Chapter 28 In Brief

Restoration options for the Amazon

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

THE AMAZON WE WANT
Science Panel for the Amazon

Restoration options for the Amazon

Jos Barlow[a], *Plinio Sist*[b], *Rafael Almeida*[c], *Caroline C. Arantes*[d], *Erika Berenguer*[a,e], *Patrick Caron*[f], *Francisco Cuesta*[g], *Carolina R. C. Doria*[h], *Joice Ferreira*[i], *Alexander Flecker*[c], *Sebastian Heilpern*[j], *Michelle Kalamandeen*[k], *Alexander C. Lees*[l], *Marielos Peña-Claros*[m], *Camille Piponiot*[n], *Paulo Santos Pompeu*[o], *Carlos Souza*[p], *Judson F. Valentim*[q]

Key Messages & Recommendations

1) 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.
2) 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.
3) 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.
4) 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 forests and waterbodies.

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.

[a] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK, jos.barlow@lancaster.ac.uk
[b] Université de Montpellier, CIRAD, UR Forests & Societies, Campus International de Baillarguet, TA C-105/D, 34398 Montpellier Cedex 5, France, sist@cirad.fr
[c] Department of Ecology and Evolutionary Biology, Cornell University, E145 Corson Hall, Ithaca NY 14853, USA
[d] Center for Global Change and Earth Observations, Michigan State University, 218 Manly Miles Building, 1405 S. Harrison Road, East Lansing MI 48823, USA
[e] Environmental Change Institute, Oxford University Centre for the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
[f] Université de Montpellier, CIRAD, ART-DEV, Campus International de Baillarguet, TA C-105/D, Montpellier 34398, France
[g] Grupo de Investigación en Biodiversidad, Medio Ambiente y Salud (BIOMAS), Universidad de Las Américas (UDLA), De Los Colimes esq, Quito 170513, Ecuador
[h] Laboratório de Ictiologia e Pesca, Departamento de Ciências Biológicas, Universidade Federal de Rondônia (UNIR), Av. Pres. Dutra 2965, Olaria, Porto Velho RO 76801-058, Brazil
[i] Embrapa Amazonia Oriental, Trav. Dr. Enéas Pinheiro, s/n°, Bairro Marco, Belém PA 66095-903, Brazil
[j] Department of Natural Resources, Cornell University, 226 Mann Drive, Ithaca NY 14853, USA
[k] School of Geography, University of Leeds, Leeds LS2 9JT, UK
[l] Department of Natural Sciences, Manchester Metropolitan University, All Saints Building, Manchester M15 6BH, UK
[m] Department of Environmental Sciences, Wageningen University and Research, PO Box 47, 6700AA Wageningen, The Netherlands
[n] Smithsonian Conservation Biology Institute & Smithsonian Tropical Research Institute, 3001 Connecticut Avenue NW, Washington DC 20008, USA
[o] Departamento de Ecologia e Conservação, Instituto de Ciências Naturais, Universidade Federal de Lavras, Aquenta Sol, Lavras MG 37200-900, Brazil
[p] Instituto do Homem e Meio Ambiente da Amazônia (IMAZON), Trav. Dom Romualdo de Seixas 1698, Edifício Zion Business 11th Floor, Bairro Umarizal, Belém PA 66055-200, Brazil
[q] Agroforestry Research Center of Acre, Embrapa Acre, Rodovia BR-364, Km 14 (Rio Branco/Porto Velho), Rio Branco AC 69900-970, Brazil

Introduction Human-driven changes across Amazonian landscapes have affected biodiversity and associated ecological processes; this, in turn, has direct and indirect impacts on human well-being. Although much of the focus in the Amazon should be on preventing further forest loss and degradation (see Chapter 27), there is growing awareness of the importance of restorative actions aimed at reversing these processes. Restoration could be a fundamental component of nature-based solutions that address critical societal challenges[1], including the protection and sustainable management of aquatic and terrestrial ecosystems, whether natural, human-made, or a combination of both[2].

Definitions and aims of restoration Before examining the role of restoration, we must define it across the aquatic and terrestrial realms. We use restoration as an overarching term that 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/or peoples' livelihoods[3]. Our use of restoration therefore includes specific terms such as *rehabilitation, remediation*, and *rewilding.* Crucially, restoration also includes the recovery of sustainable and socially-just economic activities on deforested lands. In many cases, actions will require avoiding further environmental harm as well as encouraging recovery.

Restoration actions can be either (human) assisted or (natural) passive. We specify which approach is required where relevant to the outcome, but recognize that this is often a continuum. Even passive restoration of secondary or degraded forests can require active decision-making and management interventions (e.g., fire control, fencing). Finally, spatial considerations are not considered here; the strategic planning of restoration options across the Amazon basin and within landscapes and catchments are addressed in Chapter 29.

Terrestrial restoration options

Restoration after complete soil removal Mineral and hydrocarbon extraction remove or alter soils, disrupt nutrient cycling, and severely inhibit forest recovery by destroying the soil seed bank and soil biota[4–6]. Additional ancillary effects such as soil erosion and surface and groundwater pollution through mercury (Hg) contamination and/or acid mine drainage can be detected hundreds of kilometers away from mine-leased sites[7,8]. The level of degradation from hydrocarbon extraction means that full recovery is highly unlikely, and recovery rates are low or stalled completely[5]. As a result, focusing on reviving functional (primary production, energy flows, and nutrient cycles) and ecological (species composition, dispersal mechanisms, distinct evolutionary lineages) processes through active restoration becomes crucial[9–12]. Active techniques to restore polluted lands include improving soil conditions by replanting leguminous tree species[13] or inoculating soils with degrading microorganisms[13].

Many Amazonian countries have developed systematic processes for post-mining restoration that include 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. However, there is a lack of monitoring and enforcement of mining policies, and they are generally weak or non-existent for medium to small-scale operations. Furthermore, there are no schemes to restore areas impacted by illegal mining.

Restoration of vegetation on deforested land The loss of at least 867,675 km^2 of Amazonian primary forests to date means that there are many opportunities for forest restoration. Most Amazonian secondary forests resulting from passive restoration are less than 20 years old[14]. 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[15]. The growth and ecological condition of these secondary forests can be improved through active management. In some cases, fencing can be important to protect them from livestock[16,17], but excluding fire is a key priority: secondary forests can be more flammable than primary forests as they are drier and hotter in the daytime[18], and burned secondary forests recover at a much slower rate[19]. The value of secondary forests will also be enhanced by protecting existing primary forests, as it will promote species' colonization, which can enhance the value of secondary forests for biodiversity[20] and carbon stocks[19]. Yet, protecting secondary forests from disturbance and clearance remains challenging; they are often found in heavily deforested landscapes and considered to have little value in their own right, which may be a key driver of increases in their clearance rates in the past decade[21].

Regarding active restoration, approaches vary, but one of the most popular involves planting seedlings of varying numbers of species[22]. 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[23,24].

Restoration of degraded forests It is estimated that 17% of Amazonian forests were degraded by disturbances such as logging, fires, or windthrow between 1995 and 2017[25]. Crucially, during this period, 14% of degraded forests were eventually deforested and 29% were degraded again[25], highlighting the importance of protecting these degraded forests and allowing them to recover. The enormous spatial scale and complexity of forest degradation in the Amazon means that the most cost-effective and scalable strategies must focus on preventing 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. The prevention of forest fires will involve reducing or controlling ignition sources in the landscape, such as fires used in the deforestation process, and linking early detection of fires to the rapid deployment of fire combat teams[26]. Avoiding illegal and conventional logging is key, but remains an enormous challenge across the Amazon[27]. Other efforts should try to prevent the co-occurrence of disturbances, as their combined impacts can exacerbate ecological change and limit recovery.

Restoration of sustainable economic activities in deforested lands Innovative solutions for restoration of agroecosystems and sustainable production of food, fiber, and other bioproducts on deforested lands are vital for reconciling environmental objectives with inclusive and equitable economic development, particularly at the local level. The need for sustainable and socially-just economic activities on deforested lands is greatest where agriculture is no longer or not yet profitable. Here we present three broad approaches to enhancing productivity.

(i) Sustainable intensification, i.e. increasing the productivity of land, labor, or capital while reducing environmental impacts, has particular potential for pastures, provided that effective governance systems are able to avoid further land conversion and guarantee sustainable development[28]. According to Strassburg et al.[29], 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. This would result in the mitigation of an estimated 14.3 GT CO_2e from avoided deforestation. Technological solutions for sustainable intensification of pastures include changing from continuous to rotational[30], adopting mixed grass-legume pastures[31,32], and using silvopastoral systems that integrate trees and different agroecosystems[33–36].

(ii) 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 trees and crops on the same piece of land, and can sequester carbon in soils and vegetation as a co-benefit[37]. Agroforestry contributes to more than one-third of the restoration efforts identified in the Brazilian Amazon[38], 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.

(iii) 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 common across the basin. Management options in farm-fallow systems include reducing fire-use by adopting techniques such as chop-and-mulch[39–41], shortening the cropping periods, and increasing the fallow period to restore soil and agricultural productivity[42,43]. Extended fallow periods have additional benefits, as they can help protect biodiversity, facilitate connectivity, and improve ecosystem services such as hydrological functions.

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 [44,45]. Approaches should recognize context specificities and use locally-adapted technologies, innovation, and transformation pathways to address the multiple functions of agriculture, forests, and rural activities. Restoration of agricultural land in the Amazon requires ample farming design investment, using tools for mapping land suitability[46], and communal land-use plans[47]. Despite advances in knowledge and policies[48], sustainable and socially-just economic activities have yet to overcome barriers to large-scale adoption[35,49].

Aquatic restoration options

Restoration after pollution Pollutants that degrade 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[50]. 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.

Pollution sources in Amazonian water bodies include industry, agriculture, sewage, mercury and other heavy metals from mining, and oil spills. Pollution from oil extraction and mining has received considerable attention because it is widespread, can be particularly damaging to ecosystems and difficult to clean, and affects many people who rely directly on river water for drinking and bathing, and on fish for food. In terms of directly restoring water, use of slacked lime to remove suspended particles 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[51].

Plastic increasingly affects Amazonian aquatic ecosystems, food chains[52–54], and human health[55]. The Amazon is now among the world's most plastic-contaminated rivers[56]. Large amounts of microplastics have been detected in river sediments around the city of Manaus. Especially high concentrations of microplastics were found in slower-flowing parts of rivers where sediments are deposited, such as in shallow parts of the lower Rio Negro[57]. Mitigating plastic pollution is an enormous global challenge[58]; yet, some Amazonian nations, including Colombia, Ecuador, and Peru, are beginning to develop rules governing the use and disposal of plastics[59] and Peru has legislated a progressive phase-out of single-use plastic bags[60].

Dam removal and restoring natural flow cycles and connectivity In South America, attempts to minimize the impacts of hydroelectric dams on river connectivity are mostly ineffective[61–63]. Dam removal is one alternative, and can reverse some of the environmental effects of dams[64,65]. Justifying dam removal depends on the context in which the dam was built[66], and various frameworks for prioritizing removal have been proposed in recent years[67,68]. These usually involve comparing the amount of power produced against a variety of environmental objectives (e.g., connectivity). One example of a dam that would qualify as a priority for removal is the Hydroelectric Power Plant of Balbina (Brazil). Balbina supplies only 10% of the energy consumed by Manaus (a metropolis with 1.8 million habitants), but created a more than 2,300 km² reservoir and contributed to the displacement and massacre of the Waimiri Atroari Indigenous peoples[69]. Additionally, removing a fraction of the many small dams in basins such as the Xingu could restore connectivity, improve water quality, and benefit biodiversity, without incurring large societal costs (e.g., reducing water availability).

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[70,71]. Restoring fisheries involves, in part, addressing overfishing through the development and enforcement of sustainable fishing practices and regulations, including trait-based regulations, restoring and protecting critical habitats, and improved monitoring. Enforcement over an area as extensive and complex as the Amazon is both difficult and expensive. Co-management schemes based on shared property rights can be particularly effective, especially if the responsibility for management rests with local users and governments. 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[72].

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[73]. Restoring floodplains requires reinstating natural flood regimes and connecting floodplains with other critical habitats. Floodplain restoration programs can be achieved through collaborative partnerships and stakeholder involvement[74]. Successful programs address problems with cattle grazing regulations and engage fishing communities as key beneficiaries of restored habitats.

Indicators of success There are a broad range of potential indicators of success[75,76], which vary greatly in their ease and scalability. For example, open-source platforms such as Mapbiomas allow year-on-year changes in forest cover to 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[77]. A more comprehensive understanding of restoration success will require ground-based assessments to evaluate the provision of ecosystem services, terrestrial and aquatic biodiversity, and socio-economic values[78]. These indicators are much harder to collect at scale, and they must be defined in a participatory way with local stakeholders to ensure they are cost effective, realistic given the expertise and resources available, and sustainable over time[79]. 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[80]. Finally, there is a need to learn from monitoring and evaluation; information needs to be pooled, analyzed, and used to evaluate restoration effectiveness. These analyses can also contribute to modeling exercises that explore different restoration scenarios over time, allowing stakeholders to take the most cost-effective and beneficial decisions and select the restoration programs that best fit their objectives.

Conclusions 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 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.

References

1. Seddon, N., Turner, B., Berry, P., Chausson, A. & Girardin, C. A. J. Grounding nature-based climate solutions in sound biodiversity science. *Nature Climate Change* vol. 9 84–87 (2019).
2. Cohen-Shacham, E., Walters. G, Janzen, C. & Maginnis, S. *Nature-based Solutions to address global societal challenges*. (2016).
3. Chazdon, R. & Brancalion, P. Restoring forests as a means to many ends. *Science (80-.).* 365, 24–25 (2019).
4. Lamb, D., Erskine, P. D. & Parrotta, J. A. Restoration of degraded tropical forest landscapes. *Science (80-.).* 310, 1628–1632 (2005).
5. Kalamandeen, M. *et al.* Limited biomass recovery from gold mining in Amazonian forests. *J. Appl. Ecol.* 57, 1730–1740 (2020).
6. Barrios, E., Gudeta, W. S., Keith, S. & Sinclair, F. Agroforestry and Soil Health: Trees, Soil Biota and Ecosystem Services. in *Soil Ecology and Ecosystem Services* 315–330 (Oxford University Press, 2012).
7. Diringer, S. E. *et al.* River transport of mercury from artisanal and small-scale gold mining and risks for dietary mercury exposure in Madre de Dios, Peru. *Environ. Sci. Process. Impacts* 17, 478–487 (2015).
8. Sonter, L. J. *et al.* Mining drives extensive deforestation in the Brazilian Amazon. *Nat. Commun.* 8, 1–7 (2017).
9. Chazdon, R. L. *et al.* The potential for species conservation in tropical secondary forests. *Conserv. Biol.* 23, 1406–1417 (2009).
10. Edwards, D. P., Massam, M. R., Haugaasen, T. & Gilroy, J. J. Tropical secondary forest regeneration conserves high levels of avian phylogenetic diversity. *Biol. Conserv.* 209, 432–439 (2017).
11. Rocha, R. *et al.* Secondary forest regeneration benefits old-growth specialist bats in a fragmented tropical landscape. *Sci. Rep.* 8, 1–9 (2018).
12. Ferreira, J. *et al.* Carbon-focused conservation may fail to protect the most biodiverse tropical forests. *Nat. Clim. Chang.* 8, 744–749 (2018).
13. Couic, E. *et al.* Mercury behaviour and C, N, and P biogeochemical cycles during ecological restoration processes of old mining sites in French Guiana. *Environ. Sci. Process. Impacts* 20, 657–672 (2018).
14. Chazdon, R. L. *et al.* Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. *Sci. Adv.* 2, e1501639 (2016).
15. Smith, M. N. *et al.* Empirical evidence for resilience of tropical forest photosynthesis in a warmer world. *Nat. Plants* 6, 1225–1230 (2020).
16. Griscom, H. P., Griscom, B. W. & Ashton, M. S. Forest Regeneration from Pasture in the Dry Tropics of Panama: Effects of Cattle, Exotic Grass, and Forested Riparia. *Restor. Ecol.* 17, 117–126 (2009).
17. Wassie, A., Sterck, F. J., Teketay, D. & Bongers, F. Effects of livestock exclusion on tree regeneration in church forests of Ethiopia. *For. Ecol. Manage.* 257, 765–772 (2009).
18. Ray, D., Nepstad, D. & Moutinho, P. Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. *Ecol. Appl.* 15, 1664–1678 (2005).
19. Heinrich, V. H. A. *et al.* Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. *Nat. Commun.* 12, 1–11 (2021).
20. Lennox, G. D. *et al.* Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. *Glob. Chang. Biol.* 24, 5680–5694 (2018).
21. Wang, Y. *et al.* Upturn in secondary forest clearing buffers primary forest loss in the Brazilian Amazon. *Nat. Sustain.* 3, 290–295 (2020).
22. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R. & Schwartz, G. An overview of forest loss and restoration in the Brazilian Amazon. *New For.* 52, 1–16 (2021).
23. Rodrigues, S. B. *et al.* Direct seeded and colonizing species guarantee successful early restoration of South Amazon forests. *For. Ecol. Manage.* 451, 117559 (2019).
24. Zahawi, R. A., Holl, K. D., Cole, R. J. & Reid, J. L. Testing applied nucleation as a strategy to facilitate tropical forest recovery. *J. Appl. Ecol.* 50, 88–96 (2013).
25. Bullock, E. L., Woodcock, C. E., Souza Jr, C. & Olofsson, P. Satellite-based estimates reveal widespread forest degradation in the Amazon. *Glob. Chang. Biol.* 26, 2956–2969 (2020).
26. Nóbrega Spínola, J., Soares da Silva, M. J., Assis da Silva, J. R., Barlow, J. & Ferreira, J. A shared perspective on managing Amazonian sustainable-use reserves in an era of megafires. *J. Appl. Ecol.* 57, 2132–2138 (2020).
27. Brancalion, P. H. S. *et al.* Fake legal logging in the Brazilian Amazon. *Sci. Adv.* 4, eaat1192 (2018).
28. Garrett, R. D. *et al.* Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil. *Glob. Environ. Chang.* 53, 233–243 (2018).
29. Strassburg, B. B. N. *et al.* When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Glob. Environ. Chang.* 28, 84–97 (2014).
30. Dias-Filho, M. B. Estratégias de recuperação de pastagens degradadas na Amazônia Brasileira. *Doc. / Embrapa Amaz. Orient.* Junho, 25 (2015).
31. Valentim, J. F. & Andrade, C. M. S. de. Perspectives of grass-legume pastures for sustainable animal production in the tropics. *Reun. Annu. DA Soc. Bras. Zootec.* 40, 142–154 (2004).
32. Zu Ermgassen, E. K. H. J. *et al.* Results from on-the-ground efforts to promote sustainable cattle ranching in the

Brazilian Amazon. *Sustainability* 10, 1301 (2018).
33. Uphoff, N. *et al. Biological approaches to sustainable soil systems*. (CRC Press, 2006).
34. de Sousa, S. G. A., Wandelli, E. V, Garcia, L. C., Lourenco, J. N. de P. & Uguen, K. Sistemas agroflorestais para a agricultura familiar da Amazônia. in *ABC da agricultura Familiar* (Embrapa Amazônia Ocidental, 2012).
35. Valentim, J. F. Desafios e estratégias para recuperação de pastagens degradadas e intensificação da pecuária a pasto na Amazônia Legal. in *Embrapa Acre-Artigo em anais de congresso (ALICE)* (2016).
36. Bungenstab, D. J., Almeida, R. G. de, Laura, V. A., Balbino, L. C. & Ferreira, A. D. *ILPF: Inovação com interação de lavoura, pecuária e floresta. Embrapa Acre* (Embrapa).
37. Ranganathan, J., Waite, R., Searchinger, T. & Zionts, J. Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change. *Worl d Resour. Inst.* (2020).
38. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R. & Schwartz, G. An overview of forest loss and restoration in the Brazilian Amazon. *New For.* 1–16 (2020).
39. Kato, O. R. *et al.* Projeto Tipitamba: transformando paisagens e compartilhando conhecimento na Amazônia. *Investimentos Transform. para um estilo Desenvolv. sustentável Estud. casos Gd. Impuls. (Big Push) para a sustentabilidade no Bras. Bras. CEPAL, 2020. LC/TS. 2020/37. p. 213-226* (2020).
40. Shimizu, M. K. *et al.* Agriculture without burning: restoration of altered areas with chop-and-mulch sequential agroforestry systems in the Amazon region. *Glob. Adv. Res. J. Agric. Sci.* 3, 415–422 (2014).
41. Denich, M., Vlek, P. L. G., de Abreu Sá, T. D., Vielhauer, K. & Lücke, W. A concept for the development of fire-free fallow management in the Eastern Amazon, Brazil. *Agric. Ecosyst. Environ. Environ.* 110, 43–58 (2005).
42. Nair, P. K. R. *An introduction to agroforestry*. (Springer Science & Business Media, 1993).
43. Jakovac, C. C., Peña-Claros, M., Mesquita, R. C. G., Bongers, F. & Kuyper, T. W. Swiddens under transition: consequences of agricultural intensification in the Amazon. *Agric. Ecosyst. Environ.* 218, 116–125 (2016).
44. Garrett, R. D. *et al.* Criteria for effective zero-deforestation commitments. *Glob. Environ. Chang.* 54, 135–147 (2019).
45. HLPE. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. *A Rep. by High Lev. Panel Expert. Food Secur. Nutr. Comm. World Food Secur.* 1–162 (2019).
46. Osis, R., Laurent, F. & Poccard-Chapuis, R. Spatial determinants and future land use scenarios of Paragominas municipality, an old agricultural frontier in Amazonia. *J. Land Use Sci.* 14, 258–279 (2019).
47. Pinillos, D. *et al.* Understanding Landscape Multifunctionality in a Post-forest Frontier: Supply and Demand of Ecosystem Services in Eastern Amazonia. *Front. Environ. Sci.* 7, (2020).
48. Nepstad, D. *et al.* Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science (80-.).* 344, 1118–1123 (2014).
49. Bendahan, A. B., Poccard-Chapuis, R., de Medeiros, R. D., de Lucena Costa, N. & Tourrand, J.-F. Management and labour in an integrated crop-livestock-forestry system in Roraima, Brazilian Amazonia. *Cah. Agric.* 27, 25005 (2018).
50. Bunn, S. E. Grand challenge for the future of freshwater ecosystems. *Front. Environ. Sci.* 4, 21 (2016).
51. Guedron, S. *et al.* Amazonian former gold mined soils as a source of methylmercury: Evidence from a small scale watershed in French Guiana. *Water Res.* 45, 2659–2669 (2011).
52. Diepens, N. J. & Koelmans, A. A. Accumulation of Plastic Debris and Associated Contaminants in Aquatic Food Webs. *Environ. Sci. Technol.* 52, 8510–8520 (2018).
53. Collard, F., Gasperi, J., Gabrielsen, G. W. & Tassin, B. Plastic Particle Ingestion by Wild Freshwater Fish: A Critical Review. *Environ. Sci. Technol.* 53, 12974–12988 (2019).
54. Lacerot, G., Lozoya, J. P. & Teixeira de Mello, F. Plásticos en ecosistemas acuáticos: presencia, transporte y efectos. *Ecosistemas* 29, (2020).
55. De-la-Torre, G. E. Microplastics: an emerging threat to food security and human health. *J. Food Sci. Technol.* 57, 1601–1608 (2020).
56. Giarrizzo, T. *et al.* Amazonia: the new frontier for plastic pollution. *Front. Ecol. Environ.* 17, 309–310 (2019).
57. Gerolin, C. R. *et al.* Microplastics in sediments from Amazon rivers, Brazil. *Sci. Total Environ.* 749, 141604 (2020).
58. Jia, L., Evans, S. & Linden, S. van der. Motivating actions to mitigate plastic pollution. *Nature Communications* vol. 10 1–3 (2019).
59. Abril Ortiz, A., Sucozhañay, D., Vanegas, P. & Martínez-Moscoso, A. A Regional Response to a Global Problem: Single Use Plastics Regulation in the Countries of the Pacific Alliance. *Sustainability* 12, 8093 (2020).
60. Alvarez-Risco, A., Rosen, M. A. & Del-Aguila-Arcentales, S. A New Regulation for Supporting a Circular Economy in the Plastic Industry: The Case of Peru (Short Communication). *J. Landsc. Ecol.* 13, 1–3 (2020).
61. Agostinho, A. A., Pelicice, F. M. & Gomes, L. C. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian J. Biol.* 68, 1119–1132 (2008).
62. Pompeu, P. dos S., Agostinho, A. A. & Pelicice, F. M. Existing and future challenges: the concept of successful fish passage in South America. *River Res. Appl.* 28, 504–512 (2012).
63. Pelicice, F. M., Pompeu, P. S. & Agostinho, A. A. Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish Fish.* 16, 697–715 (2015).
64. Bednarek, A. T. Undamming rivers: a review of the ecological impacts of dam removal. *Environ. Manage.* 27, 803–814 (2001).
65. Bernhardt, E. S. *et al.* Synthesizing US river restoration efforts. (2005).
66. Maclin, E. & Sicchio, M. Dam removal success stories. in *Restoring Rivers Through Selective Removal of Dams That Don't Make Sense* (American Rivers, Friends of the Earth, & Trout Unlimited, 1999).
67. Kemp, P. S. & O'hanley, J. R. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis.

Fish. Manag. Ecol. 17, 297–322 (2010).
68. O'Hanley, J. R., Pompeu, P. S., Louzada, M., Zambaldi, L. P. & Kemp, P. S. Optimizing hydropower dam location and removal in the São Francisco river basin, Brazil to balance hydropower and river biodiversity tradeoffs. *Landsc. Urban Plan.* 195, 103725 (2020).
69. Fearnside, P. M. Brazil's Balbina Dam: Environment versus the legacy of the pharaohs in Amazonia. *Environ. Manage.* 13, 401–423 (1989).
70. Heilpern, S. A. *et al.* Substitution of inland fisheries with aquaculture and chicken undermines human nutrition in the Peruvian Amazon. *Nat. Food* 2, 192–197 (2021).
71. Isaac, V. J. & De Almeida, M. C. El consumo de pescado en la Amazonia brasileña. *COPESCAL. Doc. Ocas.* I (2011).
72. Arantes, C. C. *et al.* Institutional effects on ecological outcomes of community-based management of fisheries in the Amazon. *Ambio* (2021).
73. Arantes, C. C. *et al.* Floodplain land cover affects biomass distribution of fish functional diversity in the Amazon River. *Sci. Rep.* 9, 1–13 (2019).
74. McGrath, D. G., Cardoso, A., Almeida, O. T. & Pezzuti, J. Constructing a policy and institutional framework for an ecosystem-based approach to managing the Lower Amazon floodplain. *Environ. Dev. Sustain.* 10, 677–695 (2008).
75. Ruiz-Jaen, M. C. & Mitchell Aide, T. Restoration success: how is it being measured? *Restor. Ecol.* 13, 569–577 (2005).
76. Stanturf, J. A. *et al. Forest landscape restoration as a key component of climate change mitigation and adaptation*. (International Union of Forest Research Organizations (IUFRO) Vienna, Austria, 2015).
77. de Almeida, D. R. A. *et al.* A new era in forest restoration monitoring. *Restor. Ecol.* 28, 8–11 (2020).
78. Wortley, L., Hero, J.-M. & Howes, M. Evaluating ecological restoration success: a review of the literature. *Restor. Ecol.* 21, 537–543 (2013).
79. Evans, K., Guariguata, M. R. & Brancalion, P. H. S. Participatory monitoring to connect local and global priorities for forest restoration. *Conserv. Biol.* 32, 525–534 (2018).
80. Chaves, R. B., Durigan, G., Brancalion, P. H. S. & Aronson, J. On the need of legal frameworks for assessing restoration projects success: new perspectives from São Paulo state (Brazil). *Restor. Ecol.* 23, 754–759 (2015).