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WG 10 Restoration, Conservation, and Forest Transitions (Opportunities, Strategies and Challenges in Terrestrial and Aquatic systems)

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Restoration options for the Amazon

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Chapter 28

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 aquatic and terrestrial realms, and goes beyond natural ecosystems to include the recovery of socially-just economic activities on deforested lands.

- Within terrestrial systems, site-specific restoration options include speeding up recovery after mining, reforesting the vast swathes of deforested land, facilitating the recovery of degraded primary forests, and the restoration of sustainable economic activities in 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 to restore terrestrial and aquatic systems, focusing on the local actions and benefits. Landscape and biome-wide considerations are addressed in Chapter 29. Conservation approaches are addressed in Chapter 27.

Keywords: Remediation, Rehabilitation, Rewilding, Resilience, Succession

1. INTRODUCTION

Human-driven changes across Amazonia landscapes have affected biodiversity and associated ecological processes (Chapters 19 and 20); this, in turn, has direct and indirect impacts on human wellbeing (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. These are supported internationally by initiatives such as the Bonn Challenge, New York Declaration on Forests and the 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 not just about the ecosystems and its processes and services: small-scale agriculture and fisheries are vital livelihoods for the millions of people inhabiting the region. As a result, designing successful restoration approaches need to consider the increasing evidence of benefits for people, including restoring sustainable and socially-just economic activities. This chapter examines site-specific approaches for restoration in terrestrial and aquatic systems; landscape, catchment and whole-biome considerations. It covers the aims and definitions of restoration, details site-specific restoration actions in terrestrial and aquatic systems, and briefly discusses some of the considerations related to monitoring and evaluation of restoration success. Landscape and biome level considerations of restoration are developed in Chapter 29.

2. DEFINITIONS AND AIMS OF RESTORATION

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 (Mansourian, 2018; Fagan et al., 2020). We use restoration as an overarching term that encompasses the very broad suite of objectives that can be met, including specific targets relating to 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). For example, 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 (Figure 1, 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.

Ecosystem restoration: Historically, restoration ecology focused on the processes to recover ecosystems to a reference site (e.g. primary or pristine forests) (in Palmer et al. 2014). For example, in their international principles and standards for the practice of ecological restoration, the Society for Ecological Restoration define ecological restoration as any activity with the goal of achieving substantial ecosystem recovery relative to appropriate reference models which include native ecosystems, as well as traditional cultural ecosystems. 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 Amazonia, 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).

Functional restoration: Targeting the recovery to pristine conditions is not necessarily the main objective of every restoration program. Many restoration programs developed in the framework of the Bonn challenge, target the restoration of the ecological and ecosystem functions of ecosystems at landscape level, while enhancing human well-being of populations (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, Figure 2).

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 and restoration can be very different from target-driven restoration in many temperate contexts, within Amazonia 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, most Amazonian secondary forests and rivers will provide suitable habitat for the largest vertebrates and apex predators.

Remediation: Remediation involves stopping or reducing pollution that is threatening the health of people or wildlife or ecosystems, in contrast with restoration which refers to actions that directly improve environmental services or other ecological properties (Efroymson et al., 2004). Therefore remediation generally occurs before restoration, and can help create the basic conditions for implementing restoration actions. 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 Amazonia, an example includes the remediation of localized soil contamination combined with natural attenuation and the planting of trees (Efroymson et al. 2004).

Additional definitions

Beyond defining what is restoration, there are some additional definitions that are useful to clarify. Ecological restoration 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 recognise 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 (cross cutting Box X). We use primary forests to describe forests that have never knowingly been clear-felled, accepting that there is a lack of certainty about pre-Colombian history [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 are 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 (Robinson et al. 2010; (Negrón-Juárez et al., 2010; Brando et al., 2014). The degree of degradation depends on the cause (fire, logging, fragmentation), the intensity of degradation (low logging vs high logging intensity) and the frequency (repetitive logging, repetitive fire) (Chapter 17) (Bourgoin et al., 2020; Matricardi et al., 2020).

Finally, for terrestrial restoration, we have 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 the ecological function of the landscape (Veldman, 2016).

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).

3.1. Restoration after complete removal of soil

The extraction of mineral and fossil fuels are increasingly significant drivers of tropical deforestation and degradation, biodiversity loss and greenhouse gas emissions in Amazonia (Fearnside, 2005). Around 21% of the region is under potential hydrocarbon (327 oil & 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 Western Amazonia (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 private leased lands (Asner et al., 2013; Lobo et al., 2016; Sonter et al., 2017; Kalamandeen et al., 2018), often 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 (Lamb et al., 2005; Barrios et al., 2012; Kalamandeen et al., 2020). It can also disrupt important aboveground ecosystem services such as pollination, seed dispersal and pest control. For instance, birds have been well documented for dispersing tree seeds from primary forests into recovering areas (Bregman et al., 2016). 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; Stanturf et al., 2014; Gilman et al., 2016), 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 was the most productive treatment of basal area development and height growth for restoration of 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 (Palma and Laurance, 2015; Grossnickle and Ivetić, 2017; 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 accumulated the highest biomass in the first 9-13 years, these were also the least species rich (Parrotta and Knowles, 1999; Crouzeilles et al., 2016; Chazdon et al., 2020). For instance, species richness ranged from ~17 to 35 species per plot (100 m2) in restored sites after 8 years near Paragominas, Brazil (Uhl and Almeida, 1996; Parrotta and Knowles, 1999). In contrast, planting with a mix of native species could more effectively enhance forest resilience in the longer term and reduce the risk of arrested succession (Parrotta and Knowles, 2001).

There is growing evidence that 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 suggests that above-ground conditions can also influence below ground communities: restoration with higher plant diversity encouraged plant-soil feedbacks, resulting in more favourable restoration trajectories (Jia et al., 2020).

Relative to other land uses, mining may be the most disruptive activity on biomass and forest recovery, resulting in a loss of ~2 million tons of carbon annually (Kalamandeen et al., 2020). In particular, the standards and best practices available for pre- and post-mining activity and restoration becomes important. Many Amazonian countries have systematic processes developed for post-mining restoration that include actions such as backfilling mined sites with topsoils 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 IADB and World Bank's use of the IFC 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.

3.2. Restoration of vegetation on deforested land

The loss of at least 867,675 km² of Amazonian primary forests to date 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) – although other notable deforestation hotspots exist in Colombia, Peru and Bolivia. Within the Brazilian Amazon, 20% of the 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 landholders to maintain between 50 and 80% of forest cover on their lands.

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 few actions are taken to alter the successional trajectory.

Although these unplanted secondary forests are frequently referred to as 'passive' restoration, their recovery can still 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 will 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 and clearance remains challenging. Secondary forests have their greatest extent in the most deforested regions of the Amazon, but increasing forest cover in these landscapes is challenging. For example, landscapes that were >80% deforested in 1997 continued to show an overall loss - and not recovery - of forest cover up to 2017 (Smith et al. 2021). Secondary forests in particular 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). Restoration programms will need to develop incentives to protect existing secondary forests as well as encouraging further restoration.

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 (da 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 up to 450 seed collectors at any one time has nonetheless restored just 50km² of forest (Schmidt et al., 2019), which is a tiny fraction of the natural land abandonment that occurred over the same period (Smith et al., 2020).

Species choices are important in active restoration. 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). She spatial configuration of active restoration matters - nurse trees can function to 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 (Zahawi et al., 2013; Rodrigues et al., 2019). Some active restoration approaches may 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. Despite the many challenges of finding and scaling effective active restoration should not detract from the important role it can play in certain contexts, such as when previous land use intensity has been high, if there are few seed sources in the vicinity, or when prioritising 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, even where unidimensional measures are evaluated. For example, there are ten-fold differences in estimates of carbon accumulation in passively regenerating lowland Amazonian forests, with estimates ranging from as low as 1 to as high as 10 Mg ha-1 yr-1 (Elias et al., 2020). The recovery of biodiversity is also variable. Some studies show a strong positive relationships between the recovery of species richness or composition and above-ground carbon or biomass (Gilroy et al., 2014; Ferreira et al., 2018; 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 (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 the rarest species and species with the most restricted ranges are unlikely to use all but the oldest secondary forests (Moura et al., 2013; Lennox et al., 2018).

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 (Poorter et al., 2016; Elias et al., 2020). Even small differences in previous land use, such as the intensity, frequency, duration, extent and type, affect successional pathways (Jakovac et al., 2021). Landscape context can also play a key role in driving recovery (Chapter 26), with proximity to existing forest edges (Jacovak et al. 2021) and high forest cover landscape having strong and positive effects on recovery (Leitold et al., 2018; Camargo et al., 2020).

There is also an important variation in the costs of returning agricultural land to forest. Some of these are associated with the 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 these areas 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 NTFPs, such as fruits, resins, honey or building materials (Chapter 30 Bioeconomy).

3.3. Restoration of degraded forests

There are many different drivers of forest degradation in Amazonia (Chapter 17). Human-driven disturbances 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 (Phillips et al., 2009; Espírito-Santo et al., 2014; Leitold et al., 2018). The impact of the disturbance – hence 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 that may not be easily discerned without careful studies of changes in species composition (e.g. Terborgh et al., 2008; Harrison et al., 2013). Disturbances often co-occur, and when assessed together can drive as much biodiversity loss as deforestation itself (Barlow et al., 2016).

Large-scale assessments of degradation extent focus on the 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 was 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 98% of its forest cover remaining (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 (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). Once a forest has been degraded, the probability of further change provides important insights into management. Crucially, only 14% of degraded forests are eventually deforested (Bullock et al., 2020), and there are two complementary conclusions from this. First, it is important to avoid the deforestation of these degraded forests: although they have a lower conservation value and deliver fewer ecosystem services than undisturbed forests, they often remain significantly more important than alternative land uses and secondary forests (Edwards et al., 2011; Berenguer et al., 2014; Barlow et al., 2016). Second, as most degraded forests remain in the landscape, it is important to support actions that go beyond deforestation and also tackle degradation (c.f. Barlow et al., 2016).

Bullock et al. (2020) also show that around 29% of forests that were degraded within the time-scale of the study were degraded again – a number that could be much higher if non-structural forms of degradation were included or if the assessment was carried out over longer time periods. This demonstrates the importance of avoiding further degradation, 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 (Uhl and Kauffman, 1990; Camargo and Kapos, 1995; Ray et al., 2005; Silva Junior et al., 2018). 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 (Gerwing, 2002; Brando et al., 2019b)

Up to 57% of degraded Amazonian forests are left to recover (Bullock et al., 2020). Recovery times are highly variable, depending on the type and intensity/severity of the disturbance, but our understanding has improved in recent years. They are slowest for burned forests, especially if forests have been burned more than once, and are likely to be fastest in hunted forests where game species are able to recolonise **(Box X)**. 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) while burned forests can quickly recover their capacity to cycle water (Brando et al., 2019b). 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)(Rutishauser et al., 2015; Silva et al., 2018, 2020). The recovery of species composition and large trees will be even slower – while data on slow events are limited, the slow generation time of Amazonia's largest trees (e.g. Vieira *et al.* 2005) suggests this could take millennial time-scales. Finally, 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 succession following forest fires (Flores et al., 2017).

In some contexts, active restoration may help the recovery of degraded forests. Forests that have burned more than once 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 never 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 try and 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. 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, and is only likely to be financially viable under certain economic circumstances. Finally, reintroductions of faunal communities can help reverse species extirpations and restore ecosystem processes in the Atlantic forest (Genes et al., 2019). Such programs are expensive and challenging, and in most regions fauna will be able to recolonise naturally once pressures 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 from occurring in the first place, or from re-occurring where they have already occurred. 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 aimed 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. 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 try and prevent negative stressors from combining. For example, forest fires are more likely and more damaging in agricultural frontiers and near forest edges (Silva Junior et al., 2020) and in forests that have been previously logged or degraded (Gerwing, 2002; Blate, 2005). In these cases, avoiding further deforestation, encouraging forest restoration to buffer forest edges, and avoiding logging in fire-sensitive regions of the Amazon could help limit degradation, and support the recovery of already degraded forests. 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 its impacts (Berenguer, 2021). A more detailed overview of measures taken to reduce or revert degradation are outlined in Chapter 29.

3.4. Restoration of sustainable economic activities in deforested lands

In the Amazon basin, a wide window of opportunities for restoration of production areas has been established from new or reformed policies to promoting environmental protection (Brasil, 2012; Soares-Filho et al., 2014; Sears et al., 2018; Furumo and Lambin, 2020). 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 forest transition (see Chapter 29). In this section, we consider the site-level benefits, which include improving the livelihoods and wellbeing of small and medium farmers and traditional communities by enhancing food security, access to timber and fuel (HLPE, 2017; FAO, 2018). 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.

3.4.1 Sustainable intensification of pastures

Sustainable intensification - i.e. increasing productivity (of land, labour, capital according to the socioeconomic context) while reducing environmental impacts- is particularly relevant on pastures, as extensive cattle ranching based on African grasses (Valentim and de Andrade, 2009; Valentim, 2016; Dias-Filho, 2019) 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 decoupling between cattle production, which is increasing, and deforestation, which is decreasing, or persisting in other regions, has been observed (e.g. Lapola *et al.* 2014). Cattle ranching has become more intensive in the older and more consolidated frontiers of the Brazilian Amazon states of Pará and Mato Grosso where there is better access to modern technologies and markets and stronger forest governance (Schielein and Börner, 2018).

Sustainable intensification of pasture 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 the demand for food, wood and biofuels by 2040, without the need to convert additional areas of native vegetation - therefore resulting in the mitigation of 14.3 GT CO_2e from avoided deforestation. In addition, productive pastures can be managed without fire, removing one of the highest risks and most prevalent ignition sources from the Amazon (see section on forest degradation).

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 (Uphoff et al., 2006; de Sousa et al., 2012; 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 replace costly nitrogen fertilizer by symbiotically fixed nitrogen by soil bacteria, increase soil quality and agroecosystem resilience, and reduce greenhouse gas emissions per unit of digestible protein produced (Latawiec et al., 2014; Gerssen-Gondelach et al., 2017; Gil et al., 2018). Additionally, they contribute to increase productivity of land, labor and capital (Martha Jr et al., 2012).

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 for smallholder farms. Agroforestry systems integrate the production of trees and crops species 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 (da

Cruz et al., 2020), includes many native species, and will provide benefits beyond the area being planted, such as improving the permeability of the landscape for forest biota or mediating landscape temperatures.

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, link to 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's (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) 2012, link to chapter 27 on Bioeconomy). Agroforestry can be expected to have benefits beyond the area being planted, such as improving the permeability of the landscape for forest biota or mediating landscape temperatures (see Chapter 26)

3.4.2. Farm fallow systems

Improving farm-fallow systems has vast potential for sustainable economic restoration in the Amazon, as shifting cultivation is the 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 (Nair, 1993; Jakovac et al., 2016). Extended fallow periods have additional benefits, as they can help protect biodiversity through the formation of corridors, 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 fast-growing 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 cross the barriers that would allow them to be adopted at large-scales in the region (Valentim, 2016; Bendahan et al., 2018). 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 & Lux, 2017). It is important to take into account each 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 performances and for boosting learning processes involving multiple stakeholders rather than operating through technology transfer. Moreover, restoration of agricultural land in the Amazon requires ample farming design investment, using tools for mapping land suitability (e.g. Osis *et al.* 2019) and communal land-use plans (e.g. Pinillos *et al.* 2020).

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 (Melack and Forsberg, 2001; Mayorga et al., 2005; Melack et al., 2009; Affonso et al., 2011). 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.

4.1. Restoration after pollution

Pollutants that degrade aquatic ecosystems can come from many sources and become widely dispersed across landscapes and riverscapes. 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 complexities, and in many cases requires integrating restoration across vast areas including terrestrial and aquatic habitats (Bunn, 2016). In contrast to remediation of point source pollution, restoring waterways degraded by non-point sources is considerably more difficult, and in many cases requires the restoration of vast areas of terrestrial habitats.

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. Restoration generally entails two broad approaches. First, given the strong aquatic-terrestrial linkages, remediation needs to improve terrestrial conditions by regulating chemical use in agriculture, and improving run off from urban and industrial landscapes. Second, restoration can attempt to directly improve water conditions. Pollution can travel hundreds of miles downstream, so resolving the source can have wide-ranging benefits downstream. Indeed, diffuse pollution is a common problem in many Amazonian aquatic ecosystems surrounded by human settlements. For example, less than 15% of Brazilian Amazon cities treat sewage (IBGE, 2011). 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 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 logistics associated with reaching these remote areas, lack of clear remediation standards and accountability and limited funding (Fraser, 2018).

Mining for gold, aluminium, 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 19). 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). 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 Amazon aquatic ecosystems is from plastic (see also Chapter 20), which is increasingly recognized as a serious concern to aquatic food chains (Diepens and Koelmans, 2018; Collard et al., 2019; Lacerot et al., 2020) and to 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, plastic bottles, and other plastic solid waste enter Amazon rivers, with the mainstem as a conduit of plastic pollution to the ocean. Tidal flooded forests in the lower Amazon estuary trap some transported litter, with plastic as one of the most significant litter 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 the central Amazon city of 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 the 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 Amazon 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 diet 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 risk. Mitigating plastic pollution is an enormous global challenge (Jia et al. 2019); one initial step is that some Amazon nations, including Colombia, Ecuador, and Peru, are beginning to develop rules for governance of 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), 2010;). The effects of hydropower dams as barriers to migrations 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 the dam and blocking migratory movements (e. g. see (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; Pompeu et al., 2012; Pelicice et al., 2015)). 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 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 of Brazil. Balbina is responsible for only 10% of the energy consumed by Manaus (a metropolis with around 2 Million people) but created a reservoir with more than 2300 km² and contributed to the displacement and massacre of the Waimiri Atroari indigenous peoples (Fearnside, 1989). Additionally, the methane released from the decomposition of trees and the organic matter in the soil emits more greenhouse gases per unit electricity generated than 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 (Almeida et al., 2019b). 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 which could have many local, upstream and downstream benefits, in terms of water quality, flow, and stream biodiversity.

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 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., (Tregidgo et al., 2017; Goulding et al., 2019). Historical declines in the maximum average size of the main harvested species has been observed through the Amazon (a process called “fishing down”) (Castello et al. 2013). Overfishing can be avoided by regulating fisheries and improving/implementing enforcement of regulations. Compliance with regulations such as the minimum size limits or season closure has been shown to be a major factor leading overexploited arapaima populations to recover 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 the users (fishers) has been shown to lead to widespread free rider problems. Developing co-management schemes, which are based on sharing property rights and responsibility of managing resources among local user and the government and other stakeholders can help to 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* (pirarucu, paiche) provide an example of how fishery can achieve successful outcomes when fishers’ community are truly engaged and are given rights and responsibilities to manage resources. In some cases, this has resulted in both the increase in the population of pirarucu, 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 creating mechanisms for restricting access (i.e., defining boundaries), creating incentives (e.g., marketing strategies) and enforcing rules and sanctioning offenders. An 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 the fish can also increase the gain with the fishing and reduce pressure on stocks.

Because the arapaima is a non-migratory species, the community can perceive the benefits of increased local arapaima populations. However, to address overfishing problems related to migratory species such as Dourada and Tambaqui, co-management schemes must be implemented over large regions, at a Basin wide framework level that should include even 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 role as well (De Almeida et al., 2015). Maintaining fluvial connectivity is also key for maintenance of their populations as described in other sections.

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 hold by few producers that can commercialize the products in larger scales than fishing communities do. In addition, without adequate controls, aquaculture can be responsible for the introduction of non-native species (Orsi and Agostinho, 1999; Latini et al., 2016; Casimiro et al., 2018). These non-native species can become invasive, changing the structure of the native fish population and ecosystem interactions, thereby affecting human activities such as fishing (Bailly et al., 2008; Vitule et al., 2009, 2012; Attayde, 2011; Simberloff and Rejmánek, 2011; Coca Méndez et al., 2012; Bezerra et al., 2019). Examples include *Araipama gigas* on the upper Madeira river, and *Oreochromis niloticus* in different regions of the Amazon (Carvajal-Vallejos et al., 2011; Lizarro et al., 2017; Doria et al. 2020). The technical options for recovering native stocks could be 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 go from the approach of treating symptoms to developing a systematic approach for collecting and analysing data, assessing watersheds, identifying critical issues, and formulating watershed plans to address the critical issues (Taylor et al., 2017).

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., 2019a). Amazonian floodplain ecosystems span about 8.4×10^5 km^2, 14 % of the total Amazon basin area (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 and dynamic ecosystems that are amongst the most diverse ecosystems on the planet, including diverse plant communities (e.g., herbaceous and aquatic macrophyte communities, shrubs and forests, Junk et al. 2012, Junk et al., 2012; Hess et al., 2015). These plants, and, in particular forests, provide fishes and other aquatic organisms with important food resources and seasonal access to critical nursery and refuge habitat (Goulding, 1980; Arantes et al., 2019b): recent studies have shown forest cover to be positively correlated with fish biomass and diversity and fishery yields (Castello et al., 2018; Arantes et al., 2019b).

Despite their importance, floodplains are threatened by a combination of stressors, including losses 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, over the past 40 years, large areas of floodplains in the lower Amazon river alone were deforested for agriculture (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 alone (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., 2019b).

Restoring floodplains requires recovering (or, maintaining in cases of pristine areas) natural flood pulse regimes, connecting floodplains and habitats that are essential to promote biodiversity and services these ecosystems sustain. A first step towards the Basin-Wide management framework is collecting and disseminating data, and likewise, any restoration measures of floodplains will require references standard base on unmodified systems. To this aim, it is 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). Using metrics of inter- and intra-annual variability in hydrological connectivity can provide standards for defining practical measures for recovering connectivity such as altering design and operational features, or even removing dams (for details see section on dam removal).

Floodplain restoration programs can be achieved through collaborative partnerships and stakeholder involvement (McGrath et al., 2008). Examples of collaborative partnerships in the Amazon to restore floodplain habitats include the initiatives to reforest levees and replant aquatic macrophytes in the Lower Amazon. The projects included discussion among stakeholders to define the aims and planning activities, selection and collection of seeds and seedling production and plantation (McGrath et al., 2008). Other experiments have been conducted to restore aquatic macrophyte communities of the lake margins and surface to control erosion (Arantes personal comm., McGrath and Crossa 1998). Unfortunately, these experiments are often undermined by uncontrolled cattle grazing that takes place in these floodplains. Implementing successful restoration programs of floodplains requires addressing cattle grazing regulation problems as well as developing engagement programs with fishing communities to increase awareness on the benefits of recovering floodplain habitats.

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 – yet it is rarely undertaken in a comprehensive manner in restoration (Suding, 2011; Murcia et al., 2016).

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 means 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 high-resolution imagery, (de Almeida et al., 2020). This is especially important if restoration focusses on narrow strips or small patches or when restoration does not lead to immediate canopy closure, which could be the case when it is targeting riparian zones, buffering the edges of existing forests, or when restoration aims to develop agroforestry systems rather than closed-canopy forests.

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 community properties, such as canopy cover, basal area, 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 the local stakeholder to ensure they are cost effective, realistic given the expertise and resources available, and are 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, is 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 these monitoring and evaluation, and the information needs to pooled, analyses, and used to develop modeling tools that are able to simulate in time different scenarios of restoration programs so the stakeholders can take the most adequate decision and select the restoration program which best fit with their objectives.

6. CONCLUSION

There are many opportunities for restoration that are relevant and technically feasible in diverse Amazonian contexts. Many restoration approaches are expensive and therefore face significant challenges with spatial and temporal scalability. Active restoration and remediation are particularly challenging to implement effectively and scale up, but remain essential in situations where passive approaches are ineffective. Finally, restoration should always consider priorities and co-benefits across landscapes and the basin (Chapter 29) and 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).

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BOXES

Box 1 Recovery times of anthropogenically degraded forests

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 low impact techniques. **Burned forests** are likely to take much longer to recover, as tree mortality continues for many years after the fire and is not compensated for by biomass accumulation of regrowth (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 and Peres, 2008; Brando et al., 2019a). **Forest edges** (forests within 120m of a man-made edge) also suffer long-term degradation, causing sharp 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 fire is excluded, species composition changes but biomass levels can approximate interior forests after 22 years (Almeida et al., 2019a). However, for most of the Amazon, edges remain exposed to fires – meaning biomass levels do not recover and remain 40% lower than forest interiors 15 years after edge creation (Silva Junior et al., 2020). **Hunted forests**. 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 colonisation are restricted.

Box 2. Restoration of floodplain forests: the Batata Lake case study

The complexity, high cost and long-term commitments needed for successful restoration efforts after pollution are demonstrated by the Batata Lake, a floodplain ecosystem adjacent to the clear-water Trombetas River in Pará. 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, and 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 >75 years to restore pre-disturbance similarity levels with non-impacted igapó ecosystems. The multidisciplinary team of experts involved with the restoration efforts in Batata Lake contend that thorough selection of planted species, litter and seed addition, and continuous monitoring are key for an accelerated successional trajectory in the restoration of Amazon igapó ecosystems (Scarano et al 2018).