be important to minimize risks from the restored areas, as secondary forests could themselves become 'wicks', helping conduct fire across the landscape (e.g. Ray *et al.,* 2005).

Catchment-scale restoration can also help mitigate the risk of flooding, which is exacerbated by deforestation (Bradshaw *et al.,* 2007). Evidence from China suggest broadleaf trees are especially effective (Tembata *et al.,* 2020), casting doubt on the flood mitigation value of oil palm or other species that are planted at low densities. Models suggest that sub-catchment restoration of riparian forests is likely to be one of the most effective mechanisms to reduce flooding, with restoration across 10-15% of the catchment reducing the peak magnitude of flooding by 6% after 25 years (Dixon *et al.,* 2016).

28.3.5. Meeting multiple aims and optimizing benefits

Although win-win outcomes are rare in conservation and development (e.g. Muradian *et al.,* 2013), trade-offs can be minimized and multiple benefits are more likely to be realized by implementing changes at the landscape or catchment scale (Reed *et al.,* 2016b) . Going beyond site-specific management and planning at the landscape or catchment level allows restoration to use optimization techniques to quantify trade-offs or complementarity between various restoration targets. Such approaches are helping prioritize restoration across the world (Strassburg *et al.,* 2020), and could allow restoration actions to achieve a broader range of benefits whilst minimizing losses (Stanturf *et al.,* 2015). For example, although biodiversity and carbon are positively associated in human-modified Amazonian forests, this relationship dissipates in undisturbed primary forests where turnover in species composition is high (Ferreira *et al.,* 2018). Considering this turnover in biodiversity in planning provides a way to deliver large gains for biodiversity conservation with very minor reductions in carbon storage (Ferreira *et al.,* 2018).

With so many potential co-benefits of restoration, it is vital that these are considered as part of an integrated planning process with full consideration of landscape and catchment processes (Reed *et al.,* 2019). For example, peri-urban restoration aimed at providing climatic benefits for cities could also provide important social benefits, such as for recreation or local consumption, if the species provide fruits or other products. Similarly, restoration aimed at terrestrial conservation could also support aquatic biodiversity, without any cost to terrestrial conservation objectives (Leal *et al.,* 2020).

Planning beyond specific sites also allows restoration to consider and compare the relative benefits of a full suite of interventions, helping ensure efforts are invested in the most effective measures. For example, landscape-scale planning is essential to decide when and where to adopt active or passive restoration of secondary forests, or whether strategies should target reforestation or focus on alternative measures such as avoiding degradation of existing forests or economic recovery in degraded lands. For example, it is likely that avoiding degradation in existing forests can be a cost-effective approach to conserving carbon and biodiversity when compared to active or passive restoration of forests on farmland.

29.4. Encouraging a broader forest transition

Forest loss and gain across the Amazon can be seen in terms of a forest cover transition. The term forest transition, introduced by Mather (1992), refers to a change in forest cover (shrinkage or expansion) over a given area (landscape, regional, national level) and time period. This process typically shows three main periods. First comes a phase of intensive deforestation due to forest conversion into agricultural lands and pastures, followed by a net gain of forest area through reforestation and restoration actions as well as passive natural regeneration. The third and last phase is a stabilization phase with a constant forest cover area. Europe, North America, and recently some tropical countries have already gone through their forest transition and are now witnessing sustained increases in forest cover (Mather, 1992; Meyfroidt and Lambin, 2010).

In most countries where a forest transition has occurred, the new forests are very different in structure, composition, and function. While generalist species can benefit, these new forests are unlikely to provide additional habitat for specialist species restricted to old-growth systems (Wilson *et al.,* 2017; Lees *et al.,* 2020). Moreover, evaluations of forest transitions require an understanding of global trade and leakage. Improved environmental performance and expanded forest cover in more developed countries may have come at the cost of environmental destruction elsewhere, typically in the Global South (Lees *et al.,* 2020). This leakage can also occur within regions and ecosystems; within the Amazonian context, care needs to be taken to ensure conservation and restoration activities in one area do not simply push social and environmental pressures elsewhere, including from one region of the Amazon to another, or from the Amazon to other ecosystems (e.g. de Waroux *et al.,* 2016) such as the Cerrado (Carvalho *et al.,* 2019).

While net gains in forest cover may occur over time in the Amazon, there is no evidence to suggest they have already begun, and the most deforested regions of the basin have failed to see an increase in forest cover since 1997 (Smith *et al.,* 2021). However, actions that avoid loss and stimulate gain are critical for the basin as a whole; the Amazon forest generates approximately one third of its own rainfall (Staal *et al.,* 2018) (see Chapters 6 and 22), and excessive deforestation could have huge environmental consequences, particularly on precipitation regimes and consequently on the capacity of the remaining forest to survive (Nobre *et al.,* 1991; Oyama and Nobre, 2003; Hutyra *et al.,* 2005; Sampaio *et al.,* 2007a), with tipping point estimates ranging from 20-25% (Lovejoy and Nobre, 2018) to 40% deforestation (Sampaio *et al.,* 2007b) (see Chapter 24). Furthermore, if deforestation goes beyond these estimated thresholds, forest regeneration itself could also be hampered by unfavorable climatic conditions (e.g. Elias *et al.,* 2020).

Given this context, how can restoration mitigate the loss stage of the Amazon's forest transition? One way that restoration could help is if it was partly oriented towards timber production, which could relieve pressure on natural forests, still the main provider of timber in the region. During the last 50 years of recent colonization of the Amazon, natural forests have been selectively logged, with 108 Mha of forest (20% of the total forest area) exploited for timber production (Food and Agriculture Organization of the United Nations and International Tropical Timber Organization, 2011).

There are many reasons why it would be beneficial to replace timber production from natural forests with timber plantations on deforested areas. First, although sustainable forest management practices are considered a potential tool for Amazonian forest conservation (Putz *et al.,* 2008; Edwards *et al.,* 2014) and provide income and employment (Putz *et al.,* 2012), natural timber production itself is unsustainable under present-day conditions of logging intensities and rotation cycle duration (Sist *et al.,* 2021). In the Amazon, selective logging regulations typically set a rotation cycle of 20 to 35 years with a logging intensity varying from 15 to 30 m^3/ha (Sist *et al.,* 2021). Several studies show that under such extraction regimes, less than 50% of the timber extracted can recover (Schulze, 2003; Sist and Ferreira, 2007; Putz *et al.,* 2012). A recent study simulating timber recovery in the region confirmed this result and showed that even under a long rotation length of 65 years and a logging intensity of 20 m^3/ha, the timber recovery would be only 70% (Piponiot *et al.,* 2019a). This means that under the present logging regulations natural Amazonian forests alone will not be able to supply the timber market demand in the long term (i.e. during the second rotation, 30 years from now). Second, timber in natural forests generates low profits when carried out using best practices (Putz *et al.,* 2008). Third, while it is much better than non-forest land uses for conservation and carbon storage, most logging practices in the Amazon continue to be illegal (Brancalion *et al.,* 2018) and generate high damage to the stand. Such practices also open up forests, make them more accessible to hunters (Peres, 2001) and vulnerable to forest fires (Holdsworth and Uhl, 1997). Finally, illegal logging also undermines the financial profitability of improved tropical forest management.

If restoration met some of the demand for timber, it could decrease the pressure on natural forests, allowing larger areas to be set aside for conservation and lower-intensity management of production areas. It would also allow timber from natural forests to be targeted to niche rather than mass markets, with higher prices enabling reduced offtake rates and longer reharvest intervals. This new market for timber extracted from natural forests should take into account the specific wood properties of old natural timber, the costs of sustainable forest management practices, and the social and environmental services provided by well-managed natural forests. Selective logging could be sustainable if it adopted much longer cutting cycles (65 years), reduced logging intensities (10 m^3/ha instead of 20 m^3/ha) and prevented incidental damage to the stand through reduced-impact techniques (Piponiot *et al.,* 2019b; Sist *et al.,* 2021). Additional sources of timber, such as plantations of exotic or native species, enriched secondary or degraded forests, integrated crop-livestock-forestry systems, and other agroforestry systems could be implemented within forest restoration programs under the Bonn initiative (Lamb *et al.,* 2005). The rising interest in tropical forest restoration, crystallized by the Bonn challenge in 2011, is a unique opportunity to initiate this forest transition by encouraging restoration with economically-viable timber plantations in deforested areas and promoting the management of secondary forests on abandoned agriculture lands (Ngo Bieng *et al.,* 2021). However, the success of any forest transition program depends primarily on forest law enforcement addressing illegal logging and promoting sustainable silvicultural practices.

The theory of forest transition focuses on the terrestrial part of a landscape, but what would an aquatic transition look like? Within the Amazon, avoiding the worst outcomes for aquatic systems will require preventing the most damaging new dams from being built, preventing land-use change, and regulating the use of harmful agrochemicals – all of which could be supported by alternative energy sources, novel bioeconomies, and the encouragement of better agricultural practices (see Chapter 20). Within the aquatic zone itself, overfishing might be mitigated by implementing, encouraging, and strengthening co-management systems over large regions (see Chapters 20, 28 and 30). Improving the status of fish populations would also benefit floodplain systems, as some of the species that have been declining with harvesting pressure, such as tambaqui *Colossoma macropomum* (Tregidgo *et al.,* 2017), provide important ecosystem processes (Costa-Pereira *et al.,* 2018). Aquaculture could also play an important role, but many issues require further analysis and investigation. For example, will supplying farmed fish relieve pressure on wild fish stocks? Can the many risks of aquaculture (increased nutrient loads, risks of species introduction, increased demand on natural fish populations or crops as food sources for produced fish) be managed properly? If they can, then aquaculture could also reduce demand for protein that requires orders of magnitude more land per kilo of protein, such as beef, even when inputs are considered (Piva Da Silva, 2017).

29.5. Ensuring broader societal benefits from restoration

Restoration exists within a social context, and therefore produces environmental conditions that must not only be ecologically sound but also economically feasible and socially acceptable.

A recent study showed that nearly 300 million people in the tropics live on lands suitable for forest restoration, and about a billion people live within 8 kilometers of such lands (Erbaugh *et al.,* 2020). Many of these people live in poverty. Restoration is therefore likely to occur within vulnerable social contexts, and must be socially and economically acceptable as well as maximize its potential to include local populations and improve local livelihoods over the long term (Palmer *et al.,* 2005; Reed, 2008; Lee and Hancock, 2011; Erbaugh *et al.,* 2020). It can achieve this by engaging a diverse range of stakeholders from the public, private, and civil society sectors, and building and sustaining such coalitions of support. When carried out in a participatory way, restoration has the potential to increase well-being and improve livelihoods through the sale of forest products, increase food supplies, improve water security, and support the diverse cultural values people place on landscapes (Aronson and Alexander, 2013; Sabogal *et al.,* 2015; Brancalion and Chazdon, 2017; Stanturf *et al.,* 2019). In most cases this requires thinking beyond the individual site being restored and taking into account the broader benefits at the landscape scale: it is well documented that the success of forest and landscape restoration requires the empowerment and capacity building of local communities and their engagement in decision-making processes.

Land tenure has a strong influence on the likelihood, feasibility, and success of restoration efforts. Conflicting tenure regimes and property rights may complicate restoration, especially if there are multiple landowners (de Jong *et al.,* 2018), while tenure insecurity has been cited as a disincentive to invest in restoration (Fortmann and Bruce, 1991; Cotula and Mayers, 2009). Equally, landscape restoration may in turn affect tenure and land rights for many local and Indigenous communities and landowners, as returning vegetation to the land may entitle them to legal tenure. It may also increase family incomes, employment opportunities, and community resilience (Adams *et al.,* 2016; Erbaugh and Oldekop, 2018). For example, one reforestation scheme within the Brazilian Atlantic Forest has created over 200 jobs related to native seed collection, seedling production, planting, maintenance, and downstream manufacturing of timber and non-timber products (Calmon *et al.,* 2011).

Regaining land tenure and authority over restored lands also has health benefits for many marginalized and Indigenous peoples. Well-being encompasses much more than economic solvency; indicators of health include material (food, water, shelter, security), social (identity, belonging, self-esteem), and spiritual/cultural benefits (related to sacred places, totemic animals and artefacts, beliefs, customs, and languages) (Verschuuren, Subramanian, & Hiemstra *et al*., 2014). Additionally, pollution often affects people's health, and restoration efforts need to consider a broad approach that includes physical and mental well-being. This is particularly relevant for oil and mining pollution, which have had direct effects on Indigenous and marginalized communities in the Amazon (see Chapter 20). It is vital that the full social and ecological costs of mining are factored into decisions about where and when it takes place.

Restoring degraded landscapes also offers a means to rebuild communities and decentralize governmental institutions. For instance, about 6,000 Indigenous people residing in the Xingu Indigenous Park in Brazil, along with other communities inhabiting the heart of the basin downstream of extractive reserves of the Terra do Meio, have been negatively affected by changes in the quantity and quality of water that enters their lands (Schwartzman *et al.,* 2013). The restoration of 50 km^2 of riparian forests in the Xingu River Headwaters (Schmidt *et al.,* 2019) has helped reduce run-off from crops and pastures that were contaminating water bodies (Schiesari *et al.,* 2013).

29.6. The climate resilience of restoration options

Restoring ecosystems in the context of climate change requires understanding when it is best to rebuild past ecosystems, and when it is better to attempt to build resilient ecosystems for the future (Harris *et al.,* 2006). Determining where historical baseline targets are viable and where alternative targets must be considered is site-dependent and associated with projected changes (Jackson and Hobbs, 2009). We consider these issues in terrestrial and aquatic systems.

29.6.1. Climate resilience of terrestrial restoration

A growing set of evidence reveals how the Amazon's primary forests are being affected by climate change and climatic extremes, including increased mortality of individual trees (Phillips *et al.,* 2009; McDowell *et al.,* 2018) and changes in species composition (Esquivel-Muelbert *et al.,* 2019) (see Chapter 24). Studies also show strong associations between tree mortality and climatic changes such as increased intensity and duration of the dry season (Aleixo *et al.,* 2019a; Adams *et al.,* 2017) and warmer temperatures (Sullivan *et al.,* 2020; Allen *et al.,* 2010). But what about the sensitivity of secondary forests? Here we outline five lines of evidence suggesting they may be particularly sensitive to climatic change.

The first is spatial; secondary forests may be especially vulnerable to ongoing climate change as they are mostly situated in the drier and more seasonal parts of the Amazon where deforestation has predominated (Smith et al; 2020). The second is physiological; secondary forests are dominated by fast-growing trees with low wood densities (Berenguer *et al.,* 2018; Poorter et al., 2019) or have large thin leaves that do not conserve water, and these may be especially vulnerable to drought by cavitation or carbon starvation (Phillips *et al.,* 2009; McDowell *et al.,* 2018; Aleixo *et al.,* 2019b). The third line of evidence is empirical; secondary forests monitored over time have significantly lower rates of carbon

Box 29.1: The Xingu Seed Network as a social-ecological collaboration

To reduce restoration costs, the Xingu Seed Network undertook collective action involving private landowners and local and Indigenous communities (Sanches, Futemma & Alves, 2021; Urzedo *et al*., 2016; Schmidt *et al*., 2019). This is important as many governmental officials do not always appreciate the full extent of the importance of landscapes to local and Indigenous communities in terms of food security, income, nutrition, employment, energy sources, and well-being. The principle of social involvement in restoration led to the creation of the Xingu Seed Network, involving seed collection using traditional knowledge and promoting a forest economy by generating income. This initiative involved over 450 seed collectors from 16 municipalities of Mato Grosso state (Brazil), distributed in 20 Indigenous villages and 14 agrarian reform settlements, with at least 5,000 ha under restoration, involving more than 300 landowners, and generating US $380,000 (Durigan *et al.* 2013; Urzedo *et al*., 2016; Schmidt *et al*., 2019). By restoring degraded landscapes, it provides new opportunities to build relationships between private landowners and communities, and/or between communities and governments, based on collaboration rather than confrontation. While such progress is often slow at the landscape level, partly due to entrenched attitudes in bureaucracy, it offers significant potential shifts in attitudes and working relationships that can lead to evolution in socioecological policies.

accumulation during drier periods (Elias *et al.,* 2020). This is in part driven by mortality: several studies in primary and secondary forests recorded higher tree mortality after global extreme climatic events associated with El Niño/La Niña Atlantic oscillation (NAO) in the Amazon in 2005 and 2016 (Chazdon *et al.,* 2005; Leitold *et al.,* 2018). However, in secondary forests is also driven by reduced growth (Elias *et al.,* 2020). The fourth reason relates to their structure and microclimate; low canopies and high rates of stem turnover in secondary forests mean they have higher understory temperatures and lower humidity levels (Ray *et al.,* 2005), making them more vulnerable to extreme climate conditions as well as fire events (Uriarte *et al.,* 2016). Finally, while many primary forest trees have a deep rooting depth (Nepstad et al., 1994), this seems less likely in secondary forests, where average stem sizes are much lower. It is notable that seedlings are vulnerable to drought in disturbed forests in Borneo, and that these droughts also push the community composition back towards ruderal pioneers (Qie *et al.,* 2019).

Heightened sensitivity to climate change could be offset if existing gradients in dry season intensity and rainfall drive adaptation towards greater drought or heat sensitivity. Primary forests are changing their species composition in response to climate change (Esquivel-Muelbert *et al.,* 2018); the fast turnover and high dispersal capacity of pioneer species may facilitate these changes in secondary forests, especially when they are functionally connected to a large species pool of potential colonists. It is therefore possible that more drought-resilient secondary forests could emerge in the future. These may resemble the species composition and successional trajectories found in regenerating tropical dry forests, where the initial stages of forest succession are dominated by species with drought tolerant traits (e.g. (Lohbeck *et al.,* 2013). Where forests are unable to change naturally, or where a faster rate of change is desired, then enrichment planting could help encourage species with traits that are better adapted to heat stress or longer dry seasons. The cutting of climbers and liberation thinning could provide additional support (Philipson *et al.,* 2020), although evidence from Borneo suggests that the benefits of liana cutting may be reduced during extreme droughts (O'Brien *et al.,* 2019). Finally, restoration at the landscape scale could help restoration efforts by maintaining a cooler and more humid regional climate (see Section 29.2.3).

Drought is not the only threat to forest restoration. Aleixo *et al.* (2019) showed that trees died more often during wet months than in drought years, and rain and storms that occur during the transition from dry to wet seasons in the Amazon might be the main cause of tree mortality during the wettest months (Negrón-Juárez *et al.,* 2010). Forest restoration is also highly susceptible to fire, which can arrest successional processes in *terra firme* (e.g. Berenguer *et al.,* 2018; Heinrich *et al.,* 2021) and flooded forests (Flores *et al.,* 2017). Forest restoration activities need to be aligned with actions that reduce landscape flammability, improve fire detection and combat, and support farmers in controlling ignition sources.

29.6.2. Climate resilience of aquatic restoration

Hydrological effects of climate change are likely to have a greater impact in the Amazon than in other regions of South America (Brêda *et al.,* 2020). Notably, the impacts of climate change on aquatic systems can be exacerbated by land use change. For example, coupled climatic and hydrological models forced under contrasting deforestation scenarios suggest that precipitation outcomes shift from mean positive to mean negative in response to deforestation (Lima *et al.,* 2014). In addition, deforestation can increase the duration of dry seasons and amplify seasonal variation in discharge. Importantly, water balance changes are not confined to deforested sub-basins, as atmospheric circulation spreads the effects basinwide (Coe *et al.,* 2009).

Changes in water balance associated with climate change and deforestation will likely affect floodplain and river ecosystems in many ways (see Chapter 23). Decreased mean annual rainfall (Brêda *et al.,* 2020) combined with increased frequency of extreme weather events in the Amazon (Marengo, 2009) will change seasonal inundation patterns, impacting species composition and biogeochemical cycling in Amazonian freshwater landscapes. Reduced inundation length can alter the selection for flood-tolerant species and ultimately the composition of floodplain forests; moreover, because floodplain trees generally lack traits linked to fire and drought resistance, they will be highly sensitive to any changes in the frequency, extent, or severity of fires (Flores *et al.,* 2017). In rivers, precipitation and discharge regimes regulate sediment transport and aquatic nutrient dynamics (Devol *et al.,* 1995; Almeida *et al.,* 2015), and flood extent governs the input and processing of vast quantities of organic matter produced in terrestrial and seasonally flooded ecosystems that is further outgassed as carbon gas (Abril *et al.,* 2014; Almeida *et al.,* 2017). In the biological realm, altered seasonality in flood regimes could affect plankton community interactions, with potentially cascading food web effects (Feitosa *et al.,* 2019). Thus, in addition to understanding site-level conditions prior to disturbance, effective restoration of Amazonian aquatic ecosystems should be attentive to watershed-scale hydrological, biological, and chemical alterations brought about by climate change.

29.7. Achieving meaningful restoration at scale

Restoration science has developed rapidly over recent decades, and while some knowledge gaps remain in the tropics, it has reached a point where it can provide clear evidence-based guidance to support restoration actions in a wide range of contexts (Chapter 28) and across whole biomes and landscapes. But restoration cannot happen in isolation; we have outlined how it must be linked to a broader suite of conservation measures that avoid further loss (Chapter 27). Crucially, research has shown that restoration needs to be integrated within society and the political context, and evidence can inform how to implement restoration in a way that is inclusive of all people in a landscape (while recognizing that not all stakeholders will necessarily benefit) (Reed *et al.,* 2018). But how can this knowledge be used effectively? Here we examine the policy levers and incentives that can support the large-scale restoration that is required to mitigate climate change, avoid dangerous tipping points, reduce pressure on primary forests, support local livelihoods, and develop a thriving and flourishing Amazonian bioeconomy.

29.7.1. Enforcement and Monitoring

Many have experimented with technological and organizational solutions to restore environmentally-sensitive and sustainable economic production (e.g. Brondizio *et al.,* 2021). Yet, these potential solutions will not be replicated or adopted at scale as long as the negative externalities of exploiting the forest's natural capital go unaccounted for. For example, the low market prices of illegal timber undermines the value of legal timber (Brancalion *et al.,* 2018), making it much more challenging for companies that follow legal or certified practices to fund the monitoring and enforcement required to ensure post-harvest forest integrity across expansive and remote concessions (see Chapters 14, 19, and 27). Countering this requires changes in policy and governance (laws, taxes, subsidies) to make activities such as illegal logging economically unattractive. Green investment in land and landscape restoration requires efficient tools to monitor and verify environmental performance at plot, farm, landscape, and catchment levels. Monitoring and enforcement is also key to avoiding perverse effects of economic restoration, where technologies and policies promoting greater agricultural or silvicultural productivity paradoxically lead to increased deforestation (Garrett *et al.,* 2018), or where large-scale ecological restoration causes "leakage" of environmental harm (e.g. Alix-Garcia and Gibbs, 2017).

29.7.2. Incentive-based measures

Restoration can be incentivized by carbon and/or biodiversity offsetting, payments for ecosystem services (PES) such as REDD+, and/or certification schemes. Yet, PES often fail in gaining scale (Coudel *et al.,* 2015), and market-based interventions can generate conflict and weaken social ties (Pokorny *et al.,* 2012). Interestingly, less obvious policies may have important indirect effects on restoration dynamics, such as the Brazilian School Meal Program that has been fundamental in encouraging the consolidation of agroforestry systems and agrobiodiversity in some areas of the eastern Amazon (Resque *et al.,* 2019). Understanding the most effective ways to encourage large-scale restoration remains an important research priority.

29.7.3. Community-led restoration

Some site-level restoration actions can be implemented by liaising with a relatively small set of stakeholders, such as property owners or reserve managers. Yet, to achieve sustainable transformations across landscapes and catchments, it is vital that restoration measures are viewed favorably by a broader set of people, including those who live in the landscape or will be affected economically. For example, implementing integrated farming systems on unproductive farmland requires the participation of all relevant stakeholders, both in the design and implementation of the research and extension programs to assure they meet the socio-economic needs and cultural values of the beneficiaries. Unsurprisingly, some of the most successful examples of active restoration involve strong community buy in and leadership. The Xingu Seed Network (Box 29.1) and community-led co-management of fisheries (Campos-Silva et al., 2021) are positive examples of community engagement and leadership. They demonstrate that that success of restoration initiatives involving local people will be highly dependent on effective, long-term support for capacity building and technical assistance, and ongoing and wide-ranging social collaboration and participation (Chapter 30).

29.7.4. Policies

Restoration can also be supported at the national level through official commitments and legislation. For example, the Brazilian National Vegetation Protection Law (NVPL, or forest code) sets forest-area limits for legal reserves, and requires vegetation to be preserved along watercourses and in ecologically-sensitive settings such as steep slopes (Brasil, 2012). The NVPL allows landholders to compensate for past forest clearance by buying forests elsewhere; given issues around permanence, this has provided a mechanism to support restoration of illegal farmland in national parks

(Giannichi *et al.,* 2018). Yet, national legislation varies greatly across Amazonian countries. Developing a common set of approaches could be encouraged by linking national policies to the many international declarations and incentives that promote restoration, including the New York and Amsterdam declarations, the Bonn Challenge and Initiative 20x20, Sustainable Development Goal 15 Life on Land, the Convention on Biological Diversity, the United Nations Framework Convention on Climate Change, and additional zero deforestation commitments and policies against imported deforestation.

29.8. Conclusion

To maximize its ecological and societal impact, restoration needs to be implemented in ways that consider its benefits across scales, including at the level of the biome, within landscapes and catchments, and across different groups of local actors and stakeholders. Applying the most appropriate restoration approaches to the right places will require novel prioritization exercises that consider multiple benefits, societal feasibility, ecological need, and the risks posed by climate change.

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