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Chapter 28
Restoration options for the Amazon

Barcarena, Pará; bacia de rejeitos da Alunorte, controlada pela Norsk Hydro (Foto Pedrosa Neto/Amazônia Real)

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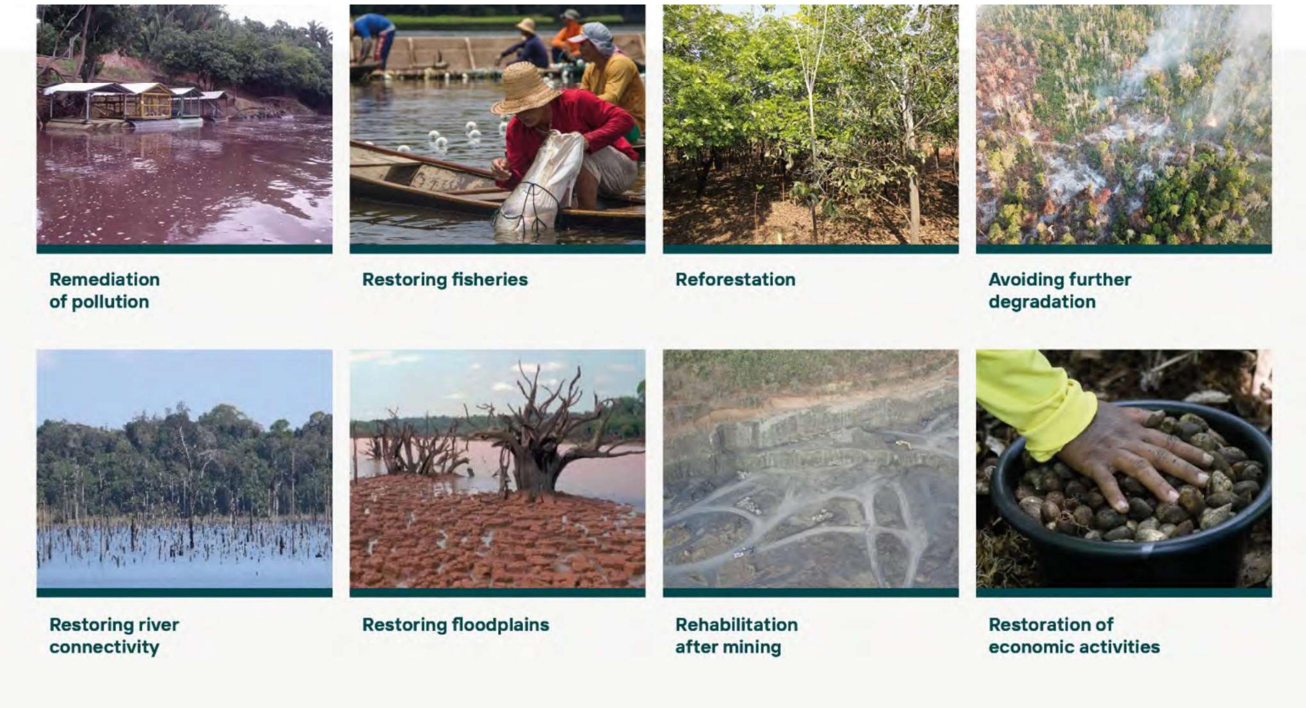
Graphical Abstract



Restorations option for the Amazon. Photographers: Nélio Saldanha, Amanda Lelis, Reinaldo Bozelli, Lilian Blanc, Alexander Lees, Jochen Schöngart, Nádia Pontes (from top-left to bottom-right).

Restoration Options for the Amazon

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Key Messages

- Restoration encompasses a broad suite of objectives related to the practice of recovering biodiversity and ecosystem functions and services, such as water quality, carbon sequestration, and peoples' livelihoods. It spans the aquatic and terrestrial realms and goes beyond natural ecosystems to include the recovery of socially-just and sustainable economic activities on deforested lands.
- Within terrestrial systems, site-specific restoration options include speeding up recovery after mining, reforesting deforested land, facilitating the recovery of degraded primary forests, and restoring sustainable economic activities on deforested lands via sustainable intensification, agroforestry, or improving farm-fallow systems.
- Restoring aquatic systems requires applying techniques to remediate polluted aquatic and terrestrial habitats, including those affected by mining, petroleum, and plastic; developing and enforcing rules to reinstate natural flow regimes; removing barriers that fragment rivers and disrupt connectivity; and implementing collaborative partnerships to recover fisheries and floodplain habitats.
- The high cost and complexity of many restoration options mean they should only be used as a last resort. For vast areas of the Amazon, the primary aim should be to avoid the need for future restoration by conserving intact forests and waterbodies.

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Abstract

This chapter examines site-specific opportunities and approaches for restoring terrestrial and aquatic systems, focusing on local actions and their immediate benefits. Landscape, catchment, and biome-wide considerations are addressed in Chapter 29. Conservation approaches are addressed in Chapter 27

Keywords: remediation, rehabilitation, rewilding, succession, fishing.

28.1. Introduction

Human-driven changes across Amazonian landscapes have affected biodiversity and associated ecological processes (Chapters 19 and 20); this, in turn, has direct and indirect impacts on human well-being (Chapter 21). Although much of the focus in the Amazon should be on preventing further ecosystem loss and degradation (see Chapter 27), there is growing awareness of the importance of restorative actions aimed at reversing these processes. Restorative actions are supported internationally by initiatives such as the Bonn Challenge, New York Declaration on Forests, and UN Decade of Ecosystem Restoration. At the same time, there is increasing recognition of the role that nature-based solutions can play in addressing societal challenges (Seddon *et al.*, 2019); these encompass protection, restoration, or sustainably managed aquatic and terrestrial ecosystems whether natural, man-made, or a combination of both (Cohen-Shacham *et al.*, 2016). Restoration is also about local livelihoods; small-scale agriculture and fisheries are vital livelihoods for millions of people inhabiting the region. There is increasing evidence of the benefits restoration can provide to people, including restoring sustainable and socially-just economic activities, that must be considered when designing successful restoration approaches. This chapter focusses on site-specific approaches for restoration in terrestrial and aquatic systems. Landscape, catchment, multiple stakeholders, and whole-biome considerations are assessed in Chapter 29. Before examining the role of restoration in different Amazonian contexts, we examine the aims and definitions across the aquatic and terrestrial realms, both internationally and within Amazonian countries (Fagan *et al.*, 2020; Mansourian, 2018).

28.2. Definitions and aims of restoration

We use restoration as an overarching term that encompasses the broad suite of objectives that can be met by improving biodiversity protection and conservation, ecosystem functions and services such as water quality, local or global climate change mitigation measures, or the livelihoods of regional stakeholders (Chazdon and Brancalion, 2019). While ecosystem and functional restoration, rewilding, rehabilitation, and remediation can be seen as different and independent actions, they can also be considered as part of a continuum which includes a range of activities and interventions that can improve environmental conditions and reverse ecosystem degradation and landscape fragmentation (Gann *et al.*, 2019). Crucially, our use of restoration also includes the recovery of sustainable and socially-just economic activities on deforested lands. Finally, restoration also encompasses preventing further degradation, recognizing that effective actions will require avoiding further environmental harm as well as encouraging recovery. As such, throughout chapters 28 and 29, the term restoration will be used to include the following approaches, many of which are non-exclusive and/or mutually beneficial.

28.2.1. Ecosystem restoration

Historically, ecosystem restoration means the recovery of ecosystems to a reference site (e.g. primary or pristine forests) (in Palmer *et al.*, 2014). Full recovery is defined as the state or condition whereby, following restoration, all key ecosystem attributes closely resemble those of the reference model, including absence of threats, species composition, community structure, physical conditions, ecosystem function, and external exchanges

(Gann *et al.*, 2019). Within the Amazon, full recovery may be a forest with equivalent richness and species composition to an old growth forest, or a river with the full complement of aquatic species. Ecosystem recovery is most likely in areas where the scale and intensity of disturbance has been minimal (e.g. recovery of faunal communities after overfishing or hunting).

28.2.2. Functional restoration

Targeting recovery to pristine conditions is not necessarily the main objective of every restoration program. Many restoration programs developed within the framework of the Bonn challenge target the restoration of ecological and ecosystem functions at the landscape level, while enhancing human well-being (Stanturf *et al.*, 2015). This "functional restoration" can also be called rehabilitation, and can facilitate the inclusion of socio-economic and human dimensions of restoration actions (Gann *et al.*, 2019). Forest landscape restoration (FLR) includes actions referring to both ecological restoration and rehabilitation (See Stanturf *et al.*, 2015, for definition of FLR). Nowadays, the human and social dimension of restoration actions can no longer be overlooked or ignored because the long-term success of restoration programs depends on it (Gann *et al.*, 2019).

28.2.3. Rewilding

The concept of rewilding has gone beyond its original association with large predators and lost Pleistocene fauna (e.g. Soulé and Noss, 1998) to deliver "*the reorganisation of biota and ecosystem processes to set an identified social–ecological system on a preferred trajectory, leading to the self-sustaining provision of ecosystem services with minimal ongoing management*" (Pettorelli *et al.*, 2018). Unlike functional or ecosystem restoration, rewilding does not aim for a specific target (e.g. biomass levels or species composition), but instead aims for a wilder system where a full suite of ecosystem processes are played out across trophic levels. While rewilding can be very different from target-driven restoration in many temperate contexts, within the Amazon the differences are less obvious; the most prevalent forms of restoration, such as the passive succession of secondary forest, could also be considered a form of rewilding under the definition of Pettorelli *et al.* (2018). Furthermore, with appropriate management interventions (including those related to hunting and fishing, see Chapter 27), most Amazonian secondary forests and rivers will eventually provide habitat for the largest vertebrates and apex predators.

28.2.4. Remediation

Remediation involves stopping or reducing pollution that is threatening the health of people, wildlife, or ecosystems, in contrast with restoration which refers to actions that directly improve environmental services or other ecological properties (Efroymson *et al.*, 2004). Remediation, therefore, generally occurs before restoration, and can help create the basic conditions for implementing restoration. Remediation actions vary, and can involve leaving contamination in place, allowing natural attenuation, removing or isolating contaminants, and improving ecological value through onsite or offsite restoration that does not involve removing contaminants (Efroymson *et al.* 2004). Within the Amazon, an example includes the remediation of localized soil contamination combined with natural attenuation and the planting of trees (Efroymson *et al.* 2004).

28.2.5. Additional definitions

Beyond defining what is restoration, there are some additional definitions that are useful to clarify. Ecosystem restoration strategies can be either (human) assisted or passive (i.e natural regeneration). We specify which approach is required where this is important to the outcome, but recognize that there is often a continuum of actions, and even passive actions require some active decision making and management interventions (e.g. fire control, fencing, etc). It is also important to clarify terminology about different disturbance classes (see Chapter 19). We use "primary forests" to describe forests that have never knowingly been clearfelled, accepting that there is a lack of certainty about pre-Colombian history (see Chapter 8), and that some forests will be considered "primary" by remote sensing if they pre-date the widespread availability of Landsat imagery in 1984. While deforestation – the loss of forest cover and conversion to an alternative land-use – is easily defined, there is less agreement over forest degradation (Sasaki and Putz, 2009) and secondary forests (Putz and Redford, 2010). We follow the definition of Parrota *et al.* (2012) that forests are considered degraded if disturbance has led to "*changes in forest condition that result in the reduction of the capacity of a forest to provide goods and services*" (Thompson *et al.*, 2012). We define secondary forests as those regrowing after clear-felling and, normally, after an alternative land-use such as pasture or cropland (Putz and Redford, 2010). We consider that forest degradation can affect both primary and secondary forests, through processes such as selective logging, extreme weather, fires, and edge or isolation effects (Brando *et al.*, 2014; Negrón-Juárez *et al.*, 2010). The degree of degradation depends on the cause (fire, logging, fragmentation), the intensity of degradation (e.g. low versus high logging intensity) and the frequency (repetitive logging, repetitive fire) (Chapter 19) (Barlow and Peres, 2008; Bourgoin *et al.*, 2020; Matricardi *et al.*, 2020). Finally, for terrestrial restoration, we retain a strong focus on forests, which are by far the most dominant ecosystem across the basin. However, other important ecosystems, including native grasslands, savannas, and paramos, also suffer from degradation and conversion, and the restoration of these ecosystems is also key to maintaining biodiversity, ecological functioning, and the provision of ecosystem services (Veldman, 2016).

28.3. Terrestrial restoration techniques and options

This section provides a technical and evidence-based review of the site-specific restoration options required in terrestrial systems following disturbances caused by the drivers addressed in Chapters 19 and 20. Each section briefly outlines when restoration is most relevant, the technical options that exist and their efficacy, the ecological and environmental benefits (and limits), and the social and economic viability (including benefits and challenges).

28.3.1. Restoration after complete removal of soil

The extraction of minerals and fossil fuels are increasingly significant drivers of tropical deforestation and degradation, biodiversity loss, and greenhouse gas emissions in the Amazon (Fearnside, 2005). Around 21% of the region is under potential hydrocarbon (327 oil and gas blocks covering ~108 million ha) and mineral (160 million ha) exploration (RAISG, 2020). Most mineral mining activities are centered around the Guiana Shield and North-Central regions of Brazil, while fossil fuel extraction occurs primarily in the western Amazon (mostly Peru, Ecuador, and Bolivia [RAISG 2020], Chapter 19). The magnitude of these industries varies from small scale artisanal activities (minerals) to large scale (mineral and hydrocarbon), with the latter often run by larger corporations on privately leased lands (Asner *et al.*, 2013; Kalamandeen *et al.*, 2018; Lobo *et al.*, 2016; Sonter *et al.*, 2017), overlapping ~20% of Indigenous territories (Herrera-R *et al.*, 2020). The process for these activities ensures that forests are cleared, and the topsoil stripped away to establish mines, wells, pipelines, and infrastructure associated with roads and housing (Laurance *et al.*, 2009; McCracken and Forstner, 2014; Sonter *et al.*, 2017).

The extent of soil damage and chemical contamination associated with both mineral and hydrocarbon excavation sets it apart from other traditional deforestation drivers such as agriculture and pasture-based cattle ranching (Santos-Francés *et al.*, 2011; Wantzen and Mol, 2013). Mineral and hydrocarbon extraction alter soil structure, disrupt nutrient cycling (nitrogen and phosphorus), and severely inhibit forest recovery by destroying the soil seed bank and soil biota (Barrios *et al.*, 2012; Kalamandeen *et al.*, 2020; Lamb *et al.*, 2005). It can also disrupt important aboveground ecosystem services such as pollination, seed dispersal, and pest control. Additional ancillary effects such as soil erosion and surface and groundwater pollution through mercury contamination and/or acid mine drainage can be detected hundreds of kilometers away from mine-leased sites (Diringer *et al.*, 2015; Sonter *et al.*, 2017). For such severely degraded and polluted systems, distance to primary forest seed banks appear to have limited impact on recovery (Kalamandeen *et al.*, 2020).

The level of degradation from hydrocarbon extraction means that full recovery is highly unlikely, and recovery rates are low or can be stalled completely (Kalamandeen *et al.*, 2020). As a result, focusing on reviving functional (primary production, energy flows, and nutrient cycles) and ecological processes (e.g. species composition, dispersal mechanisms, distinct evolutionary lineages) through active restoration becomes crucial (Chazdon *et al.*, 2009; Edwards *et al.*, 2017; Ferreira *et al.*, 2018; Rocha *et al.*, 2018).

Restoration will be most effective in these systems if active revegetation or mixed approaches are used (Ciccarese *et al.*, 2012; Gilman *et al.*, 2016; Stanturf *et al.*, 2014), depending on the type of mining that occurs. For instance, Parrotta and Knowles (1999, 2001) showed that mixed commercial species plantings of mostly exotic timber trees were the most productive treatment for basal area development and height growth in areas formerly under bauxite mining. Mixed approaches may include the planting of seedlings of native and/or exotic species, the assistance of natural regeneration, or the establishment of agroforestry systems (Macdonald *et al.*, 2015; Stanturf *et al.*, 2015; Viani *et al.*, 2017). The most commonly used technique beyond natural regeneration is a combination of treating soils to increase fertility and reduce acidity (e.g. with calcium carbonate, nitrogen fertilizer, biochar) and seedling and tree planting (Grossnickle and Ivetić, 2017; Palma and Laurance, 2015; Rodrigues *et al.*, 2019). Studies comparing different restoration approaches highlight how the benefits change according to the restoration targets – while areas planted with commercial tree species accumulate the highest biomass in the first 9-13 years, these are often the least species rich (R. L. Chazdon *et al.*, 2020; Crouzeilles *et al.*, 2016; Parrotta and Knowles, 1999). Planting with a mix of native species could more effectively enhance forest resilience in the long term and reduce the risk of arrested succession (Parrotta and Knowles, 2001).

Below-ground diversity has a significant impact on ecosystem functioning and can play a greater role in restoration of degraded mining systems (Harris, 2009). Positive relationships have been discovered between the diversity of arbuscular mycorrhizal fungi and ecosystem net primary productivity, and between arbuscular mycorrhizal fungal community evenness and ecosystem phosphorus-use efficiency (Lovelock and Ewel, 2005). Among the relevant soil micro-organisms, arbuscular mycorrhizal fungi and ectomycorrhizal fungi can be expected to play a major role during restoration of degraded sites (Caravaca *et al.*, 2002, 2003), yet this role is poorly understood. Recent evidence from restoration in China reveals how above-ground conditions can influence below ground communities during restoration; higher plant diversity encouraged plant-soil feedbacks, resulting in more favorable restoration trajectories (Jia *et al.*, 2020).

The standards and best practices available for pre- and post-mining activities are crucial for restoration. Many Amazonian countries have systematic processes developed for post-mining restoration that include actions such as backfilling mined sites with topsoil and treating and refilling tailing ponds as part of 'close as you go' strategies. For larger mines, enforcement of restoration after mine closure is often tied to environmental and social safeguards from major multilateral financial institutions, such as the Inter-American Development Bank and the World Bank's use of the International Finance Corporation's Performance Standard (PS) 1 ('Assessment and management of environmental and social risks and impacts') and PS6 ('Biodiversity conservation and sustainable management of living natural resources', see World Bank, 2019). However, there is a lack of monitoring, and enforcement of mining policies are weak or non-existent for medium to small-scale operations.

Furthermore, there are no schemes to restore areas impacted by illegal mining, which often takes place in remote regions.

28.3.2. Restoration of vegetation on deforested land

The loss of over 865,000 km² of Amazonian primary forests to date (Smith *et al.*, 2021) means that there are many opportunities for forest restoration. These opportunities are greatest in the Brazilian Amazon as (i) it covers 60% of the basin's forested area, and (ii) accounts for 85% of all deforestation to date (Smith *et al.* 2021, Chapter 19). Other notable deforestation hotspots exist in Colombia, Peru, and Bolivia. Within the Brazilian Amazon, 20% of deforested land has been abandoned and is covered by secondary forests; these are concentrated in the 'arc of deforestation' and alongside waterways and major highways (Smith *et al.*, 2020). Further restoration of unproductive farmland in the Brazilian Amazon could be encouraged by the Native Vegetation Protection Law (often referred to as the Forest Code), which requires most rural properties to maintain between 50 and 80% of forest cover on their lands (Nunes *et al.* 2016).

The vast majority of restoration on agricultural lands is passive, where forests are left to return naturally (Chazdon *et al.*, 2016; Smith *et al.*, 2020). Most Amazonian secondary forests resulting from passive restoration are less than 20 years old (Chazdon *et al.*, 2016). Within the Brazilian Amazon, the median age is just seven years, and very young secondary forests (≤5 years old) represent almost half of the total secondary forest extent (Smith *et al.*, 2020). These secondary forests develop for two distinct reasons. First, forest regrowth is a way for farmers to restore soil fertility and reduce weed infestation after agriculture. These forests are often subject to clearance for new agricultural uses, but there may be limited interventions such as the enrichment of the regrowth with useful plant species (e.g. Padoch and Pinedo-Vasquez, 2010). Second, secondary forests develop as the result of abandoning farmland; here, there is no specific objective for high diversity or functioning forests, and normally nothing is done to alter the successional trajectory.

Although naturally regenerating secondary forests are frequently referred to as 'passive' restoration, their recovery could be improved through active management. In some cases, fencing can be important to protect them from livestock (e.g. Griscom *et al.*, 2009; Wassie *et al.*, 2009). Excluding fire is a key priority: secondary forests can be more flammable than primary forests as they are drier and hotter in the daytime (Ray *et al.*, 2005), and burned secondary forests recover at a much slower rate (Heinrich *et al.*, 2021). Secondary forest value will also be enhanced by protecting existing forests, as older forests bring greater benefits for biodiversity conservation (Lennox *et al.*, 2018) and carbon stocks (e.g. Heinrich *et al.*, 2021). Yet, protecting secondary forests from disturbance or clearance remains challenging. They are often considered to be of little value, which may have contributed to an increase in clearance rates in recent decade (Wang *et al.*, 2020). Furthermore, there has been no overall increase in forest cover in Amazonian landscapes that were heavily deforested over 20 years ago (Smith *et al.* 2021). Restoration programs therefore need to develop incentives to protect existing secondary forests and encourage restoration in regions where there is the greatest extent of deforested land.

Active restoration approaches vary, but some of the most popular involve direct seeding of pioneer species, lower density planting of non-pioneer species, as well as plowing and soil preparation (Cruz *et al.*, 2021; Vieira *et al.*, 2021). Despite some successes in highly deforested landscapes (e.g. Vieira *et al.* 2021), active restoration of abandoned farmland will always be difficult and expensive at the very large scales required across the Amazon. For example, a review of over 400 restoration projects in the Brazilian Amazon found that assisted natural regeneration was used in just 3%, while an ambitious and innovative active restoration project that involved multiple communities and up to 450 seed collectors (see Box 1 in Chapter 29) has nonetheless restored just 50 km² of forest (Schmidt *et al.*, 2019), a tiny fraction of the forests developing due to land abandonment over the same period (Smith *et al.*, 2020).

Where active restoration is implemented, species must be carefully chosen. Active restoration should not be restricted to fast-growing pioneers; evidence from the Atlantic forest shows old growth species provide many benefits when planted in open areas (Piotto *et al.*, 2020). The species provenance is important; local seed collection schemes and nurseries are vital to maintain local seed sources and appropriate species mixes, but without long-term co-development of seed collecting schemes (e.g. Schmidt *et al* 2018) there are often limitations regarding the availability of seeds from native species (Nunes *et al.*, 2020). In many ecosystems, restoration should focus on using provenances that reflect future conditions (Breed *et al.*, 2012). However, this is not possible in the lowland tropics, where climate change is creating novel climates without present-day analogues (Williams *et al.*, 2007).

The spatial configuration of active restoration matters. Nurse trees can encourage seed dispersal into restoration areas, and applied nucleation (where planting in small patches encourages forest recovery at larger scales) has proven successful in other parts of the Neotropics (Rodrigues *et al.*, 2019; Zahawi *et al.*, 2013). Some active restoration approaches can even be counter-productive; in the Cerrado, Sampaio *et al.* (2007) demonstrate that intensive restoration efforts in abandoned pasture may actually slow early succession of seasonal deciduous forest. The many challenges of developing and scaling effective active restoration should not detract from the important role it can play in certain contexts. It will be particularly useful when previous land use intensity has been high, if there are few seed sources in the vicinity, or when speeding up the restoration of areas with high social and ecological value such as riparian forests (Schmidt *et al.*, 2019; Vieira *et al.*, 2021).

The ecological benefits of forest restoration are highly variable. For example, there are large differences in estimates of carbon accumulation in passively regenerating lowland Amazonian forests, with estimates ranging from <1 to > 4Mg C ha-1 yr-1 (Poorter *et al.* 2016, Elias *et al.*, 2020). The recovery of biodiversity is also variable. Some studies show strong positive relationships between the recovery of species richness or composition and above-ground carbon or biomass (Ferreira *et al.*, 2018; Gilroy *et al.*, 2014; Lennox *et al.*, 2018). However, this relationship attenuates with increasing biomass levels (Ferreira *et al.* 2018), and older secondary forests (c. 50 years old) may stop accumulating additional species if isolated from primary forests (Elias *et al.* 2020). Furthermore, although secondary forests in favorable contexts can hold a high diversity of fauna and flora, the species composition tends to be very different (Barlow *et al.*, 2007), and many species with restricted ranges only use the oldest secondary forests (Lennox *et al.*, 2018; Moura *et al.*, 2013).

The variation in recovery trajectories of secondary forests reflects the wide range of drivers that affect the recovery process. Climate is a key driver, and forest recovery is slower in drier and more seasonal climates (Elias *et al.*, 2020; Poorter *et al.*, 2016). Differences in previous land use, such as the intensity, frequency, duration, extent, and type, also affect successional pathways (Jakovac *et al.*, 2021). Landscape context can also play a key role in driving recovery (Chapter 29), with proximity to existing forest edges and high forest cover landscapes (Jakovac *et al.* 2021) having strong and positive effects on recovery (Camargo *et al.*, 2020; Leitold *et al.*, 2018).

There is also an important variation in the cost of returning agricultural land to forest. Some costs are associated with restoration actions, such as planting, fencing, etc. However, opportunity costs are also fundamental. Most of the secondary forests that exist do so because farming generates low profits; e.g. (Garrett *et al.*, 2017). Encouraging further restoration in similar regions will therefore have low opportunity costs. However, restoring forests on productive agricultural land with high profit margins will incur much higher costs. Not all actors will be able to bear these costs equally; it is likely that smallholders will face greater challenges if they are required to increase secondary forest coverage or move from farm-fallow systems to permanent areas of restoration. The benefits for local actors could be enhanced where secondary forests provide marketable non-timber forest products (NTFPs), such as fruits, resins, honey, or building materials (Chapter 30).

28.3.3. Restoration of degraded forests

There are many different drivers of forest degradation in the Amazon (Chapter 19). Human-driven disturbances that lead to degradation include selective logging, forest fires, edge effects, and hunting (Asner *et al.*, 2005; Barlow and Peres, 2008; Broadbent *et al.*, 2008; Aragão *et al.*, 2018; Silva Junior *et al.*, 2020; Bogoni *et al.*, 2020). Natural disturbances include extreme droughts and windthrows (Espírito-Santo *et al.*, 2014; Leitold *et al.*, 2018; Phillips *et al.*, 2009). The impact of the disturbance and the degree of degradation is variable. For example, repeated forest fires can eliminate almost all of the original trees, and cause a complete turnover of faunal communities (Barlow and Peres, 2008), while hunting leads to more subtle changes in plant communities that have been detected in longer-term studies of changes in tropical forest species composition (Terborgh *et al.*, 2008; Harrison *et al.*, 2013). Disturbances often co-occur; edges and logged forests are often burned (e.g. Silva Junior *et al.* 2020), and the effects of extensive forest fires are superimposed upon the effects of extreme droughts (Berenguer *et al.*, 2021). When all forms of degradation are assessed together, they can drive as much biodiversity loss as deforestation itself in human modified Amazonian landscapes (Barlow *et al.*, 2016).

Existing large-scale assessments of degradation focus on structural changes in the forest that can be detected by satellites. These suggest that at least 17% of Amazonian forests were degraded by disturbances such as logging, fires, or windthrow between 1995 and 2017 (Bullock *et al.*, 2020). In the Brazilian portion of the basin, this degraded area covers a greater area than that deforested to date (Matricardi *et al.*, 2020). The extent and impacts of cryptic disturbances such as defaunation are far less certain than those of canopy disturbance (Peres *et al.*, 2006). Recent studies estimate a 57% reduction in local fauna across the Neotropics (Bogoni *et al.*, 2020). Within the Amazon, defaunation is highest in the arc of deforestation and the Andes, but even intact areas have lost key species (Bogoni *et al.*, 2020). For example, white-lipped peccary (*Tayassu pecari)* are estimated to be absent from 17% of Brazil's state of Amazonas, despite it retaining 98% of its forest cover (Parry and Peres, 2015). Bushmeat consumption in small urban centers is also prevalent (Parry and Peres, 2015) and can deplete game species for over 100 km from the urban center (Parry and Peres, 2015).

The impacts and longevity of degradation effects mean conservation efforts should first focus on avoiding human-driven disturbances in the first place, retaining as much of the intact forests as possible (Watson *et al.*, 2018). But once a forest has been degraded, the probability of further change provides important insights into management. Crucially, 14% of degraded forests are eventually deforested (Bullock *et al.*, 2020). Avoiding this deforestation is important; although these degraded forests have a lower conservation value and deliver fewer ecosystem services than undisturbed forests, they remain significantly more important for biodiversity and ecosystem functioning than agricultural land uses (Barlow *et al.*, 2016; Berenguer *et al.*, 2014; Edwards *et al.*, 2011).

Bullock *et al.* (2020) also estimate that around 29% of forests that were degraded within the time-scale of the study were degraded again – a number that would be considerably higher if non-structural forms of degradation (such as hunting) were included, or if the assessment was carried out over longer time periods. This demonstrates the importance of avoiding further disturbance events in degraded forests, which is particularly important where disturbances facilitate the occurrence of others or amplify their effects. For example, extreme droughts, selective logging, and edge effects all make forests more susceptible to fires, due to changes in microclimatic conditions and/or fuel loads (Camargo and Kapos, 1995; Ray *et al.*, 2005; Silva Junior *et al.*, 2018; Uhl and Kauffman, 1990). These events can also amplify effects of subsequent degradation, as tree mortality from fire is much higher close to forest edges, or in forests that have been previously logged or burned (Brando, Silvério, *et al.*, 2019; Gerwing, 2002)

Recovery times of degraded forests are highly variable, depending on the type and intensity/severity of the disturbance (Box 1). Recovery rates are also dependent on the metric of interest; for example, logged forests can return to baseline humidity and temperature conditions within a few years, when canopy cover recovers after human-driven disturbance (Mollinari *et al.*, 2019), and some burned forests can quickly recover their capacity to cycle water (Brando, Silvério, *et al.*, 2019). In contrast, carbon stocks are likely to take decades to recover, and may reach an alternative lower biomass state following forest fires (Rutishauser *et al.*, 2015; Silva *et al.*, 2018, 2020). The recovery of species composition and large trees will be even slower (de Avila *et al.*, 2015; Avila *et al.*, 2015); while data on slow events are limited, the slow generation time of the Amazon's largest trees (e.g. Vieira *et al.*, 2005) suggests this could even take millennial time-scales (but see Vidal *et al.*, 2016). Some Amazonian ecosystems appear to be particularly sensitive to disturbance, and may not recover at all; for example, flooded forests enter a state of arrested or impeded succession following forest fires (Flores *et al.*, 2017).

In some contexts, active restoration could assist the recovery of degraded forests. Forests that have burned more than once can lose almost all of their above ground biomass (Barlow and Peres, 2004), and recovery is likely to be impeded by the dominance of vines and bamboos and tree species that are not normally found in primary or later successional forests (Barlow and Peres, 2008). In these forests, or in forests severely damaged by repeated conventional logging, enrichment planting might be a valid approach to improve the ecological condition and societal benefits that can be derived from the forests. Most research on this relates to post-harvesting efforts to improve future timber yield. This research shows that enrichment planting can be effective at small scales when planting has been combined with vine cutting (Keefe *et al.*, 2009) or tending (Schwartz *et al.*, 2013). A study in Borneo shows that active restoration and enrichment can also double carbon uptake over a 20-year time period (Philipson *et al.*, 2020). However, enrichment planting is expensive, difficult to apply at scale, and is only likely to be financially viable under certain economic circumstances (Schulze, 2008; Schwartz *et al.*, 2016). Finally, reintroductions of faunal communities could help reverse species extirpations and restore ecosystem processes, and have been carried out in highly deforested and defaunated ecosystems such as the Atlantic Forest (Genes *et al.*, 2019). Such programs are expensive and challenging, and in most Amazonian regions the terrestrial fauna will be able to recolonize naturally once pressures such as hunting are removed. However, active reintroductions may be worth considering for some of the most fragmented forests, and have been proposed for Woolly Monkeys in the Colombian Amazon (Millán *et al.*, 2014).

The enormous spatial scale and complexity of degradation in the Amazon means the most cost-effective and scalable strategies must focus on avoiding disturbance events in the first place, or prevent reoccurrence. The complex set of human drivers of disturbance means this will involve a broad range of strategies. Some degradation can be avoided by reducing deforestation itself; for example, edge and isolation effects are a direct consequence of forest clearance. Actions to prevent forest fires will involve reducing or controlling ignition sources in the landscape and linking early detection of fires with the rapid deployment of fire combat teams (e.g. Nóbrega Spínola *et al.*, 2020). Avoiding disturbance from illegal and conventional logging will be key, but remains an enormous challenge across the Amazon (Brancalion *et al.*, 2018). Measures addressing activities closely linked to local livelihoods, such as hunting and fire-use in agriculture, will require careful co-development with communities. Management interventions can also try to prevent disturbances from co-occurring. For example, although it may not be possible to prevent climate-driven disturbance without rapid global action on climate change, local management of fires and/or logging could help mitigate their impacts (Berenguer, 2021). Other measures required to reduce or revert degradation are outlined in Chapter 27.

BOX 28.1: Recovery times of anthropogenically degraded forests

Figure B.28.1 Degraded forests in the central Amazon. Photo: Adam Ronan/Rede Amazônia Sustentável (RAS)

Forests affected by selective logging tend to recover their biomass in a timeframe that is almost directly proportional to the biomass removed in the logging process, meaning that on average there would be a 27-year recovery time for a 20% loss of biomass (Rutishauser et al., 2015). However, there are high levels of variation related to soil fertility and climate (Piponiot et al., 2016), and this linear relationship may not hold if the offtake exceeds that permitted by reduced impact techniques. Burned forests are likely to take much longer to recover, as tree mortality continues for many years after the fire (Barlow et al. 2003, Silva et al. 2018). Even low intensity fires in forests that have burned just once lead to 25% reductions in above-ground biomass up to 30 years later, although there are high levels of uncertainty beyond the first 10 years (Silva et al. 2020). Recovery of twice- or thrice-burned forests will be even slower given the very high tree mortality rates (Barlow & Peres, 2008; Brando, Paolucci, et al., 2019). Forest edges (forests within 120 m of a man-made edge) also suffer long-term degradation, with pronounced decreases in above ground biomass in the first five years after edge creation. The longevity of edge effects on forest biomass depends on how the edges are managed; where fires are logging are excluded, species composition changes but biomass levels can approximate interior forests after 22 years (Almeida et al., 2019). However, for most of the Amazon, edges remain exposed to additional disturbances, and biomass levels remain 40% lower than forest interiors 15 years after edge creation (Silva Junior et al., 2020). There is growing evidence that large vertebrates can recover their populations when hunting pressure is alleviated, with increases in game densities following reserve creation. However, group living species such as white-lipped peccaries may take much longer to return to pre-impact levels due to Allee effects (i.e. low individual fitness at low population densities), and recovery will be slower (or even non-existent) in fragmented landscapes where movement and colonization are restricted.

28.3.4. Restoration of sustainable economic activities in deforested lands

In the Amazon basin, opportunities for the restoration of production areas have been established from new or reformed policies to promote environmental protection (Brazil, Lei N° 12.651,de 25 de Maio de 2012; Furumo and Lambin, 2020; Sears *et al.*, 2018; Soares-Filho *et al.*, 2014). Innovative solutions for restoration and sustainable production of food, fiber and other bioproducts in these deforested lands are vital for reconciling inclusive and equitable economic development, in particular at the local level, with environmental conservation in the Amazon basin. The need for the restoration of sustainable and socially-just economic activities in deforested lands is greatest where agriculture is no longer or not yet profitable. There are many landscape-level benefits of this, including increasing overall tree cover, creating space for natural regeneration by increasing productivity (Chazdon *et al.*, 2017), and reducing pressure on natural systems through a forest transition (see Chapter 29). In this section, we focus on the site-level benefits, which include improving the livelihoods and wellbeing of small and medium farmers and traditional communities by enhancing food security, and access to timber and fuel (FAO, 2018; HLPE, 2017). The next paragraphs outline some of the techniques that can be used to meet these aims, focusing on three promising approaches to enhancing productivity: the sustainable intensification of pastures, agroforestry, and improving farm-fallow cropping.

28.3.4.1 Sustainable intensification of pastures

Sustainable intensification, i.e. increasing productivity (of land, labor, and capital, according to the socioeconomic context) while reducing environmental impacts, is particularly relevant on pastures, as extensive cattle ranching based on African grasses (Dias-Filho, 2019; Valentim, 2016; Valentim and de Andrade, 2009) accounts for 89% of the farmed area in the Amazon biome (MAPBIOMAS, 2020) and tends to generate very low or even negative profits (Garrett *et al.* 2017). Productivity rates of these pastures have been estimated to be only 32-34% of their potential (Strassburg *et al.*, 2014). More recently, however, cattle ranching systems are breaking away from the rationale of land occupation and rapid depletion of soil resources that has characterized past decades (Wood *et al.*, 2015). A partial decoupling between cattle production and deforestation has been observed (e.g. (Lapola *et al.*, 2014). Although deforestation has once again increased at the frontier (Smith *et al.* 2021), cattle ranching has become more intensive in the older and more consolidated frontiers of the Brazilian states of Pará and Mato Grosso where there is better access to modern technologies and markets and stronger governance (Schielein and Börner, 2018).

Sustainable intensification of pastures requires effective governance systems that are able to avoid further land conversion and guarantee sustainable development models (Garrett *et al.*, 2018). According to Strassburg *et al.* (2014), increasing the productivity of pastures in the Brazilian Amazon to just 49-52% of their potential would be sufficient to meet national and export demands for meat by 2040, as well as free up land to produce other foods, timber, and biofuels without the need to convert additional areas of native vegetation. This would result in the mitigation of 14.3 GT CO_2e from avoided deforestation.

Technological solutions for sustainable intensification of pastures include changing continuous to rotational grazing associated with increasing pasture productivity (Dias Filho, 2011), adopting mixed grass-legume pastures (Valentim and Andrade, 2004; Zu Ermgassen *et al.*, 2018), and agrosilvipastoral and silvopastoral systems that integrate trees and different agroecosystems (de Sousa *et al.*, 2012; Uphoff *et al.*, 2006; Valentim, 2016). Along with other agroecological approaches, these alternatives are more aligned with regenerative agriculture, as they encompass a set of practices aimed at restoring and maintaining soil quality, supporting biodiversity, protecting watersheds, improving above and belowground linkages and, ultimately, ecological and economic resilience (Bardgett and Wardle, 2010; Ranganathan *et al.*, 2020; White, 2020). For example, these systems could help replace costly nitrogen fertilizer with symbiotically fixed nitrogen by soil bacteria, increase soil quality and agroecosystem resilience, and reduce greenhouse gas emissions per unit of digestible protein produced (Gerssen-Gondelach *et al.*, 2017; Gil *et al.*, 2018; Latawiec *et al.*, 2014). Additionally, they could contribute to increase productivity of land, labor, and capital (Martha Jr *et al.*, 2012). Finally, productive pastures can be managed without fire, removing one of the most prevalent ignition sources from the Amazon (see section on forest degradation).

28.3.4.2. Agroforestry

Agroforestry offers another option to regenerate unproductive lands and maintain production on already deforested lands, and is particularly well-suited to smallholder farms. Agroforestry systems integrate the production of trees and crops on the same piece of land, and can sequester carbon in soils and vegetation as a co-benefit (Ranganathan *et al.*, 2020). Agroforestry contributes to more than one third of the restoration efforts identified in the Brazilian Amazon (Cruz et al., 2020) and will provide benefits beyond the area being planted, such as improving the permeability of the landscape for forest biota or mediating landscape temperatures (see also Chapter 29).

Agroforestry systems have a long history in the region as they date back to the domestication of native plants for agriculture in pre-Columbian times (Miller and Nair, 2006; Clement *et al.*, 2015; Iriarte *et al.*, 2020; see Chapter 8). Contemporary agroforests still include many native species, and the most frequently used are those that have strong demand in local, regional, and international markets such as Brazil nuts (*Bertholletia excelsa*), açai (*Euterpe oleracea*), cocoa (*Theobroma cacao*), cupuaçu (*Theobroma grandiflorum*), and peach palm (*Bactris gassipaes*). Agroforestry systems have been widely applied throughout the basin, from Brazil to Bolivia, Colombia, Ecuador, Peru, Suriname, and Venezuela (Porro *et al.*, 2012). Examples of effective agroforestry can be found in the Japanese-Brazilian colonists of Tomé-Açu's Multipurpose Agriculture Cooperative (CAMTA) in the state of Pará (Yamada and Gholz, 2002) and in the Association of Agrosilvicultural Smallholders of the RECA Project (Intercropped and Dense Economic Reforestation) in Rondônia state (Porro *et al.*, 2012; see Chapter 30).

28.3.4.3. Farm fallow systems

Improving farm-fallow systems has vast potential for sustainable economic restoration in the Amazon, as shifting cultivation is a pillar of traditional farming systems and is common across the entire basin. Restoration options in farm-fallow systems include reducing fire-use by adopting chop-and-mulch and other techniques (Denich *et al.*, 2005; Shimizu *et al.*, 2014), and shortening the cropping periods and increasing the fallow period to restore soil and agricultural productivity (Jakovac *et al.*, 2016; Nair, 1993). Extended fallow periods have additional benefits, provided they do not encourage additional clearance; they can help support the conservation of biodiversity and may improve hydrological functions and other ecosystem services (Chazdon and Uriarte, 2016; Ferreira *et al.*, 2018). Enriching the fallow areas with selected species (e.g. nitrogen fixing legumes, or trees with economic value) could improve economic returns, especially when natural regeneration is no longer adequate to re-establish agricultural productivity (Marquardt *et al.*, 2013).

Whichever approach is adopted or encouraged, it is important that the restoration of economic production enhances biological complexity and diversity, instead of promoting uniformity and specialization as a way to control nature and maximize profit (Garrett *et al.*, 2019; HLPE, 2019). But despite advances in knowledge and policies (Nepstad *et al.*, 2014), restoration of sustainable and socially-just economic activities have yet to overcome the barriers that would allow them to be adopted at large-scales in the region (Bendahan *et al.*, 2018; Valentim, 2016). These systems therefore require a paradigm shift in agriculture and rural development, incorporating principles of equity, local participation and empowerment, food sovereignty, and local marketing systems (Bernard and Lux, 2016). It is important to take into account context specificities through adapted technologies, innovations, and transformation pathways that address the multiple functions of agriculture, forests, and rural activities. They thus call for the design of new methods and metrics to assess performance, and the boosting of learning processes involving multiple stakeholders rather than operating through technology transfer. Moreover, restoration of agricultural land in the Amazon requires much better investment in farming design, using tools for mapping land suitability e.g. (Osis *et al.*, 2019), and communal land-use plans e.g. (Pinillos *et al.*, 2020).

28.4. Aquatic restoration techniques and options

Freshwater systems in the Amazon encompass a tremendous variety of environments, ranging from small streams with short-lived, unpredictable spates to large river floodplain mosaics organized by seasonal annual floods. Although we treat aquatic ecosystem restoration separately in this section, there is important overlap with terrestrial and seasonally flooded landscapes which can have profound influences on water quality and the health of aquatic communities (Affonso *et al.*, 2011; Mayorga *et al.*, 2005; Melack *et al.*, 2009; Melack and Forsberg, 2001).

The spatial dispersion of degradation sources can vary greatly across landscapes and riverscapes. Restoration strategies will differ depending on the types and magnitude of degradation, and whether degradation arises from a diffuse set of sources originating over large areas or more concentrated point sources. In general, restoration from point sources, which can be readily targeted, is more an economic and political challenge, rather than a technical challenge (Bunn, 2016). In contrast, restoring waterways degraded by non-point sources is considerably more complicated, and in many cases requires the restoration of vast areas of terrestrial habitats. Thus, restoration of terrestrial and seasonally flooded landscapes will often be the first filter for the successful restoration of Amazonian aquatic ecosystems and their associated biota, as terrestrial and aquatic ecosystems are inextricably linked.

28.4.1. Restoration after pollution

Amazonian water bodies are polluted by myriad sources, including industrial and agricultural pollution, sewage run-off, mercury and other heavy metals from mining, and oil spills (Chapter 20). These pollutants can come from many sources and become widely dispersed across landscapes and riverscapes. Pollution can travel hundreds of miles downstream, so resolving the source can have wide-ranging benefits downstream. While controlling point sources of pollution is technically feasible, economics, poor governance, and lack of appropriate policies pose a challenge. Addressing non-point sources adds further complexity, and in many cases requires integrating restoration across vast areas, including both terrestrial and aquatic habitats (Bunn, 2016). For example, improvements in terrestrial conditions include regulating chemical use in agriculture and improving run off from urban and industrial landscapes. Diffuse pollution is a particular problem in Amazonian aquatic ecosystems surrounded by human settlements. For example, only 12% of cities in the Brazilian Amazon treat sewage (ANA, 2017). Thus, it is noteworthy that while restoration of Amazonian aquatic ecosystems is key, basic wastewater infrastructure needs to be expanded in the first place.

Pollution from oil extraction and mining has received considerable attention because it is widespread, can be particularly pernicious to ecosystems, and affects many people who rely directly on river water for household use (e.g., drinking, bathing) and fish for food (see chapter 21). In terms of oil extraction, areas in the western Amazon have been widely affected by wastewater and waste oil discharge, and are the focus of clean-up efforts (Finer *et al.*, 2015). However, tools developed in temperate zones can be difficult to apply in tropical ecosystems. For example, one of the most successful methods for remediation in temperate regions involves microbial degradation of oil and gas pollutants, but the most commonly available strains are not necessarily suited for the anoxic conditions of many systems in the Amazon (Maddela *et al.*, 2017). Although new strains are being developed, implementation is further challenged by the logistics associated with reaching remote areas, lack of clear remediation standards, lack of accountability, and limited funding (Fraser, 2018).

Mining for gold, aluminum, copper, and other metals can also result in widespread ecosystem degradation with strong implications for human well-being, particularly because they release toxic materials such as mercury (see chapter 20). Active techniques to restore polluted lands involve improving soil conditions by replanting tree species (Gastauer *et al.*, 2020) or inoculating soils with degrading microorganisms (Couic *et al.*, 2018), but it is not clear how these terrestrially-focused approaches benefit polluted water bodies. In terms of directly restoring water, use of slacked lime for SPM (suspended particulate matter) decantation appears to be an efficient and non-onerous process for gold miners to avoid Hg methylation in tailings ponds when it is combined with rapid drainage of the mine waters (Guedron *et al.*, 2011). The addition of litter and seed to tailing ponds located in wetlands, such as *igapó* flooded forests, can also accelerate plant recovery (Dias *et al.*, 2011).

Another source of contamination in the Amazon's aquatic ecosystems is plastic (see also Chapter 20), which is increasingly recognized as a serious concern for aquatic food chains (Collard *et al.*, 2019; Diepens and Koelmans, 2018; Lacerot *et al.*, 2020) and human health (De-la-Torre, 2020). The Amazon is now among the most plastic contaminated rivers in the world, second only to the Yangtze River in China (Giarrizzo *et al.*, 2019). Plastic bags, bottles, and other plastic solid waste enter Amazonian rivers, with the mainstream a conduit of plastic pollution to the ocean. Tidal flooded forests in the lower Amazon estuary trap some transported litter, with plastic one of the most significant components (Gonçalves *et al.* 2020). As plastic degrades into smaller microplastic pieces (<5 mm), it enters food chains via ingestion by fish and other consumers. To date, a relatively small number of studies have examined microplastic contamination in the Amazon (Kutralam-Muniasamy *et al.*, 2020); however, these existing works help document the enormity of microplastic contamination. A recent study revealed large amounts of microplastics in river sediments around Manaus. Especially high concentrations of microplastics were found in depositional river reaches where backwater effects reduce flow velocities, such as in shallow parts of the lower Rio Negro (Gerolin *et al.*, 2020).

Food web analyses in the Xingu River (Andrade *et al.* 2019) and lower Amazon estuary (Pegado *et al.* 2018) indicate ingestion of microplastics by a broad suite of fish species from different trophic groups, and the transmission of microplastics through the food web. In addition to ecological consequences of plastic pollution in Amazonian waters, a grave concern is the threat of microplastic contaminated fish to food security and human health (De-la-Torre 2020). Given the importance of fish to human diets in the Amazon, there is an urgent need to learn more about microplastics and their capacity to act as endocrine disruptors, mutagens, and other human health risks. Mitigating plastic pollution is an enormous global challenge (Jia *et al.* 2019); one initial step is that some Amazonian nations, including Colombia, Ecuador, and Peru, are beginning to develop rules to govern plastics (Ortiz e al. 2020), and Peru has legislated a progressive phase-out of single-use plastic bags (Alvarez-Risco *et al.*, 2020).

4.2. Dam removal and restoring natural flow cycles and connectivity

Watercourse fragmentation, associated with the construction of dams or other artificial in-stream structures such as culverts, has been identified as one of the main drivers of population declines and reductions in the spatial distribution of freshwater vertebrates (Strayer and Dudgeon, 2010; see Chapter 20). The effects of hydropower dams as barriers to migration and dispersal of aquatic animals are well documented (Anderson *et al.*, 2018) and are related to the formation of the reservoir, modification of the natural flow regime downstream of dams, and the blocking of migratory movements (e.g. Baxter, 1977; Poff *et al.*, 2007; Val *et al.*, 2016). In South America, attempts to minimize their effects on river connectivity are mostly ineffective (Agostinho *et al.*, 2008; Pelicice *et al.*, 2015; Pompeu *et al.*, 2012). Dam removal has arisen as an alternative capable of reversing the impacts generated by dams (Bednarek, 2001; Bernhardt *et al.*, 2005), but such a restoration measure is still restricted to a small number of countries, and no case has been reported for the Amazon.

The reasons that justify the removal of a dam depend on the context in which it is inserted (Maclin and Sicchio, 1999), and various barrier removal prioritization methods have been proposed in recent years (Kemp and O'hanley, 2010; O'Hanley *et al.*, 2020). These usually involve comparing the amount of power produced and the associated environmental costs. One example of a dam that would qualify as a priority for removal is the Hydroelectric Power Plant of Balbina, on the Uatumã river in Amazonas state (Brazil). Balbina is responsible for only 10% of the energy consumed by Manaus (a metropolis with around 2 million people), but created a reservoir of more than 2,300 km² and contributed to the displacement and massacre of the Waimiri Atroari Indigenous peoples (Fearnside, 1989). Additionally, methane released from the decomposition of submerged trees and soil organic matter is comparable, in terms of greenhouse gases per unit electricity generated, to a same-sized coal-fired power plant (Kemenes *et al.*, 2007, 2011). In fact, many existing hydropower dams currently in operation in the lowland Amazon are more carbon-intensive than fossil-fueled power plants (R. M. Almeida *et al.*, 2019). Strategically removing some of them may restore ecosystem services and could reduce the greenhouse gas footprint of the region's power sector if they were replaced with alternative ways of producing renewable energy.

Although the removal of hydropower plants in the Amazon seems unlikely in the short and medium term, there is great potential for restoration actions related to the elimination of smaller barriers. Small dams built to provide water for cattle, small-scale fish production, and local hydroelectric power generation are widespread (Souza *et al.* 2019). For example, 10,000 small impoundments have been estimated only in the Upper Xingu Basin in the lower Amazon (Macedo *et al.* 2013). These small impoundments and lentic water bodies are increasing in abundance as deforestation continues. Removing and improving these smaller impoundments and barriers could be a restoration measure that is feasible in socio-economic terms, as it would have minimal impact on farming systems but could have many local benefits, both upstream and downstream, in terms of water quality, flow, and stream biodiversity.

28.4.2.1. Restoring fisheries and curbing overfishing

Fish provide millions of people in the Amazon, from Indigenous peoples to urban populations, with their primary source of protein, omega-3s, and other essential nutrients (Heilpern *et al.*, 2021; Isaac and De Almeida, 2011). Although there are many commercially viable species, the largest and most important fisheries are based on a subset of about 10-18 species groups found in and around the productive floodplains and estuaries (Barthem and Goulding, 2007). In the Amazon River and tributaries, for example, 10 taxa (species groups) contribute to 85% of the multispecies catch in weight (Barthem *et al.*, 2007; Doria *et al.*, 2018).

The restoration of fisheries in the Amazon involves, in part, addressing overfishing problems through the development of sustainable fishing practices. Data has shown that important fishery resources such as the dourada (*Brachyplatystoma rousseauxii*), piramutaba (*Brachyplatystoma vaillantii,*), and tambaqui (*Colossoma macropomum*) are overexploited (e.g., Goulding *et al.*, 2019; Tregidgo *et al.*, 2017). Historical declines in the maximum average size of the main harvested species have been observed throughout the Amazon (a process called "fishing down") (Castello *et al.*, 2013). Overfishing can be avoided by regulating fisheries and improving and implementing enforcement of regulations. Compliance with regulations such as minimum size limits or season closure has been shown to be a major factor in the recovery of overexploited Pirarucu or Paiche (*Arapaima gigas*) populations in the Middle Solimoes-Amazon River floodplain (Castello *et al.*, 2011;Arantes *et al*. 2010). However, enforcement over an area as extensive and complex as the Amazon is very difficult and expensive. In addition, the lack of engagement and participation of users (fishers) has led to widespread free rider problems. Co-management schemes based on sharing property rights and the responsibility of managing resources among local users, the government, and other stakeholders can help overcome these problems. Co-management can also strengthen local organizations, enhance relations among stakeholders, create mechanisms for restricting access (i.e., defining boundaries), create incentives (e.g. marketing strategies), and improve rule enforcement (Arantes *et al.*, 2021).

Co-management schemes developed for *Arapaima gigas* provide an example of how fisheries can achieve successful outcomes when the fishers' community is truly engaged and given rights and responsibilities to manage resources. In some cases, this has resulted in both the increase in the population of *Arapaima gigas*, and stronger fisher participation in the management process, as they benefited from increased monetary returns (Castello *et al.*, 2009). To expand this effort, it is extremely important to strengthen local organizations and enhance relations among stakeholders, as well as create mechanisms for restricting access (i.e., defining boundaries) and incentives (e.g., marketing strategies), and enforce rules and sanction offenders. Assessing average prices practiced in the international market (Barthem and Goulding, 2007) can improve the recognition of the social and economic value of fishing in the region. Improving the market value of fish can also increase the gain to fishers and reduce pressure on stocks.

Because *Arapaima gigas* is a non-migratory species, the community can perceive the benefits of increased local populations. However, to address overfishing problems related to migratory species such as *Brachyplatystoma rousseauxii* and *Colossoma macropomum*, co-management schemes must be implemented over large regions, within a basin-wide framework that should include international treaties (Cruz et al., 2020). Co-management associated with measures such as quota policies and closed seasons with the remuneration of fishermen (such as the *seguro defeso* in Brazil) can play an important additional role (De Almeida *et al.*, 2015). Maintaining fluvial connectivity is also key for the maintenance of their populations (Chapters 20, 27, and 29).

Fish farming has been growing in the Amazon region, encouraged by local governments, to supply a high demand for fish, as well as a management tool to reduce fishing pressure on native stocks. However, industrial aquaculture can compete with artisanal fishing, producing large quantities of fish and placing it more easily in large markets, marginalizing the value of native fish (Pauly, 2018). The benefits of aquaculture are also held by few producers, who can commercialize the products at larger scales than fishing communities. In addition, without adequate controls, aquaculture can be responsible for the introduction of non-native species (Casimiro *et al.*, 2018; Latini *et al.*, 2016; Orsi and Agostinho, 1999). These non-native species can become invasive, changing the structure of native fish populations and ecosystem interactions, thereby affecting human activities such as fishing (Attayde, 2011; Bailly *et al.*, 2008; Bezerra *et al.*, 2019; Coca Méndez *et al.*, 2012; Simberloff and Rejmánek, 2011; Vitule *et al.*, 2009, 2012). Examples include *Araipama gigas* on the upper Madeira River, and tilapia *Oreochromis niloticus* in different regions of the Amazon (Carvajal-Vallejos *et al.*, 2011; Lizarro *et al.*, 2017; Doria *et al.* 2020). Technical options for recovering native stocks could include the elimination of non-native species by encouraging targeted fishing for these species (Britton *et al.*, 2009; Ribeiro *et al.*, 2015).

Lorenzen *et al.* (2013) proposed that controlling fishing effort, habitat (restoration, rehabilitation), and aquaculture-based enhancement are the principal means by which fisheries can be sustained and improved. It is possible that multiplicative gains may be made through a combination of these approaches, but more research is needed to understand the factors contributing to success or failure, and the application of a more methodical and scientific approach to fisheries restoration should be encouraged. We must move away from treating symptoms to developing a systematic approach for collecting and analyzing data, assessing watersheds, identifying critical issues, and formulating watershed plans to address those issues (Taylor *et al.*, 2017).

28.4.2.2. Restoring floodplains

Floodplains are threatened by a combination of stressors, including loss of hydrological connectivity and habitat, both of which have cascading effects on biota and negatively impact local and regional fish production and diversity (Arantes *et al.*, 2019b). Amazonian floodplain ecosystems span about 8.4×10^5 km^2, 14% of the total Amazon Basin (Hess *et al.*, 2015). They are maintained by seasonal inundation cycles, with a flood pulse that remobilizes riverbed sediment and drives lateral exchanges of organic and inorganic materials between river channels and floodplain habitats, thereby influencing biogeochemical cycles and boosting biological production (Junk *et al.* 1989). These floodplains are heterogeneous, dynamic ecosystems that are amongst the most diverse on the planet, including speciose plant communities (e.g., herbaceous and aquatic macrophyte communities, shrubs, and trees) (Junk *et al.*, 2012; Hess *et al.*, 2015). These plants, in particular forests, provide fish and other aquatic organisms with important food resources and seasonal access to critical nursery and refuge habitat (Arantes *et al.*, 2019a; Goulding, 1980). Recent studies have shown forest cover to be positively correlated with fish biomass and diversity and fishery yields (Arantes *et al.*, 2019a; Castello *et al.*, 2018).

Despite their importance, floodplains are threatened by a combination of stressors, including loss of hydrological connectivity and habitat. Several large and small dams are operating and planned for Amazonian floodplains (e.g, Madeira, Xingu, Tapajos), leading to alterations of river hydrology and sediment/nutrient dynamics (Forsberg *et al.*, 2017). Although a basin-wide assessment of deforestation in these ecosystems is still missing, large areas of floodplains in the lower Amazon River alone were deforested for agriculture over the past 40 years (Reno *et al.* 2018). Jute (*Corchorus capsularis*) plantations and cattle ranching resulted in a loss of 56% of floodplain forest cover by 2008 in the lower Amazon (Reno *et al.* 2011), while even forested areas are becoming impoverished by intensification of acai production (Freitas *et al.*, 2015). Changes in hydrology and deforestation have cascading effects on vertebrate assemblages, and negatively impact fish production and diversity at local and regional scales (Arantes *et al.*, 2019a).

Restoring floodplains requires recovering natural flood pulse regimes and connecting floodplains and habitats that are essential for supporting the biodiversity and services these ecosystems sustain. A first step towards a basin-wide management framework is collecting and disseminating data, and likewise, any restoration measures of floodplains will require as reference a standard base on unmodified systems. It is therefore essential to implement and disseminate effective monitoring systems of hydrology and land cover in floodplains across the basin (e.g., based on sensors, satellite images, gauges). Metrics of inter- and intra-annual variability in hydrological connectivity can help provide standards for defining practical measures for recovering connectivity, such as altering design and operational features, or even removing dams (see section 28.4.2).

Floodplain restoration programs can be achieved through collaborative partnerships and stakeholder involvement (McGrath *et al.*, 2008). Examples include initiatives to reforest levees and replant aquatic macrophytes in the Lower Amazon. Discussion among stakeholders was used to help define project aims and planning, select and collect seeds, and produce seedlings (McGrath *et al.*, 2008). Other experiments have been conducted to restore aquatic macrophyte communities on lake margins

BOX 28.2 Restoration of floodplain forests: the Batata Lake case study

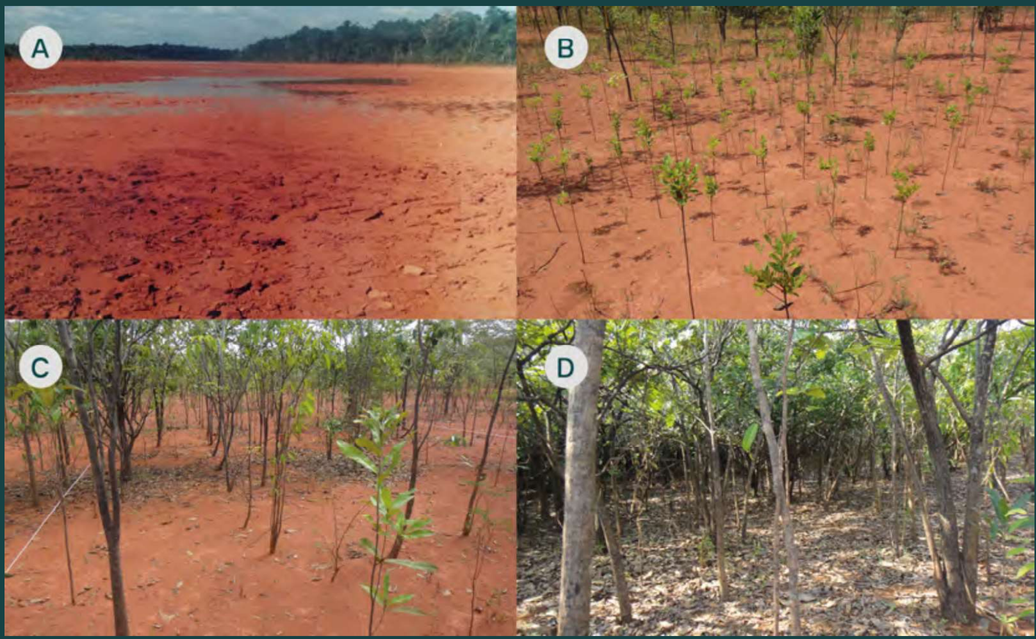

Figure B.28.2. A. Mining sediment in Batata Lake, PA, Brazil, in low water period (December) before the intervention for planting seedlings of igapó species. B. Mining sediment in Batata Lake, PA, Brazil, in low water period (December), planted with igapó species. Larger plants about 15 years old and smaller plants about 2 years old. C. Mining sediment in Batata Lake, PA, Brazil, in low water period (December), planted with igapó species. Larger plants about 20 years old. D. Mining sediment in Batata Lake, PA, Brazil, in low water period (December), planted with igapó species around 20 years old. In addition to closing the canopy, it is possible to observe the recruitment of seedlings and the accumulation of litter on the bauxite tailings, aspects that indicate the sustainability of the planting.

The complexity, high cost, and long-term commitments needed for successful restoration efforts after pollution are demonstrated by Batata Lake, a floodplain ecosystem adjacent to the clear-water Trombetas River in Pará (Brazil). Between 1979 and 1989, millions of cubic meters of bauxite tailings were continually deposited in Batata Lake. As a result, a tailings layer of 2-5 m buried about 600 hectares of the lake, equivalent to ~30% of the lake's area during the flood season, and vast areas of *igapó* vegetation vanished (Bozelli et al., 2000). A long-term restoration program began in the early 1990s and has been ongoing for nearly 30 years; it is considered the largest-scale restoration effort in a seasonally-flooded Amazonian ecosystem (Scarano et al., 2018). Restoration of the newly-deposited sterile substrate was complicated by the low nutrient availability typical of *igapó* ecosystems. As a result, active restoration was undertaken, and approximately half a million individuals of various *igapó* tree species were planted between 1993 and 2005, focusing on the areas where natural regeneration was not occurring. To avoid eutrophication, restoration avoided chemical fertilizers and instead made successful use of litterfall from pristine nearby *igapós* (Dias et al. 2012). By 2018, the combined effect of natural and human-intervened regeneration resulted in the re-establishment of *igapó* vegetation in nearly 70% the impacted area, and the speed of recovery was associated with topography, species introduced, and inundation patterns. However, floristic similarities with native, non-impacted sites remain moderate in most parts of the impacted area; estimates suggest some areas may take over 75 years to restore to levels similar to those of non-impacted *igapó* ecosystems. The multidisciplinary team of experts involved with the restoration efforts contend that species selection, litter and seed addition, and continuous monitoring are key for an accelerated successional trajectory in the restoration of Amazonian *igapó* ecosystems (Scarano et al 2018) and surfaces, and to control erosion (Arantes personal comm.; McGrath and Crossa 1998). Unfortunately, these experimental initiatives are often undermined by uncontrolled cattle grazing in the floodplains. Implementing successful floodplain restoration programs therefore requires addressing cattle grazing regulations. It would also benefit from developing engagement programs with fishing communities, to understand the challenges whilst increasing awareness of the benefits of recovering floodplain habitats.

28.5. Indicators of success

The broad range of restoration techniques outlined above provide a toolkit for site- and target-specific restoration actions, but how do you evaluate success or failure? This is key to understanding the factors underpinning restoration performance, learning from them in an adaptive manner to inform policies and improve interventions in the future, tracking national commitments made for climate change and biodiversity, and holding businesses to account. But despite the many advantages, such monitoring and evaluation is rarely undertaken in a comprehensive manner in restoration (Murcia *et al.*, 2016; Suding, 2011).

There are a broad range of potential indicators of success (e.g. Ruiz-Jaen and Mitchell Aide, 2005; Stanturf *et al.*, 2015), and they vary greatly in their ease and scalability. For example, open-source platforms such as MapBiomas mean that year-on-year changes in forest cover can be assessed across the Amazon with reasonable accuracy. However, property-level or landscape- and catchment-specific changes will likely require more tailored assessments and higher-resolution imagery (D. R. A. de Almeida *et al.*, 2020). This is especially important when restoration focusses on narrow strips or small patches, including riparian zones; buffers the edges of existing forests; develops agroforestry systems rather than closed-canopy forests; or focusses on aquatic systems, non-forest ecosystems or fauna.

A more detailed understanding of restoration success will require ground-based assessments to evaluate carbon stocks, biodiversity, aquatic condition, or socio-economic values (Wortley *et al.*, 2013). Monitoring might encompass different plant community properties, such as canopy cover, basal area, and density and richness of regenerating plants (Chaves *et al.*, 2015; Suganuma and Durigan, 2015). These indicators are much harder to collect at scale, and they must be defined in a participative way with local stakeholders to ensure their sampling is cost effective, realistic given the expertise and resources available, and sustainable over time (Evans *et al.*, 2018). New technology such as the mobile app Ictio, which is designed to collect standardized information on fisheries from individual users at scale, provides an example of one potential solution. Additional, practical tools using simple criteria should be developed for assessing mandatory restoration projects in the context of public policies (Chaves *et al.*, 2015). Finally, we need to learn from monitoring and evaluation efforts; the information needs to pooled, analyzed, and used to create a comprehensive, evidence-based understanding of effectiveness. This information can also support the development of modeling tools that are able to simulate different scenarios of restoration, providing stakeholders with a means to take the most adequate decision and select the restoration program which best fits their objectives. The inclusion of a diverse range of stakeholders will be essential in this process (Chapter 29)

28.6. Conclusion

There are many opportunities for restoration that are relevant and technically feasible in diverse Amazonian contexts; the Alliance for Restoration in the Amazon has identified 2,773 terrestrial initiatives in the Brazilian Amazon alone, covering around 1,130 km^2 (Alliance for Restoration in the Amazon, 2020). Yet many of the restoration approaches are small scale, with 79% under 5 ha (Alliance for Restoration in the Amazon, 2020). They are also expensive, and face significant challenges with spatial and temporal scalability. Resolving this requires a broad program of investment, dialogue, and prioritization (Alliance for Restoration in the Amazon, 2020), and should always consider priorities and co-benefits across landscapes and the basin (Chapter 29). Finally, restoration should only ever be seen as a last resort. For vast areas of the Amazon, the primary aim should be to avoid the need for future restoration by conserving intact forests and waterbodies (Chapter 27).

28.7. References

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