Amazon Assessment Report 2021

Chapter 20

Drivers and impacts of changes in aquatic ecosystems

Pescadores vendem peixes frescos em suas canoas, no centro de Manaus (Foto: Bruno Kelly/Amazônia Real)

THE AMAZON WE WANT
Science Panel for the Amazon

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

About the Science Panel for the Amazon (SPA)

The Science Panel for the Amazon is an unprecedented initiative convened under the auspices of the United Nations Sustainable Development Solutions Network (SDSN). The SPA is composed of over 200 preeminent scientists and researchers from the eight Amazonian countries, French Guiana, and global partners. These experts came together to debate, analyze, and assemble the accumulated knowledge of the scientific community, Indigenous peoples, and other stakeholders that live and work in the Amazon.

The Panel is inspired by the Leticia Pact for the Amazon. This is a first-of-its-kind Report which provides a comprehensive, objective, open, transparent, systematic, and rigorous scientific assessment of the state of the Amazon's ecosystems, current trends, and their implications for the long-term well-being of the region, as well as opportunities and policy relevant options for conservation and sustainable development.

ISBN: 9781734808001

Suggested Citation

Fearnside PM, Berenguer E, Armenteras D, Duponchelle F, Guerra FM, Jenkins CN, Bynoe P, García-Villacorta R, Macedo M, Val AL, Almeida-Val VMF, Nascimento N. 2021. Chapter 20: Drivers and Impacts of Changes in Aquatic Ecosystems. In: Nobre C, Encalada A, Anderson E, Roca Alcazar FH, Bustamante M, Mena C, Peña-Claros M, Poveda G, Rodriguez JP, Saleska S, Trumbore S, Val AL, Villa Nova L, Abramovay R, Alencar A, Rodríguez Alzza C, Armenteras D, Artaxo P, Athayde S, Barretto Filho HT, Barlow J, Berenguer E, Bortolotto F, Costa FA, Costa MH, Cuvi N, Fearnside PM, Ferreira J, Flores BM, Frieri S, Gatti LV, Guayasamin JM, Hecht S, Hirota M, Hoorn C, Josse C, Lapola DM, Larrea C, Larrea-Alcazar DM, Lehm Ardaya Z, Malhi Y, Marengo JA, Melack J, Moraes R M, Moutinho P, Murmis MR, Neves EG, Paez B, Painter L, Ramos A, Rosero-Peña MC, Schmink M, Sist P, ter Steege H, Val P, van der Voort H, Varese M, Zapata-Ríos G (Eds). Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. Available from https://www.theamazonwewant.org/spa-reports/. DOI: 10.55161/IDMB5770

INDEX

Graphical Abstract

Figure 20.A Graphical Abstract

Drivers and Impacts of Changes in Aquatic Ecosystems

Philip M. Fearnside[*a], *Erika Berenguer*[bc], *Dolors Armenteras*[d], *Fabrice Duponchelle*[e], *Federico Mosquera Guerra*[f], *Clinton N. Jenkins*[g], *Paulette Bynoe*[h], *Roosevelt García-Villacorta*[i], *Marcia Macedo*[e], *Adalberto Luis Val*[1], *Vera Maria Fonseca de Almeida-Val*[1], *Nathália Nascimento*[j]

Key Messages

- Over the last four decades, and especially over the last two, many Amazonian aquatic ecosystems have become less connected and more polluted.
- Prior to the massive impacts of dams built over the past four decades, overexploitation of plant and animal species was the most significant factor causing aquatic ecosystem degradation in the Amazon Basin. This degradation continues to advance.
- The spatial distribution of impacts on biodiversity and ecological processes is uneven.
- Agricultural and industrial waste and sewage contaminate Amazonian waters.
- Mercury contamination from gold mining (legal or not) is a major environmental and public-health concern.
- Hydroelectric dams block fish migrations and the transport of sediments and associated nutrients, as well as altering river flows and oxygen levels.
- Deforestation greatly affects the physical and chemical characteristics of watercourses and when agriculture replaces forests can release fertilizers, herbicides, and other pollutants into the water, as well as sediments from soil erosion.
- Petroleum extraction and resulting oil spills can have catastrophic impacts on aquatic ecosystems.
- The biological productivity of aquatic ecosystems is affected both downstream and upstream of these impacts.

Abstract

The Amazon's aquatic ecosystems are being destroyed and threats to their integrity are projected to grow in number and intensity. In this chapter we review a number of these threats. Hydroelectric dams (307 existing or under construction) have changed almost every aspect of Amazonian aquatic ecosystems, and many more dams are planned (239), posing threats to the region's enormous aquatic biodiversity and fisheries resources. By blocking fish migrations dams affect important commercial species, as well as the flow of sediments and nutrients that sustain aquatic food chains and support fish populations. By altering stream flows and flooding regimes, dams and their reservoirs also disrupt downstream ecosystems,

---

[a] Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil, pmfearn@inpa.gov.br
[b] Environmental Change Institute, School of Geography and the Environment, University of Oxford, OX1 3QY, Oxford, UK
[c] Lancaster Environment Centre, Lancaster University, LA1 4YQ, Lancaster, UK
[d] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia Sede Bogotá, Colombia
[e] Institut de Recherche pour le Développement, 44 bd de Dunkerque, Immeuble Le Sextant CS 90009, F-13572 Marseille cedex 02, France
[f] Fundación Omacha, Colombia
[g] Florida International University, Department of Earth and Environment & Kimberly Green Latin American and Caribbean Center, Miami, FL 33199, United States of America
[h] University of Guyana, Guyana
[i] Centro Peruano para la Biodiversidad y Conservación (CPBC), Iquitos, Perú
[j] Universidade Federal do Espírito Santo - UFES, Instituto de Estudos Climáticos, Vitória, Espírito Santo, Brazil.

including flooded forests and the floodplain lakes that are essential for breeding of many fish species. The low-oxygen (anoxic) conditions found near reservoir bottoms cannot be tolerated by many fish species. They also favor the formation of highly toxic methylmercury and the production of methane, a powerful greenhouse gas. Small dams and reservoirs can have substantial impacts that are often even greater than large dams on a per-Megawatt (MW) or per-hectare basis. In Brazil the definition of "small" dams has progressively increased from less than 10 to 30 to 50 MW, opening an expanding loophole in the environmental licensing system. Overharvesting of fish for both food and the ornamental trade has depleted fish stocks and altered their ecological roles. Native species are threatened by invasive species that escape from aquaculture operations and potentially from proposed inter-basin river diversions. Deforestation changes the chemical and physical properties of streams, including releasing natural deposits of heavy metals (such as mercury from erosion) and eliminating aquatic species that inhabit watercourses in Amazonian forests. Pollution sources include toxins from agriculture and industrial and urban waste, such as plastic; mercury; transition metals like Cu, Cd, Pb, and Ni; urban sewage; and various forms of toxic waste. Oil spills have had disastrous consequences in Ecuador and Peru. Gold mining releases large amounts of sediments, in addition to releasing mercury and provoking the clearing and degradation of floodplain forests. Roads contribute to the fragmentation of streams and river tributaries as well as generating sediments through soil erosion, in addition to the sediment from the deforestation that roads provoke. Navigational waterways cause multiple impacts on rivers converted to this use, particularly affecting the reproduction habitats of freshwater species. Climate change impacts aquatic ecosystems through increased temperature and extreme droughts and floods. Interactions among drivers mean many of these impacts are even more harmful to aquatic ecosystems. The authors of this chapter recommend that no more hydroelectric dams with installed capacity ≥10 MW be built in the Amazon, that investments in new electricity generation should be redirected to wind and solar sources, and that all environmental assessments should incorporate synergistic and cumulative impacts in their analyses. In addition to the ecosystem impacts that are the subject of this chapter, the extraordinarily great social impacts of Amazonian dams (Chapter 14) lead to the same conclusion. Fortunately, countries like Brazil have abundant undeveloped wind and solar potential.

Keywords: Climate change, dams, fish, invasive species, mercury, oil spills, pollution, river diversion, toxic waste, waterways

20.1 Introduction

The Amazon's rivers and streams reflect the landscapes through which they flow. The great Amazon limnologist Harald Sioli (1984) explained that "The big rivers receive their waters from a dense network of Igarapés, streams and brooklets. The total length of their courses exceeds more than a thousand times that of the Amazon; this implies an intimate contact of the Amazon aquatic system with its terrestrial surroundings and a determining influence of the latter on the chemistry and biology of the small watercourses." This influence reflects not only geological differences such as those that produce the region's white-, black- and clear-water rivers, but also the effects of human activity. These watercourses are often compared to a person's blood or urine - the subject of medical testing to identify problems in a human body. In the same way, the deteriorating health of a terrestrial or aquatic ecosystem will be reflected in the quality and quantity of the water flowing from its hydrographic basin.

The sheer magnitude of the flows in the Amazon reflect the region's global significance, annually discharging 6.6 trillion cubic meters of fresh water to the oceans, along with 600-800 million tons of suspended sediments (Filizola and Guyot 2011). The Amazon's aquatic biodiversity is also globally significant. So far, 2406 fish species have been described (Jézéquel *et al.* 2020), although hundreds more remain to be described such that the actual number is likely to be above 3,000 species (Val 2019). Described floodplain tree species total 918 (Wittmann *et al.* 2006). As mighty as the Amazon River is, its aquatic ecosystems are also fragile (e.g., Castello *et al.* 2013a). The multiple threats these ecosystems face are the focus of this chapter.

Amazonian rivers and streams connect distant parts of the vast Amazon Basin, and impacts originating at any given location may be felt thousands of kilometers away. A dam altering downstream sediment flows, for example, can affect ecosystems all the way to the Atlantic Ocean and even in the Amazon's estuary. Likewise, a dam blocking migratory species causes upstream effects reaching all the way to the Amazon's headwaters in the foothills of the Andes. The same is true for other drivers of change in freshwater systems (Figure 20.1); overharvesting of fish stocks (both commercial and ornamental species) can disrupt aquatic food webs; introduction of invasive species can disturb native species communities, causing habitat loss; and deforestation can alter water quality, temperature, and climate at various scales. Water pollution (e.g., agricultural and industrial wastes, plastics, medicines, oil spills, and transition metals such as mercury) can have widespread and cumulative effects, as can infrastructure such as dams, roads, river diversions, and waterways. Other factors include urban and industrial growth, agriculture, and regional climate change. These drivers have synergistic interactions among themselves and, when acting together, can amplify each other's impacts (Costa *et al.* 2011; Anderson *et al.* 2018; Athayde *et al.* 2019; Castello and Macedo 2016; Silva *et al.* 2019). The construction of dams, for example, inevitably results in the construction of roads, which in turn may increase deforestation for pasture and commodity crops such as soy (Fearnside 1989; Guerrero *et al.* 2020). These land-use changes ultimately result in the pollution of rivers and streams, be it from the large-scale use of fertilizers and agricultural chemicals, the formation of toxic methylmercury in reservoirs, or rapid population growth from migration spurred by dam construction. These multiple impacts on aquatic ecosystems threaten the Amazon's enormous aquatic biodiversity, as well as the health and well-being of many Amazon residents who depend on fisheries and other aquatic resources for their livelihoods (see Chapter 21).

Aquatic systems in the Amazon are environmentally diverse and include many characteristics that can pose unique challenges for aquatic organisms. Among these are habitat heterogeneity, different river types (such as white-, black- or clearwater), and dramatic seasonal flood events (i.e., flood pulses) when rivers overflow their banks and invade adjacent forests, creating habitats such as *várzeas* (white-water floodplains) and *igapós* (black-water swamps) that are essential for feeding and nurturing fish (Barletta *et al.* 2010). Water-quality indicators, such as dissolved oxygen, temperature, electrical conductivity, and pH, may also vary seasonally and spatially depending on the drainage area (e.g., the Andes, Guiana, and Brazilian shields), requiring aquatic organisms to adjust to changing conditions. These challenges have favored the evolution of adaptive strategies at all levels of biological organization (Junk *et al.* 1989; Campos *et al.* 2019; Val 2019; Piedade *et al*. 2000). Fish and other aquatic animals have evolved strategies to cope with extreme environments (e.g., water with low oxygen, high acidity, low ion concentrations, and high temperatures) and high seasonal variability in food resources, resulting in high biotic diversity (Val *et al.* 2006; Val and Almeida-Val 1995; Zuanon *et al*. 2005).

Interactions between extreme habitat conditions and anthropogenic disturbance are driving many organisms to their physiological limits; adaptations to their natural environment do not always promote survival under anthropogenic stresses. An emblematic example is the effect of oil spills on fish. Among the many strategies Amazonian fish have developed to cope with low oxygen is the ability exploit the water-air interface that, in the case of an oil spill, increase their contact with pollutants concentrated at the top of the water column

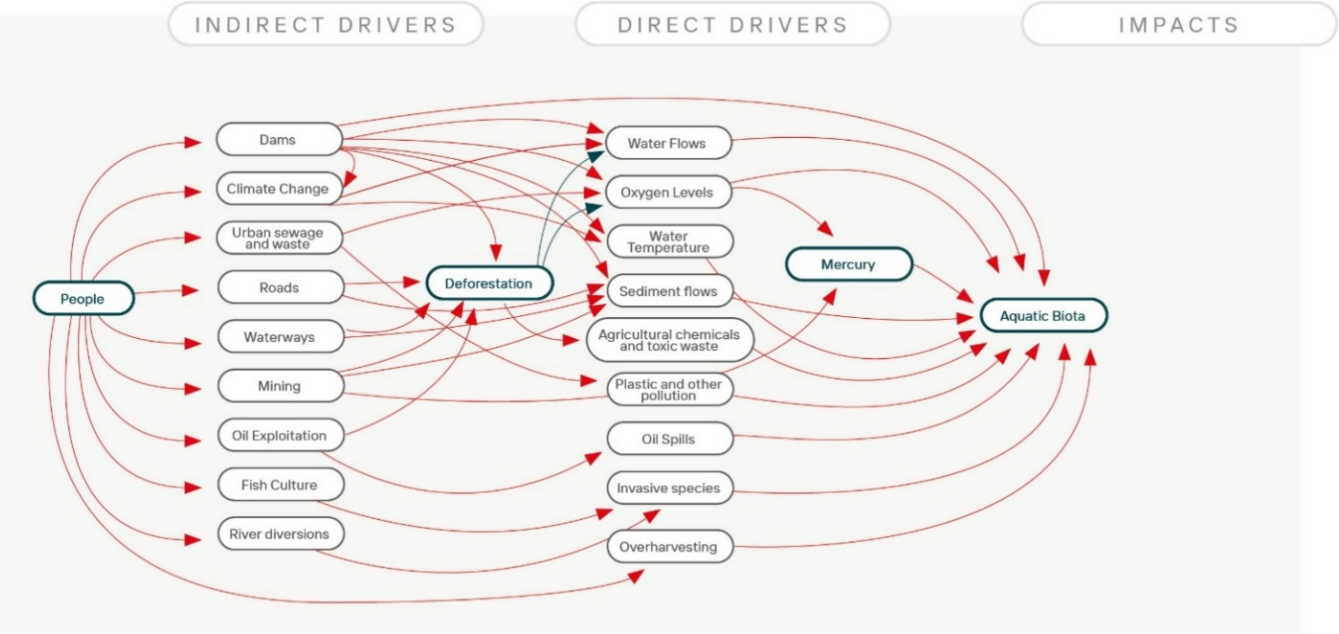


Figure 20.1 Flowchart of relationships among drivers leading to impacts on aquatic life.

(Val and Val 1999; Dos Anjos *et al.* 2011; Souza *et al.* 2020).

The interactions among the different drivers of degradation in aquatic systems are summarized in Figure 20.1. This chapter begins with a discussion of hydroelectric dams because of their very large and diverse impacts in the region, and the many connections between dams and other drivers of change in aquatic ecosystems. It then reviews the effects of overharvesting, invasive species, pollution, mining, roads, river diversions, waterways, and climate change on Amazon aquatic systems. The chapter concludes with a discussion of synergistic effects among drivers, followed by conclusions and recommendations.

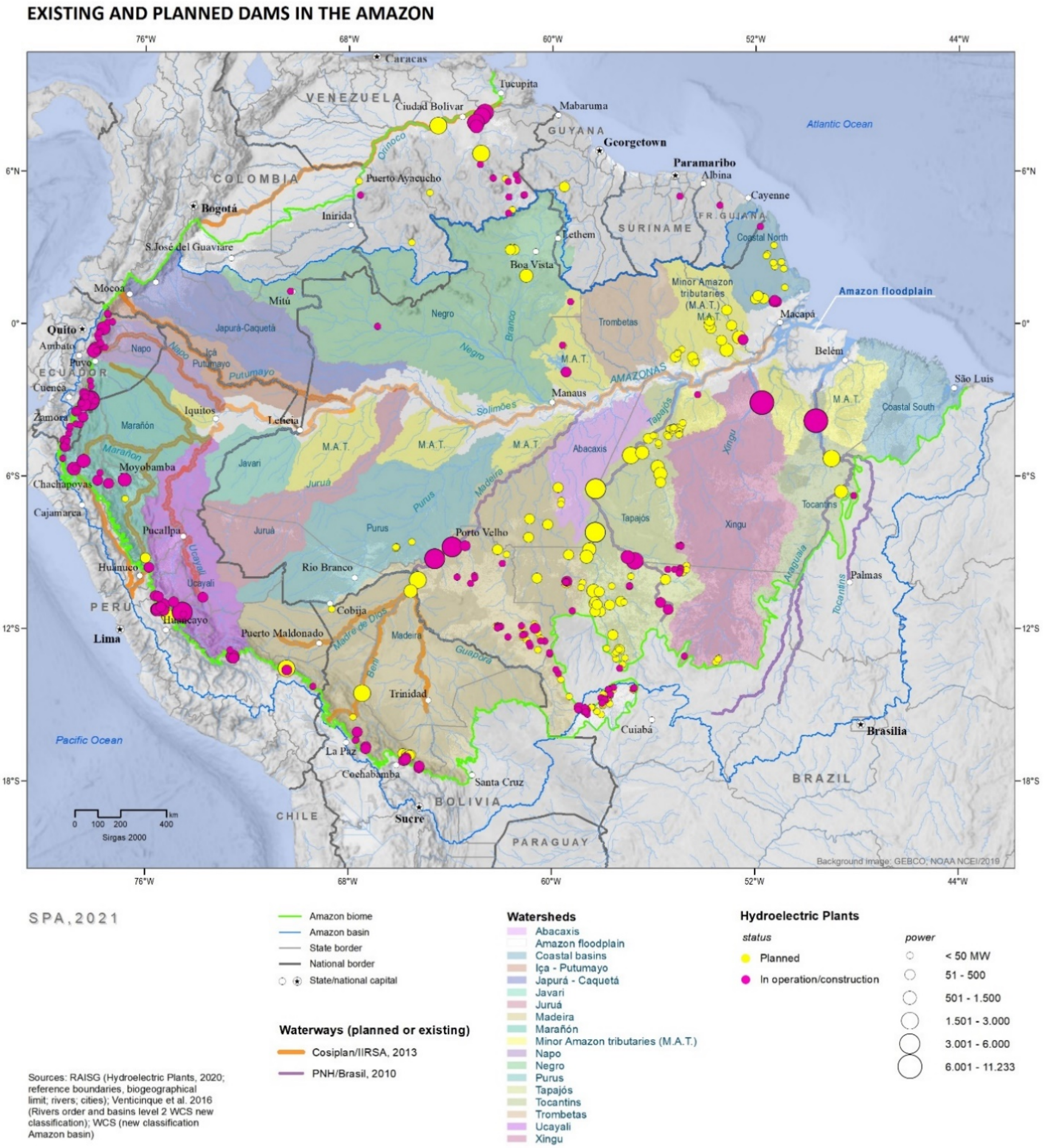
20.2 Infrastructure

20.2.1 Dams

20.2.1.1 Existing dams and future plans

We identified 307 dams that exist or are under construction and 239 that are planned or projected (Figure 20.2). These numbers vary in the literature (Finer and Jenkins 2012; Lees *et al.* 2016; Almeida *et al.* 2019) due to differences in the areas covered, inconsistent definitions of what constitutes a "planned" dam (especially for small dams), and variable information across the eight countries and one overseas territory comprising the Amazon Basin. Plans for future hydroelectric dams are also continually in flux.

"Small" dams have less hydrological impact than large dams in absolute terms, but relative to their installed capacity for energy generation they have a significantly greater impact (Timpe and Kaplan 2017). Since 2016, "small" hydroelectric dams have been defined in Brazil as those with less than 50 MW of installed capacity; the limit was 30 MW from 2004 to 2016, and 10 MW before 2004. Dams in this category are exempt from federal environmental licensing and can be built with (generally less-rigorous) state licensing, thus motivating both the expansion of this loophole by redefining "small" dams and a rapidly increasing number of "small" dams in the Brazilian Amazonia. The definition of "small" dams varies widely among countries, with 10 MW being "increasingly recognized as the international standard" (Couto and Olden



Sources: RAISG (Hydroelectric Plants, 2020; reference boundaries, biogeographical limit; rivers; cities); Venticinque et al. 2016 (Rivers order and basins level 2 WCS new classification); WCS (new classification Amazon basin)

Figure 20.2 Existing and planned hydroelectric dams and waterways in the Amazon. Currently there are 307 dams existing or under construction, and 239 planned or projected (total = 546).

2018). Brazil's relaxing its definition to include dams up to 50 MW represents a significant setback in environmental control.

20.2.1.2 Fish communities

Hydroelectric dams negatively impact fish communities both above and below the reservoir due to habitat loss and severe changes in the hydrological regimes of flooded forests (Ribeiro and Petrere 1988; Ribeiro *et al.* 1995; Santos *et al.* 2018). The conversion of a stretch of river from running water (lotic) to still water (lentic) either eliminates or greatly reduces the populations of many species, few of which are adapted to the new environment (Agostinho *et al.* 2016). Fish communities become structurally and functionally different from the pre-dam baseline (Araújo *et al.* 2013; Arantes *et al.* 2019a, b), with one of the most evident impacts being the impediment of both upstream and downstream migration (Pelicice *et al.* 2015a). Only some of the highly diverse migratory fish species are able to use fish passages (Pelicice and Agostinho 2008). The famous "giant catfish" of the Madeira River (*Brachyplatystoma* spp.) is among those that have not been able to use the passages in the large Santo Antônio and Jirau Dams in the Brazilian Amazon, although they are physically able to climb the passages if placed inside them (Figure 20.3). This is because the instinct of the fish during their annual migration to spawn in the headwaters is to swim up the main channel of the river, not to enter small streams like the ones imitated by the passages. Although not yet documented for the Amazon, basin-wide extirpations of migratory species have occurred in many rivers of the world due to ineffective fish ladders (see Pringle *et al.* 2000; Freeman *et al.* 2003). Amazonian dams and their ineffective fish passages have already seriously disrupted the migration routes of many fish species, resulting in declining fisheries both above and below the dams and in changes in assemblage structure and functional traits of fish communities (review in Duponchelle *et al.* 2021). Ineffective fish ladders in the Amazon have caused declines of migratory species at the Santo Antônio Dam on the Madeira River in Rondônia (Hauser *et al.* 2019) and the Lajeado Dam on the Tocantins River in the state of Tocantins (Agostinho *et al.* 2007, 2012). In other cases, no fish passage was provided, as at the Coaracy Nunes Dam on the Araguari River in Amapá (Sá-Oliveira *et al.* 2015a), the Samuel Dam on the Jamari River in Rondônia (Santos 1995), and the Tucuruí Dam on the Tocantins River in Pará (Ribeiro *et al.* 1995). The resulting loss of fisheries has severe social impacts."

Figure 20.3 The various species of "giant catfish" in the Madeira River are already heavily impacted by the Santo Antônio and Jirau Dams that have blocked their annual spawning migration since 2011. Source: Kileen (2007). Photograph: Russell Mittermeier

20.2.1.3 Aquatic mammals, reptiles, amphibians, and insects

Many other aquatic taxa are affected by hydroelectric dams (Lees *et al.* 2016). For example, dams can cause the fragmentation of populations of dolphins, amphibians, and reptiles (especially larger ones such as caimans and turtles). Dams can also affect these animals indirectly – e.g., they can decrease prey availability for dolphins (Salisbury 2015; Araújo and Wang 2015). Population fragmentation by dams disrupts gene flow and can result in small and therefore vulnerable populations (Gravena *et al.* 2014; Paschoalini *et al.* 2020).

The beaches on which turtles often lay their eggs are commonly flooded by dam-altered hydrology (Alho 2011). This occurs not only in the reservoir area itself (Norris *et al.* 2018), but also in downstream areas where water levels vary depending on power generation (Salisbury 2016). A number of planned dams are particularly threatening to turtles (Gonzales 2019). For instance, on the Rio Branco in Roraima the planned Bem Querer Dam (Fearnside 2020a) is likely to impact downstream turtle breeding beaches (e.g., Nascimento 2002). On the Trombetas River in Pará, the dam that is planned to be the centerpiece of the Barão do Rio Branco Project announced by Brazil's current presidential administration (The Intercept 2019) would be just upstream of one of the Amazon's largest turtle-breeding beaches, the "*tabuleiro do Jacaré*" (e.g., Forero-Medina *et al*. 2019; Zwink and Young 1990).

In a study of frogs at the Santo Antônio Dam on the Madeira River, the composition of species assemblages present near the natural river margin before reservoir flooding did not re-establish on the new margin up to four years after the reservoir was filled (Dayrell *et al.* 2021). Frog species richness near the new margins increased by 82% one year after filling, but this percentage had declined to 65% by four years after filling and showed "no tendency to return to the original assemblage."

Dam impacts on aquatic insects vary; species that depend on fast-moving water lose habitat with the creation of reservoirs and thus decrease in abundance; while others that breed in the standing water of a reservoir, such as mosquitos, can undergo population explosions. At the Tucuruí Dam, in Brazil's Pará state, up to 39% of the reservoir was covered by macrophytes (aquatic plants) in the first years after impoundment (Lima *et al.* 2000), providing breeding sites for mosquitos in the genus *Mansonia* (Fearnside 2001). The resulting "mosquito plague" caused many of the people who had been resettled near the reservoir to abandon their lots and initiate a new hotspot of deforestation elsewhere (Fearnside 1999). Conversely, *Anopheles* mosquitos (the vectors of malaria) diminished in abundance after completion of the Tucuruí Dam (Tadei *et al.* 1991). At the Samuel Dam (in Brazil's state of Rondônia) *Culex* mosquitos exploded dramatically and *Anopheles* mosquitos, which were already abundant before construction of the dam, are also believed to have increased (Fearnside 2005) (Chapter 21).

Alteration of flows downstream of dams can also impact aquatic insects drifting in the water (Castro *et al.* 2013; Patterson and Smokorowski 2011) and those that inhabit the edges of the river, such as mayflies (Ephemeroptera) (Kennedy *et al.* 2016). Changes in substrate composition (i.e., from coarse to fine substrates) downstream of dams is also known to negatively affect aquatic insects (Wang *et al.* 2020).

20.2.1.4 Reservoir stratification

Reservoirs commonly stratify into layers with colder water at the bottom and a division (thermocline) at 2-10 m depth separating the warmer and colder layers. Water does not mix between the two layers. Oxidation of organic material at the bottom consumes oxygen to produce CO_2 until oxygen is no longer available, after which decomposition must end in methane (CH_4). Stratification is essentially universal in storage dams such as Tucuruí on the Tocantins River (Figure 20.4). In run-of-river dams, stratification will depend on the velocity with which the water moves through the reservoir. In run-of-river dams where the main channel remains free of stratification, as at the Santo Antônio Dam on the Madeira River, bays and flooded tributaries can still stratify (Fearnside 2015a).

Underwater biomass decomposition leads to the emission of both CO_2 and CH_4. One ton of methane has an impact on blocking the passage of infrared radiation that is 120 times that of a ton of CO_2 while it remains in the atmosphere (Myhre *et al.* 2013). If we are to stay within either of the Paris Agreement's limits (mean global temperature "well below 2°C" or below 1.5°C above the preindustrial mean), then the impact of CH_4 in terms of CO_2-equivalents must be considered on a 20-year basis, which essentially triples the impact of hydroelectric dams on global warming (Fearnside 2015b, 2017a,b). The impacts of different green-

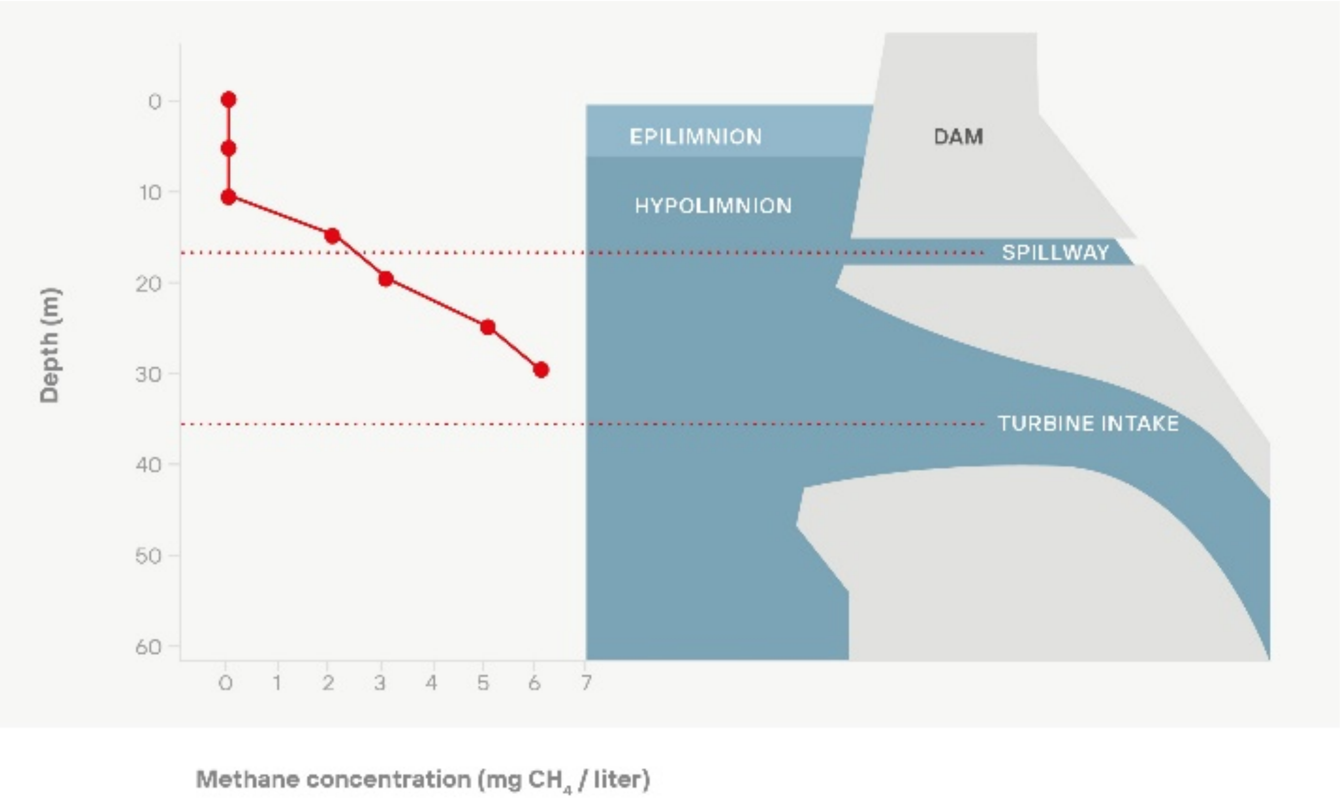


Figure 20.4 Reservoir stratification in the Tucuruí reservoir. In the bottom water (hypolimnion) oxygen is depleted and methane (CH4) levels increase with depth, reaching high levels at the levels of the spillways and turbine intakes. Source: Fearnside and Pueyo (2012).

house gases are expressed in terms of CO_2 equivalents based on global-warming potentials (GWPs), which represent the effect on global temperature over a given time horizon from emitting one ton of the gas relative to the simultaneous emission of one ton of CO_2. Considering the 20-year GWPs from the IPCC's 5th Assessment Report, 25% of lowland dams would emit even more CO_2 equivalents per megawatt-hour generated than a coal-fired power plant, and 40% of them would emit more than generation from natural gas (Almeida *et al.* 2019). The result would be even worse for Amazonian dams if emissions from the water passing through the turbines and spillways were included in these calculations. Box 20.1 explains the contribution of Amazonian dams to greenhouse-gas emissions.

Considerable uncertainty exists in calculating greenhouse-gas emissions (i.e., CO_2, CH_4 and N_2O) from dams on the scale of the Amazon as a whole. There is much variation from dam to dam with reference to key variables such as the depth of water at the intakes of the turbines and spillways, the average turnover time of water in the reservoir, and the existence of bays and other areas in the reservoir where turnover times are much longer than the average (Fearnside 2013a, 2015a). For example, run-of-river dams emit less than storage ones because they have smaller reservoirs with faster water turnover times and less variation in water level. However, run-of-river dams can still emit methane even if the water flow is sufficient to prevent stratification in the main channel of the river because the tributaries and bays stratify, and methane produced in them reaches the spillways and turbines to be emitted downstream (Fearnside 2015a; see also Bertassoli Jr *et al.* 2021). Another key aspect in the variation in dam-related emissions is dam location; lowland dams (eleva-

BOX 20.1 Greenhouse-gas emissions from Amazonian dams

Greenhouse-gas emissions from Amazonian dams include both methane produced in stratified reservoirs and CO_2 from trees killed by flooding (Figure B20.1). The dead trees subsequently decay and release greenhouse gases (i.e., Abril et al. 2013; Fearnside 1995, 2002a, 2005). In addition, trees near the edges of reservoirs suffer stress from the high water table, causing mortality (dos Santos Junior et al. 2013, 2015; Fearnside 2009). The large amount of initial biomass when a reservoir is flooded (which is especially high in tropical forests), in addition to the presence of easily oxidized labile carbon in the soil, leads to young reservoirs being larger emitters than older ones (Barros et al. 2011). After these carbon pools are depleted, emissions decline but do not fall to zero (Fearnside 2009, 2016).

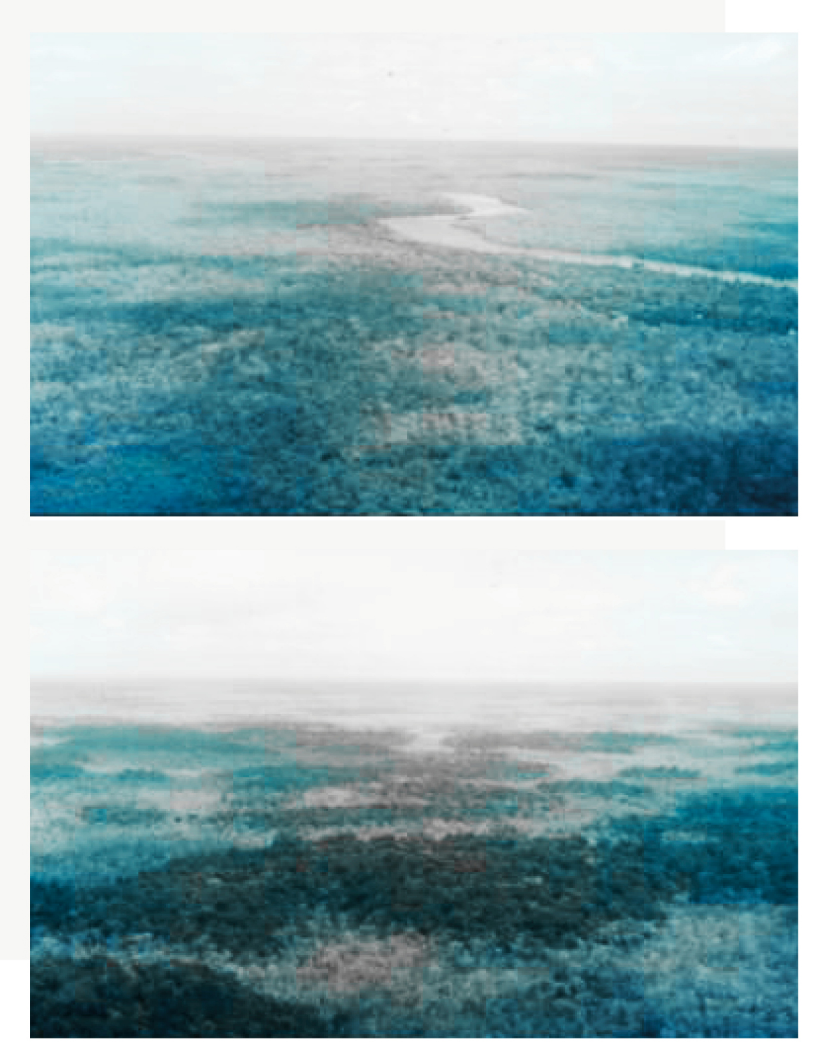


Figure B20.1 Some of the approximately 100 million trees (diameter > 10 cm) killed in the shallow reservoir behind the Balbina Dam. The light-colored trees are dead. The reservoir has over 3,000 islands (bottom panel), increasing the impact on emissions from tree mortality, as well as the fragmentation impact on terrestrial fauna. Source: Fearnside 1989. Photographs: Philip Fearnside.

tion <500 m) produce more than triple the emissions per megawatt-hour generated than dams at higher elevations (Almeida *et al.* 2019). Similarly, tropical dams have higher emissions than those at higher latitudes (Barros *et al.* 2011). Because a substantial amount of information is needed about each dam in order to estimate greenhouse-gas emissions, it is difficult to make valid regional, national, or global estimates. Simple extrapolation based on installed capacity, which has been done in various global estimates, is insufficient.

Emissions resulting from the reservoir surface tend to be the only ones considered when evaluating the impacts of dams on climate change, which greatly underestimates total dam emissions (e.g., Brazil 2004). Reservoir surfaces can emit gases both by diffusion and by bubbling (ebullition). Diffusion is a large source in the first two years after reservoir filling, but subsequently declines in importance (Dumestre *et al.* 1999). Bubbling is greater in shallow parts of the reservoir, and it occurs at irregular intervals, with short periods of intense bubbling interspersed with long periods with few bubbles (Lima 2002). The treatment of these effects in calculating annual emissions from a reservoir can have dramatic effects on the calculated impact (Pueyo and Fearnside 2011; Fearnside and Pueyo 2012). The often-neglected emissions from turbines and spillways ("downstream emissions") are critical (Fearnside 2013a, b, 2015a). Downstream emissions, which are largely proportional to water flow, are generally greater than those from the reservoir surface, which are proportional to reservoir area. This is the case of the Petit Saut Dam in French Guiana, which has much more data on emissions than any other Amazonian dam (Delmas *et al.* 2001; Abril *et al.* 2005). In Balbina, which has a large reservoir and little water flow, surface emissions are slightly larger than downstream emissions, whereas in Tucuruí, which has approximately the same reservoir area as Balbina but much more water flow, downstream emissions predominate (Fearnside 2002a; Kemenes *et al.* 2007, 2011, 2016).

In the first years after impoundment there is normally an explosion of floating and rooted aquatic plants (macrophytes) due to a flush of nutrients in the water when the soil and litter are first flooded and from leaves dropped by dying trees. The macrophytes add to the oxygen depletion provoked by decay of the flooded vegetation. The macrophyte cover subsequently declines to lower levels, as occurred at Tucuruí and Balbina (Fearnside 1989, 2001). Lower oxygen content in a reservoir as compared to the running water of the natural river is one of the changes that cause populations of most of the original fish species to either disappear or be reduced to minimal levels, being replaced by a different and less-diverse assembly of species (Sá-Oliveira *et al*. 2015a,b).

20.2.1.5 Alteration of sediment flows

Dams reduce sediment flows by retaining sediments in reservoirs (Fearnside 2013c). Downstream, reduced sediment load results in scouring, where erosion of the riverbanks and bottom accelerates (Santos *et al.* 2020). Reduction in sediment flow deprives the downstream river of the nutrients associated with sediment particles. In the Madeira River, sediment transport downstream of the Santo Antônio and Jirau Dams decreased by 20% compared to pre-dam quantities (Latrubesse *et al.* 2017), which may have contributed to the observed sharp decline in fish catches downstream of the dams (Lima *et al.* 2017; Santos *et al.* 2020). Because suspended particulate organic matter and aquatic macrophytes are the base of the food chain of the lower Amazon (Arantes *et al.* 2019c), reduction of sediment loads by Andean dams are likely to have far-reaching consequences for aquatic food webs by reducing nutrient supplies and thereby affecting primary production (Forsberg *et al.* 2017). Along with reduced oxygen, reduced nutrient flows may have contributed to the collapse of fish and freshwater shrimp populations below the Tucuruí Dam (Odinetz Collart 1987), an impact these populations have never recovered from (Cintra 2009).

Reducing sediment flows also impacts aquatic biota by modifying river geomorphology. Andean tributaries provide over 90% of the sediment budget of lowland rivers in the Amazon Basin (Filizola and Guyot 2009), playing critical roles in geomorphological processes such as river meandering and floodplain formation (Dunne *et al.* 1998; Meade 2007; McClain and Naiman 2008; Constantine *et al.* 2014). Interfering with these processes disrupts the lateral connectivity between river channels and floodplains and ultimately reduces fish yields (Forsberg *et al.* 2017; Almeida *et al.* 2020). The fishes' seasonal use of floodplains has essential nursery and feeding roles (Bayley 1995; Nilsson and Berggren 2000; Castello *et al.* 2015; Hurd *et al.* 2016; Bayley *et al.* 2018).

Impacts from reduction of sediment flows are especially problematic in white-water rivers. In some cases, the process of dam construction can have the opposite effect of temporarily increasing sediment loads in clear-water and black-water rivers, which is also damaging. In either case, dam-induced downstream modifications affect fishes' longitudinal upriver spawning migrations (Agostinho *et al.* 2004, 2008; Lytle and Poff 2004; Bailly *et al.* 2008). These migrations are affected by modifying the physical and chemical cues to which fish have adapted (Freitas *et al.* 2012; McIntyre *et al.* 2016; Timpe and Kaplan 2017). This impact is in addition to the catastrophic effect of physical blockage of migration routes by dams.

20.2.1.6 Alteration of streamflow

Storage dams can cause downstream flow changes over longer periods than run-of-river dams, but the large variation in daily or hourly time scales for run-of-river dams can also provoke significant changes in streamflows (Almeida *et al.* 2020). Alteration of flow patterns in the river below a dam has multiple effects on downstream ecosystems. Timpe and Kaplan (2017) related ecological impacts to hydrological measures within four groups of hydrological parameters: 1) frequency and 2) duration of high and low pulses (flood pulses), and 3) the rate and 4) the frequency of water condition (level) changes. Other impacts on streamflow occur when the reservoir is filling, such that downstream river stretches dry out during all or part of the filling period. The Balbina Dam was an extreme case, with flow stopped for over a year (Fearnside 1989). The Belo Monte Dam produces a similar effect that is permanent and on a grand scale; water flow is greatly reduced in a 130-km stretch known as the "big bend of the Xingu River" (*Volta Grande do Rio Xingu*), with 80% of the river's annual flow diverted (Figure 20.5).

Modifications in the hydrological regime directly impact aquatic biodiversity. Fish behavior, especially as related to migration and reproduction, is attuned to flow changes, and false signals caused by dams can induce fish to behave in ways that jeopardize their reproductive success (Agostinho *et al.* 2004; Bailly *et al.* 2008; Freitas *et al.* 2012; Vasconcelos *et al.* 2014; Nunes *et al.* 2015; McIntyre *et al.* 2016). Reduction in water flow also negatively affects ornamental species, such as the zebra pleco (*Hypancistrus zebra*), which is threatened with extinction in the wild due to the Belo Monte Dam (Gonçalves 2011). In addition, alteration of flow and of river stages (height of the water level) can also affect turtle reproduction on river beaches, as is reported by Indigenous people for beaches below the Teles Pires and São Manoel Dams in the Tapajós Basin.

Flooded forests are impacted by the construction of mega-dams by increasing tree mortality due to extreme flooding (Resende *et al.* 2019; Oliveira *et al.* 2021). In the Uatumã River below Brazil's Balbina Dam, streamflow alterations resulted in the death of 12% of the swamp (*igapó*) forest along a 125-km stretch of river below the dam (Assahira *et al.* 2017; Schöngart *et al.* 2021). During years with high rainfall the water level no longer reaches the minimum of the natural river, leaving trees in low topographic positions underwater beyond their tolerance limits (Figure 20.6).

Figure 20.5 The Belo Monte hydroelectric project has diverted water from the "Volta Grande" (big bend) of the Xingu River, a 130-km stretch between the two dams that comprise the project. Source: Watts (2019). Photograph: Fábio Erdos/The Guardian.

Figure 20.6 *Igapó* (black-water swamp forest) killed by alteration of water levels downstream of the Balbina Dam. Photo: Jochen Schöngart, INPA.

20.3 Roads

Amazonian roads are often built without adequate passages for water, such as culverts or bridges, which results in the fragmentation of small tributaries and seasonal streams. Roads can act as dams, and their impact is especially strong for seasonal streams, with roads causing ponding along the road, blocking the passage of aquatic life and disrupting stream connectivity. On Brazil's BR-319 (Manaus-Porto Velho) highway such blockages impede the seasonal migration of stream fishes (Stegmann *et al.* 2019). Roads also influence water quality and sediment deposition in aquatic systems. A study of 82 of the 242 points at which watercourses intersect BR-319 showed higher water turbidity downstream, as compared to upstream, of the road crossings (Maia 2012). A road without accompanying deforestation in Brazil's state of Amazonas resulted in sediment from erosion of the roadbed and from dust raised by truck traffic that had notable effects on the community of aquatic insects in nearby streams, reducing richness and density in all functional groups, especially shredder species (Couceiro *et al.* 2011). One factor contributing to this is the burial of fallen leaves under the sediments, making these unavailable to insects in the shredder functional group (Couceiro *et al.* 2011). This reduces an important input to the base of the trophic pyramid in the aquatic ecosystem.

20.4 Navigational waterways and river diversions

Navigational waterways (Figure 20.7) have severe impacts on aquatic ecosystems. One is the dynamiting and removal of rocky habitats in order to allow barges to pass unimpeded. Many species of fish are endemic to these habitats and could go extinct when they are removed (e.g., (Zuanon 2015). The planned removal of the extensive rock outcrops of the Pedral do Lourenço upstream from Marabá on the Tocantins River in the Brazilian Amazon would have these effects on a large scale (Higgins 2020).

In addition to removing rock outcrops, dredging of river channels to ensure yearlong navigability results in deepening shallow zones and removing woody debris (Castello *et al*. 2013a) that can hold rich, endemic fish fauna (Hrbek *et al.* 2018). Populations of these species are unlikely to recover once their specific habitat has been removed. In the Peruvian Amazon a project has recently been contracted for implanting the roughly 2,700-km Hidrovía Amazónica (Anderson *et al.* 2018; Bodmer *et al.* 2018). Recent field data on fluvial sediment movements and fish biodiversity in the Marañon and Ucayali Rivers in the Peruvian Amazon suggest that the Hidrovía Amazónica project could significantly alter river-channel morphology and consequently impact fish diversity and productivity on which local economies depend. Measurements of sediment transport in these rivers have shown that the filling time of the riverbed is very fast, with an average transport of 1.3 million tons of total sediments per day (Centro de Investigación y Tecnologia del Agua CITA 2019).
Among the most critical impacts that the Hidrovía Amazónica would cause to the Peruvian Amazon's fish biodiversity, habitats, and fishery resources are (i) contamination of rivers due to fuel and oil spills from dredging vessels, (ii) disturbance of local and regional fish migrations, (iii) impact on fish spawning and refuge habitats, (iv) impact on the abundance of fish populations, (iv) mortality of fish eggs, larvae, and juveniles, (v) disturbance of the natural floods along the river banks, and (vi) impacts on fish productivity (García-Villacorta 2019). Other potential consequences are the degradation or destruction of breeding and feeding grounds, particularly for detritivorous species.

20.5 Overharvesting

20.5.1 Aquatic fauna harvested for human consumption

The unsustainable exploitation of plant and animal species has long been a significant factor in degrading aquatic ecosystems in the Amazon Basin (Castello *et al*. 2013a, Chapter 15). Most large, high-valued fish species, such as the giant pira-

Figure 20.7 Existing and planned waterways across the Amazon biome. Sources: Fearnside 2002b, 2014a; Mariac *et al*. 2021

rucu or paiche (*Arapaima* spp.), which is already on the CITES II list of endangered species (Castello and Stewart 2010; Castello *et al.* 2015), the large fruit-eating tambaqui or gamitana, *Colossoma macropomum* (Isaac and Ruffino 1996; Campos *et al.* 2015), and many of the largest catfishes (e.g., Isaac *et al.* 1998; Ruffino and Isaac 1999; Petrere *et al.* 2004; Alonso and Pirker 2005; Córdoba *et al.* 2013) are considered overfished in their natural distribution areas. In several places, local management programs are in place and fisheries are under systematic control, as is the case with participatory management of *Arapaima* fishing in the Mamiraruá Sustainable Development Reserve in Brazil (IDSM 2021) and the Pacaya-Samiria National Reserve in Peru (Kirkland *et al*. 2020).

Overfishing is no longer restricted to large, highly sought species, it also affects several of the smaller Characiformes species that now dominate fish landings, such as *Prochilodus nigricans* (Catarino *et al.* 2014; Bonilla-Castillo *et al.* 2018) *Psectrogaster* spp. (García-Vásquez *et al.* 2015), *Triportheus* sp, *Osteoglossum bicirrhosum*, and *Mylossoma duriventre* (Fabré *et al.* 2017). This is particularly visible around large cities, such as Manaus and Iquitos, which can cast defaunation shadows of over a thousand kilometers, as evidenced for tambaqui (Tregidgo *et al.* 2017; Garcia *et al*. 2009). The progressive replacement in fisheries of large, long-lived species by smaller species with faster turnover is a well-described phenomenon known as "fishing down" (Welcomme 1995, 1999), or "fishing down the food web" when an associated decline in trophic levels is observed in the exploited species (Pauly *et al.* 1998).

Most commercial and overexploited fish species in the Amazon Basin are migratory, traveling from a few hundred to several thousand kilometers (Barthem and Goulding 2007; Goulding *et al*. 2019). Migratory species account for over 90% of fisheries landings in the Amazon Basin, generating incomes of over US $400 million (Duponchelle *et al.* 2021). Although the proportion of migratory species is slightly lower in unmonitored subsistence fisheries, which represent at least as much volume as the landed commercial fisheries (Bayley 1998; Crampton *et al.* 2004), they still dominate the catches (Batista *et al.* 1998; Castello *et al.* 2011; Castello *et al*. 2013b). Migratory fishes are the species most at risk from the growing anthropogenic activities threatening the Amazon's aquatic ecosystems (review in Duponchelle *et al.* 2021).

Fish overharvesting could have indirect negative effects on terrestrial plant biodiversity and conservation because many commercial species have frugivorous diets and play key roles in dispersing seeds (ichthyochory) and in seed germination processes (review in Correa *et al*. 2015a). This is further aggravated by the fact that larger fish, which are the main targets for fisheries, are also the most effective seed-dispersal agents (Correa *et al*. 2015a,b; Chapters 3 and 4).

Modern aquaculture could contribute to the conservation of endangered species, which are overharvested. Most of the aquaculture farms around major Amazon cities have only recently begun operation and focus on much-consumed species. Tambaqui is the native fish species most frequently farmed in Brazil (Araújo-Lima and Goulding 1998; de Oliveira and Val 2017). Pirarucu (*Arapaima*) and some other fish species, such as matrinchã (*Brycon amazonicus*), are also farmed. The major challenge to fish farming in the Amazon is feeding because local production of fish feed is limited. Other inputs, such as ice and rock salt, can also be difficult to obtain. The improvement of transportation and other conditions would also contribute to the use of by-products (such as leather) from these fish species. Other aquatic groups, such as turtles, are illegally harvested for sale as food (Salisbury 2016). Dolphins are under severe pressure from the practice of killing them to use their flesh as fish bait, especially for the piragatinga or mota catfish (*Callophysius macropterus*), and caimans are also killed for this purpose (Brum *et al.* 2015).

20.5.2 Ornamental fish

The aquarium trade is a growing, multi-billion-dollar industry (Andrews 1990; Stevens *et al.* 2017). Fish are among the most popular pets in the world (Olivier 2001), and the harvesting of wild specimens for the international ornamental trade is a major conservation issue (Andrews 1990; Chao and Prang 1997; Moreau and Coomes 2007) The Amazon Basin accounts for ~10% of the global trade of freshwater ornamental fish, with Brazil, Colombia, and Peru as the major exporters; in 2007, the total declared (greatly underestimated) export value from these three countries was around US $17 million (Monticini 2010). Although artificial breeding could be beneficial for the conservation of aquarium species (King 2019), nearly all specimens exported from South America are taken directly from the wild (Olivier 2001). There is no up-to-date published estimate of the overall number of Amazonian fish species exploited by the ornamental trade, but about 700 species are exported from Brazil (IBAMA 2012), >100 from Colombia (Ortega Lara *et al.* 2015) and >300 from Peru (Gerstner *et al.* 2006). These lists share many species, but widespread species may also hold cryptic diversity (e.g., Estivals *et al.* 2020). These figures are probably underestimates, as many different species can be exported under a single name (Moreau and Coomes 2007). Therefore, a conservative estimate could consider that between 700 and 1,000 species of fish are exploited by the ornamental trade in the Amazon Basin.

One major impact of the ornamental trade is that it favors invasion of exotic species and their associated parasites (Chan *et al.* 2019; Gippet and Bertelsmeier 2021). The effects of the ornamental trade on natural fish populations in the Amazon, however, remain poorly studied. Anecdotal information suggests population collapses or declines under exploitation pressure at some locations in the Rio Negro for discus (*Symphysodon discus*) (Crampton 1999) and cardinal tetra (*Paracheirodon axelrodi*) (Andrews 1990; Chao and Prada-Pedreros 1995). In the Peruvian Amazon, exploitation for the ornamental trade has led to reductions in ornamental species at study locations by over 50% in fish abundance, diversity, and biomass (Gerstner *et al.* 2006).

The cardinal tetra is the number-one export species in the ornamental fish trade in Brazil, accounting for 68% of the total value of Brazilian ornamental fish exports (Anjos *et al*. 2018). The cardinal tetra inhabits the middle and upper Rio Negro, and its trade corresponds to 60% of the economy of the municipality of Barcelos. However, fishery data have yet to be collected to better evaluate the effects of this artisanal fishery on fish populations. Based on information from fishers and the data obtained from sampling ornamental fish (fish caught per area sampled), the world economic collapse that began in 2008 directly affected the gross amount of exported ornamental fish (mostly cardinal tetra).

After the 2008 global financial crisis there was a decrease in both the number of people involved in exploiting ornamental fish and in the catch volume. In fact, the decrease in the 2010s, followed by another economic crisis, ended the boom in ornamental fish export from Brazil. Considering bycatch (other species caught together with the target species), ornamental fisheries would not be sustainable without an observatory group comprising the fisher community, dealers, and researchers. The observatory program is viable for the ornamental fish market and can increase sales by emphasizing fish preservation and the well-being of the local communities that are still active in this trade in a manner similar to what occurred with fair-trade coffee (Zehev *et al.* 2015).

Owing to the increasing exploitation of ornamental fish, the silver arowana (*Osteoglossum bicirrhosum*) has been placed on the Red Book list in Colombia (Mojica *et al*. 2012), and this species may also be threatened in Peru (Moreau and Coomes 2006, 2007). Export of this species for ornamental purposes is prohibited in Brazil (Lima and Prang 2008).

20.6 Invasive Species

The introduction of invasive fish species worldwide is responsible for the homogenization of aquatic fauna, driven especially by a few species, such as *O. niloticus*, *C. carpio* and *P. reticulata* (Villéger *et al.* 2011; Toussaint *et al.* 2016a,b), all of which have been introduced into the Amazon. Invasive species are used for farming, cultivation of ornamental species, and recreational fishing (Lima-Junior *et al.* 2018). Fish introduced to the lakes and reservoirs of the Brazilian Amazon often belong to predatory species (*Cichla* spp., *Astronotus* spp. And *Pygocentrus nattereri*), contributing to the reduction in abundance or loss of native fish species, with whole-ecosystem consequences such as loss of native species' habitats, decrease of local species due to the many invasive species that eat native fish species' eggs, and competition for food, leading to changes in species composition and to modifications of food-webs (Zaret and Payne 1973; Latini and Petrere 2004; Pelicice and Agostinho 2009; Pelicice *et al.* 2015b; Fragoso-Moura *et al.* 2016). In Andean watercourses in Bolivia and Peru the introduction of the predatory rainbow trout *Oncorhynchus mykiss* resulted in local extirpation or greatly reduced abundance of native *Astroblepus* spp. (Ortega *et al.* 2007; Van Damme *et al.* 2011). In the lake Titicaca system, introduced rainbow trout (*Oncorhynchus mykiss*) and pejerrey (*Odonthestes bonariensis*) resulted in the extinction of *Orestias cuvieri* and in declines in many other native species (Anderson and Maldonado-Ocampo 2011; Ortega *et al.* 2007; Van Damme *et al.* 2009).

Sport fishing and collection for ornamental and aquaculture purposes have motivated the introduction of tilapia (*Oreochromis niloticus*), guppy (*Poecilia reticulate*), and common carp (*Cyprinus carpio*), but their impacts are still poorly investigated (Ortega et al., 2007; Anderson and Maldonado-Ocampo 2011; Van Damme *et al.* 2011; Gutiérrez *et al.* 2012; Doria *et al.* 2020). In 2020, the Brazilian government authorized and initiated the promotion of raising tilapia in cages in reservoirs (Charvet *et al.* 2021), despite the fact that tilapia can affect native species through competition and spread of diseases (Deines *et al.* 2016). If tilapia populations become dense, they can release enough phosphorus into the water to cause eutrophication, which leads to widespread fish mortality, as has already occurred in lakes outside the Amazon (Starling *et al.* 2002).

The proliferation of hydroelectric dams in the Amazon makes the region more vulnerable to invasive species, as dams facilitate invasive fish species. For example, specialist species adapted to running water progressively disappear from the newly created reservoirs upstream of dams and, if eurytopic native species (species able to tolerate a wide range of ecological conditions) cannot take their place, then the niche is often taken by alien species (Liew *et al.* 2016). This is facilitated by potential tilapia entry into reservoirs; in addition to the recently legalized rearing of tilapia in cages in reservoirs in Brazil, many aquaculture farms are installed close to reservoirs and fish may escape when water is drained from the ponds.

The introduction of some Amazonian predatory fish species into regions outside their original range can have major effects on local fish communities. This is the case for tucunaré (*Cichla* spp.) and pirarucu or paiche (*Arapaima* spp.) (Miranda-Chumacero *et al.* 2012). A recent review revealed 1,314 records of non-native fish species (in 9 orders and 17 families), in the Amazon Basin since the first record in 1939, with a sharp increase in the last 20 years (75% of occurrences) (Doria *et al.* 2021). Non-native species were mainly introduced by the ornamental trade, or for aquaculture and sport-fishing. The most widespread non-native species were *Arapaima gigas* (outside of its native range), *Poecilia reticulata,* and *Oreochromis niloticus*. Overall, our current understanding of impacts of invasive fish species in the Amazon remains limited due to a paucity of studies (Frehse *et al.* 2016; Doria *et al.* 2021).

20.7 Deforestation

Deforestation is a driver of aquatic degradation that can have effects that differ between the directly impacted areas and areas downstream; local deforestation can have regional consequences. At the small to medium scale, deforestation usually results in increased runoff and discharge; for example, deforestation resulted in a 25% increase in discharge in large river systems such as the Tocantins and Araguaia Rivers, with little change in precipitation (Coe *et al*. 2009). At a larger scale, atmospheric feedbacks (reduced precipitation caused by decreased evapotranspiration) can change the water balance, not only in the basins where deforestation has occurred but throughout the entire Amazon via atmospheric circulation (Coe *et al*. 2009).

By increasing water runoff and sediment loads carried by the rivers, deforestation typically alters geomorphological and biochemical processes downstream with consequences for soil erosion and the biological productivity of aquatic ecosystems (Neill *et al*. 2001; Coe *et al*. 2009; Deegan *et al*. 2011; Iñiguez-Armijos *et al*. 2014; Ilha *et al*. 2018). For example, stronger floods result in the washing out of substrate and associated production of the benthos on which migratory detritivores feed (Flecker 1996). Decreased water transparency reduces algal and zooplankton production in floodplain lakes, which are important feeding and nursery areas for most fish species (Bayley 1995; Pringle *et al*. 2000).

The chemical properties of streams flowing through pastures are radically different from those of streams in neighboring forests (Krusche *et al*. 2005; Neill *et al*. 2006; Deegan *et al*. 2011). Solutes in groundwater are also affected, thereby contributing to changes in stream chemistry (Williams *et al*. 1997). Direct exposure to sun and changes in temperature, oxygen, chemical content, and bottom substrates greatly affect aquatic fauna (da-Silva Monteiro Júnior *et al*. 2013). Increased water temperatures and reduced oxygenation during the dry period can be lethal to fish (Winemiller *et al*. 1996).

Cardinal tetras are sensitive to increased temperatures (Fé-Gonçalves *et al*. 2018). The two congeneric species of cardinal tetras are distributed in inter-fluvial areas in the upper part of the Rio Negro Basin and inhabit two distinct environments with different vegetation covers and temperatures (Marshall *et al*. 2011). The water temperatures of these environments differ by less than 2°C but coincide with the maximum thermal limits for both species (Campos *et al*. 2017). Small characins are usually found in small, forested *terra firme* (upland) streams. The increase in water temperature caused by deforestation will therefore affect fish species living in streams in deforested areas. Overall, severe disturbances in fish communities can result because many species live in streams with temperatures close to their critical tolerance limits (Campos *et al*. 2018).

In small streams, deforestation reduces the availability of large instream wood, which plays critical roles in the structure, diversity, and abundance of fish communities, thus impacting fisheries and ecosystem functions (Wright and Flecker 2004). Loss of smaller debris could impact the benthic insects and macroinvertebrates that fish eat. Recent studies have demonstrated negative impacts of deforestation on fishery yield (Castello *et al*. 2018) and fish species richness, taxonomic diversity, abundance (Lobón-Cerviá *et al*. 2015; Arantes *et al*. 2018), biomass, and functional diversity (Arantes *et al*. 2019a). All these impacts can be reduced if riparian forests are maintained; for example, if an area is converted to pasture but a forested strip is left along the margins of waterbodies, these waterbodies will be less affected (de Paula *et al*. 2021). The wider the strip, the less the impact on aquatic ecosystems; for example, in the eastern Amazon the percentage of forest cover within 100 m of a stream is closely related to macroinvertebrate diversity in the stream (de Paula *et al.* 2021). Even a small fraction of forest loss in a catchment is sufficient to transform communities of benthic invertebrates and vertebrates (mainly fish) in Amazonian streams (Brito *et al.* 2020; Campos *et al.* 2018). Reducing forest cover by only 6.5% within 50 m of a stream is enough to cross thresholds for aquatic invertebrates (Dala'corte *et al.* 2020). Furthermore, a forest border protects stream banks from erosion, prevents destruction of the stream bed, maintains cooler temperatures, and helps maintain better water quality. In Brazil, the legal requirement for such protection has been greatly reduced since 2012, when the country's Forest Code was replaced by a law that redefines the water level from which the required forest border is measured, changing the basis for measurement from the maximum to the minimum level of the river. This eliminated almost all requirements for protection along most medium and large Amazonian rivers due to their great annual variation in water level.

20.8 Pollution

20.8.1 Agricultural chemicals

Expansion of chemical-intensive crops such as soybeans and oil palm increases the risk of water contamination from agricultural chemicals. The expansion of soybean production in the southern Amazon is of particular concern due to the heavy use of herbicides, including glyphosate (e.g., Roundup©). There are few direct measurements of Amazonian watercourses. A 2016 review on pesticides in Brazilian freshwaters found no studies in the country's Amazon biome (Albuquerque *et al.* 2016). A 2020 study in the area near Santarém, where soybeans are expanding, sampled watercourses and/or groundwater at 28 sites, detecting glyphosate at 11 sites at levels between 1.5 and 9.7 µg/L (Pires *et al.* 2020). The presence of pesticides in aquatic animals indicates water contamination, as in the case of organochlorine pesticides in fish in the Tapajós River (Mendes *et al.* 2016), turtles in the Xingu River (Pignati *et al.* 2018), and Amazon River dolphins in the Solimões (Upper Amazon) and Madeira Rivers (Lailson-Brito Jr. *et al.* 2008). The same dolphins also had polychlorinated biphenyls in their blubber (Lailson-Brito Jr. *et al.* 2008; Torres *et al.* 2009). In Brazil, several hundred agricultural chemicals have been newly authorized for use under the current administration, many of which are banned in other countries (Ferrante and Fearnside 2019). Pesticides, herbicides, and medicines and other drugs (including endocrine disrupters) are released into the environment. For many compounds, the period of time they remain in the environment is still undetermined. Transition metals and other pollutants in Amazonian aquatic communities may affect local fish species differentially due to their respiration, reproduction, trophic position, and metabolic characteristics, which vary among different fish assemblages (Duarte *et al.* 2009; Braz-Mota *et al.* 2017). In Venezuelan streams, for example, particulate or dissolved compounds coming from agricultural effluents resulted in strong water de-oxygenation through micro-organismal decomposition and, subsequently, in the loss of fish species (Winemiller *et al.* 1996). By killing mostly adult fish, these relatively localized effects have potentially long-term consequences (Braz-Mota *et al.* 2017). The herbicide glyphosate and the pesticide Malathion have been shown to cause metabolic and cellular damage in fish exposed to concentrations lower than their 50% lethal concentrations (LC_{50}) (Silva *et al.* 2019; Souza *et al.* 2020).

Laboratory experiments on fish have shown that glyphosate and other herbicides cause damage to the liver and gills, as well as DNA breakage and increased expression of oncogenes (Braz-Mota *et al.* 2015; Silva *et al.* 2019; Souza *et al.* 2020). Field observations on frogs monitored before and after these herbicides were applied in an area in the central Amazon revealed that two species (*Scinax ruber* and *Rhinella marina*) developed malformations that were not present before the herbicide application or at a location 600 m from the application site. In addition, three previously abundant *Leptodactylus s*pecies became locally extinct (Ferrante and Fearnside 2020).

20.9 Oil spills and toxic waste

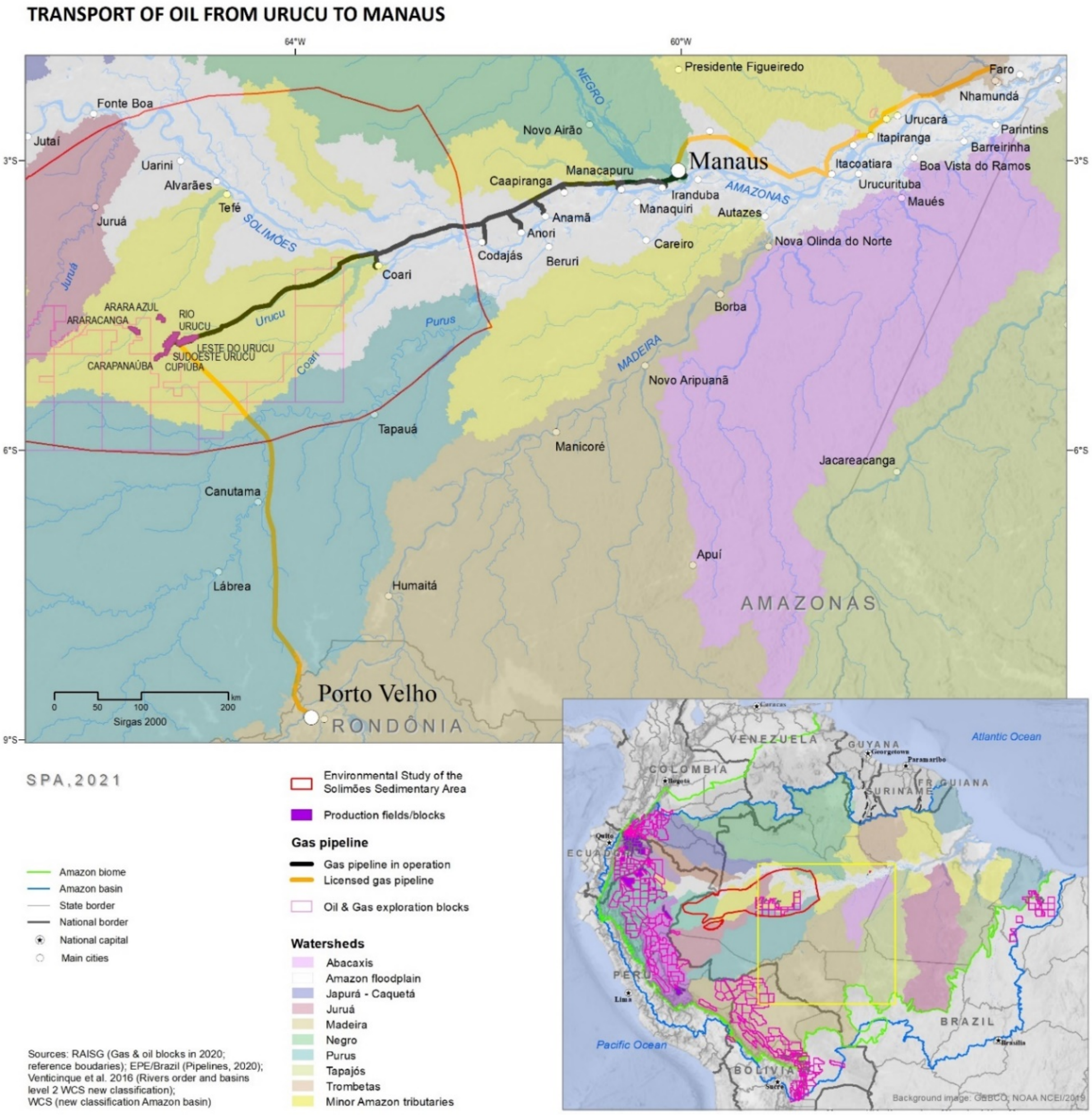
The western part of the Amazon Basin has large oil reserves (Chapter 19). Crude oil spills and untreated toxic waste from oil and gas exploitation are notorious in the Amazon portions of Ecuador (Jochnick *et al*. 1994) and Peru (Kimerling 2006; Orta Martínez *et al.* 2007; Yusta-García *et al*. 2017) (Figure 20.8). In the Ecuadorian Amazon between 1972 and 1992, 73 billion liters of crude oil was discharged into the environment, 1.8 times the 41 billion liters released by the Exxon Valdez disaster in Alaska (Sebastián and Hurtig 2004; Kimerling 2006). Over this period, 43 billion liters of produced water (oilfield brine) was also released, which contains salts that disrupt fish migrations (Kimerling 2006)**.**

Oil is toxic to fish (Sadauskas-Henrique *et al.* 2016), and oil-associated contamination can have far-reaching impacts on Amazonian aquatic communities because the oil can disperse over the entire downstream network (Yusta-García *et al.* 2017). Oil extraction produces large amounts of toxic mud and produced water, which in Peru and Ecuador have been routinely released into the environment rather than being pumped back into wells (Kimerling 2006, pp. 450-453; Moquet *et al.* 2014). This brine has both high salt concentrations and a variety of toxic substances (including heavy metals), in addition to significant amounts of oil. Concentrations of hydrocarbon-related toxins have been found in Ecuadorian streams up to 500 times higher than those allowed by regulations in Europe (Sebastián and Hurtig 2004).

Figure 20.8 Oil leaks from a submerged pipeline in Peru. Source: Fraser (2014).

The effects of oil can last for decades, as seen following a spill of 11 billion liters of crude into the Coca and Napo Rivers in Ecuador in 1987; as of 2006, the affected rivers had not recovered their fish biodiversity (Kimerling 2006, p. 458). Oil spills also greatly impact aquatic invertebrate communities, reducing both abundance and species richness, as shown by studies in streams and floodplains affected by oil near Manaus, Brazil (Couceiro *et al*. 2006, 2007a).

Extraction of oil and natural gas near the Urucu River, in the western part of the Brazilian Amazon, is a concern due to potential impacts on adjacent waterbodies. Although the oil company responsible (Petrobras) ensures that all safety operation protocols are being observed, there is always the possibility of an oil spill. Oil pumped from the Urucu wells travels in large barges down the Solimões (Upper Amazon) River from Coarí to Manaus, where it is refined (Figure 20.9).



Sources: RAISG (Gas & oil blocks in 2020; reference boudaries); EPE/Brazil (Pipelines, 2020); Venticinque et al. 2016 (Rivers order and basins level 2 WCS new classification); WCS (new classification Amazon basin)

Figure 20.9 Transport of oil by pipeline from Urucu (RUC) to Coarí and then by barge from Coarí to Manaus. The inset map shows oil project areas throughout the Amazon.

Amazon fishes have evolved in hypoxic water and have developed many strategies to either breathe air or take water from the film at the top of the water column, which is richer in oxygen (Val *et al.* 1998; Soares *et al.* 2006). As mentioned above, these strategies threaten air-breathing fish if oil spills occur (Val and Almeida-Val 1999).

Brazil's proposal for the Solimões Sedimentary Basin oil and gas project is rapidly moving forward and will open a vast "strategic influence area" covering 47 million hectares (larger than the US state of California) to exploitation in the western Brazilian Amazon (Fearnside 2020b) (Figure 20.10). Within this area, wells would be located at the most-promising locations (green lines in Figure 20.10) where seismic surveys have already been completed. Rights to the first drilling blocks have already been sold to Rosneft, a Russian company that Greenpeace-Russia accuses of causing over 10,000 oil spills throughout the world (Fearnside 2020c). This oil and gas project also carries a substantial risk of improving road access to the vast "trans-Purus" region between the Purus River and Brazil's border with Peru, resulting in deforestation of the last great block of intact forest in the Brazilian Amazon (Fearnside et al. 2020; see also the views of Brazil's Ministry of Mines and Energy in Brazil EPE 2020a,b; Fearnside 2020b,c; Vieira 2020a,b).

20.10 Mining

Gold mining, much of which is illegal, is widespread in the Amazon Basin (Figure 20.11). In Brazil it occurs in rivers such as the Tapajós,

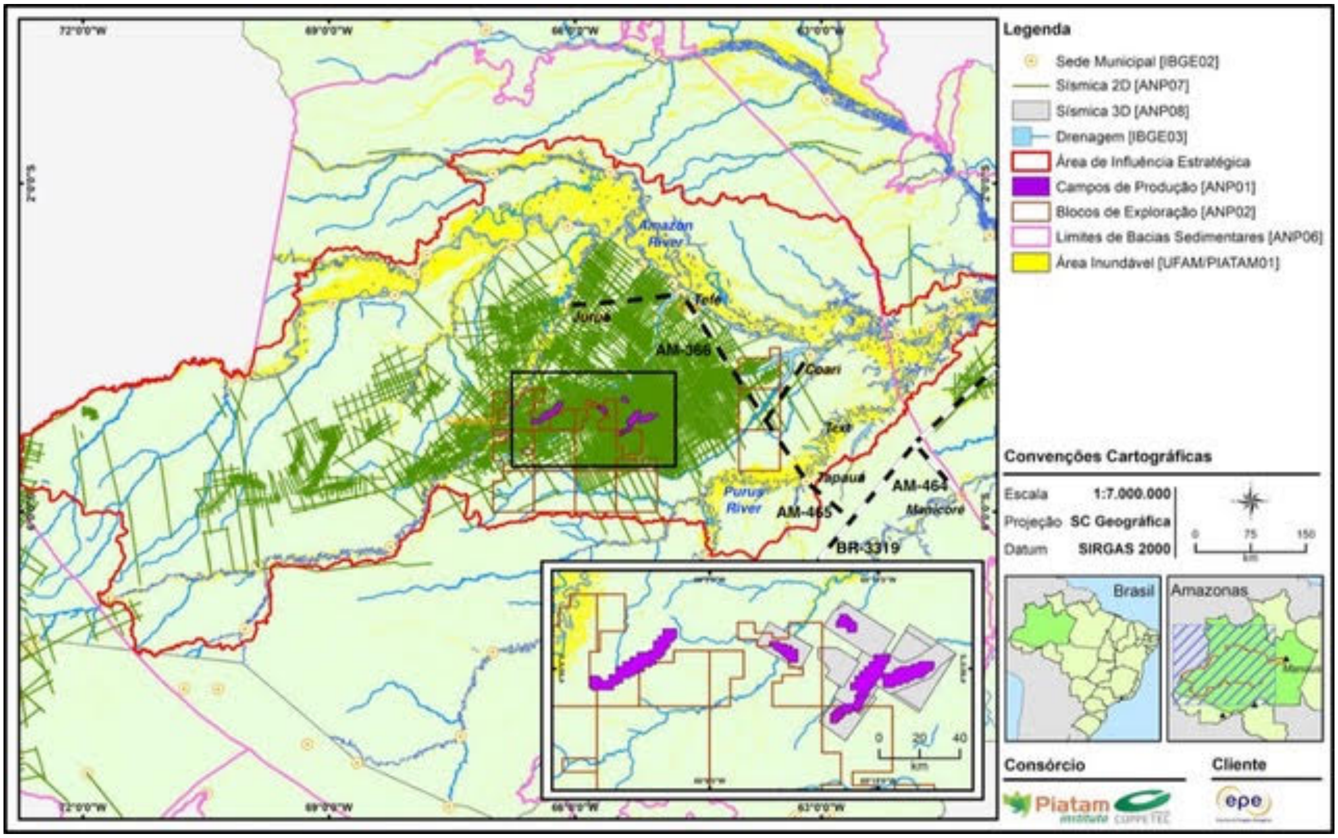


Figure 20.10 Brazil's proposed "Solimões Sedimentary Basin" oil and gas project. The purple areas are the Urucu production field where wells are currently in production. The thin green lines represent locations for future drilling where seismic surveys have already been carried out. The proposed project's "Strategic Influence Area," delimited by the red line, covers 47 million hectares (larger than the US state of California). Source: Brazil, EPE (2020a, p. 65).

Tocantins, Madeira, Xingu, Negro, Amapari, and Solimões or Upper Amazon (Figure 20.12; Roulet *et al.* 1999; dos Santos *et al.* 2000); in Bolivia in the Madeira, Beni, and Iténez Rivers (Pouilly *et al.* 2013); in Colombia in the Putumayo, Caquetá, Guanía, Vaupés, and Inirída Rivers (Nuñez-Avellaneda *et al.* 2014); in Ecuador in the Nambija River, and in French Guiana along the tributaries of the Black River (Barbosa and Dorea 1998). Illegal invasion of Indigenous areas in Brazil by gold miners (*garimpeiros*) has long been a major impact on these areas (Figure 20.13), including their aquatic ecosystems. A bill that would legalize these and other activities in Indigenous areas has the potential to greatly increase these impacts (Branford and Torres 2019; Villén-Pérez *et al.* 2020; Ferrante and Fearnside 2021). It is estimated that more than 200,000 tons of mercury have been shed by gold mining in the Brazilian Amazon since the late 19th Century (Bahía-Oliveira *et al.* 2004).

Gold mining is estimated to account for 64% of the mercury entering Amazonian aquatic systems (Roulet *et al.* 1999, 2000; Artaxo *et al.* 2000; Guimaraes *et al.* 2000). The remaining amount comes from runoff from natural deposits that are eroded by deforestation (33%) and atmospheric emissions resulting from deforestation and forest fires (3%) (Roulet *et al.* 1999; Souza-Araújo *et al.* 2016). On the basin scale, the dynamics of mercury involve abiotic physical processes (i.e., downstream transport of sediments). Elemental mercury can then be turned into toxic methylmercury by specific bacteria in anoxic environments, such as those created at the bottom of reservoirs (Section 20.2.1.4) or in thermally stratified natural lakes and rivers.

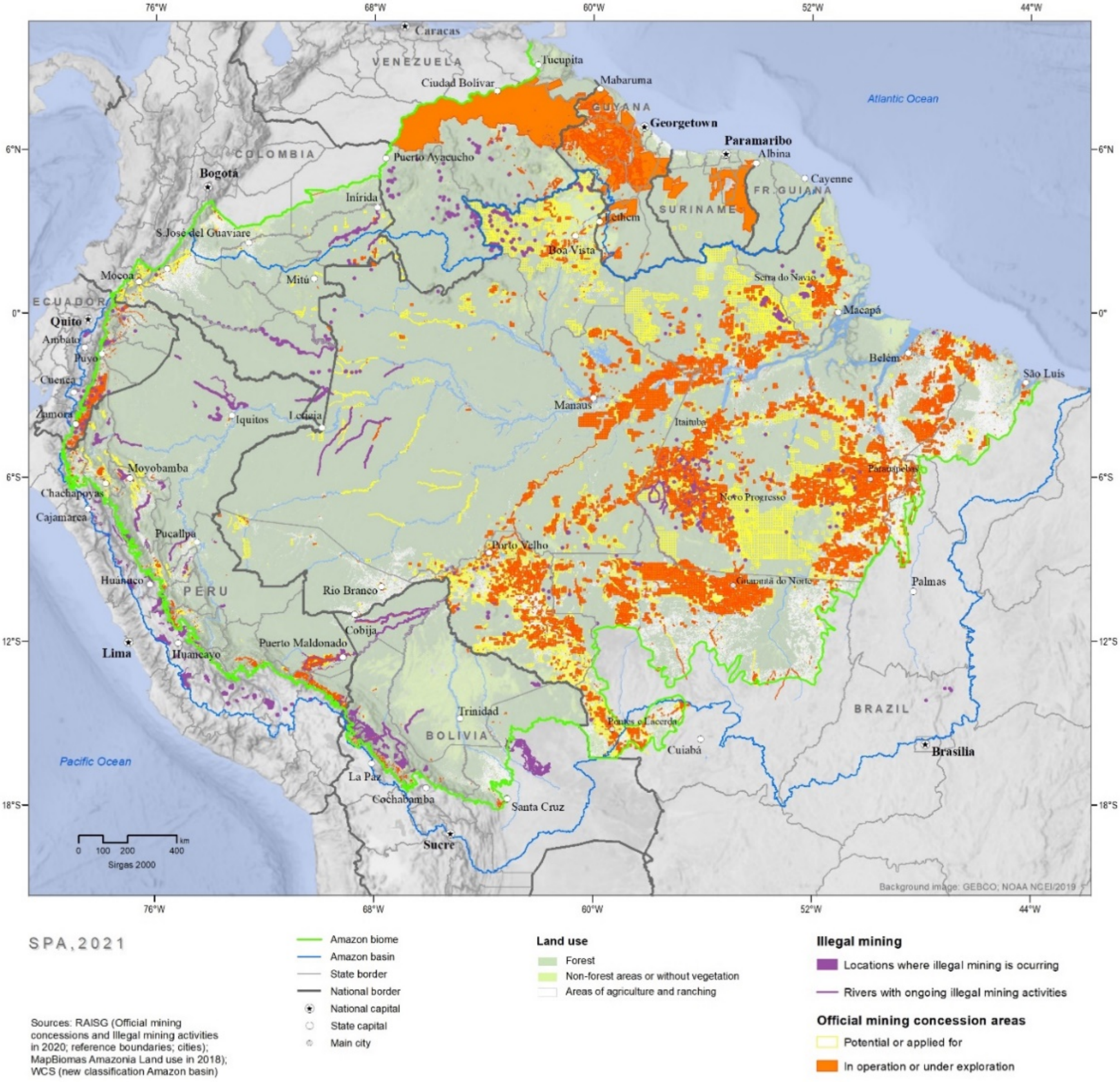
Methylmercury enters aquatic food webs and bioaccumulates in successively higher trophic levels (Morel *et al.* 1998; Ullrich *et al.* 2001). Vertebrate populations that have accumulated mercury migrate upstream, including both fish migrations for spawning and side migrations in the floodplains (Molina *et al.* 2010; Nuñez-Avellaneda *et al.* 2014; Mosquera-Guerra *et al.* 2019). High concentrations of total mercury (Hg) and methylmercury (MeHg) in aquatic trophic networks have been documented since the 1980s (Martinelli *et al.* 1988; Lacerda 1997; Lacerda and Salomons 1998).

soil independent of human activities; since Amazonian soils are ancient, they have slowly accumulated mercury that is injected into the atmosphere by volcanic eruptions and deposited by precipitation worldwide. Fish consumption by the Amazon's human communities causes some of the world's highest recorded mercury levels in human hair, along with associated health issues (Passos and Mergler 2008). Through fish consumption, humans also bioaccumulate mercury (Chapter 21).

Among endangered species, high concentrations of mercury have been reported in the giant otter (*Pteronura brasiliensis*) in Brazil (Dias Fonseca *et al.* 2005); in the Amazon River dolphin (*Inia geoffrensis*) in Colombia, Brazil, and Bolivia (Rosas and Lethi 1996; Mosquera-Guerra *et al.* 2015, 2019); and in the gray river dolphin (*Sotalia fluviatilis)* in Brazil (Mosquera-Guerra *et al.* 2019). Along the coast of the Amazon, mercury was also found in tissues of the coastal dolphin (*S. guianensis*) (de Moura *et al.* 2012). Effects of mercury on small cetaceans include liver abnormalities and serious disorders in the kidney and brain (Augier *et al.* 1993). Elsewhere, the combination of mercury with other pollutants in small cetaceans resulted in sensory deficits, behavioral deficiency, anorexia, lethargy, reproductive disorders and death of fetuses, as well as deficiencies in the immune system that facilitate the appearance of pneumonia and other infectious diseases (Cardellicchio *et al.* 2002). It remains unknown whether the same impacts are occurring in Amazon River dolphins and marine dolphins.

Preparations for large-scale industrial mining operations are rapidly moving forward (Arsenault 2021). The Canadian mining company Belo-Sun is preparing a massive operation just downstream of the Pimental Dam (part of the Belo Monte complex on the Xingu River). The operation would extract

MINING: OFFICIAL CONCESSIONS AND ILLEGAL ACTIVITIES



Sources: RAISG (Official mining concessions and Illegal mining activities in 2020; reference boundaries; cities); MapBiomas Amazonia Land use in 2018); WCS (new classification Amazon basin)

Figure 20.11. Official mining concessions and illegal activities.

Figure 20.13 Mining in Yanomami Indigenous Territory in 2020. Source: Chico Batata - Greenpeace).

Figure 20.12 Sediment from gold mining enters the Tapajos River at its confluence with the Crepuri, one of several tributaries in central Pará discharging sediments from gold mining into the Tapajós. Source: Guimarães (2020). Photograph: Jean R.D. Guimarães.

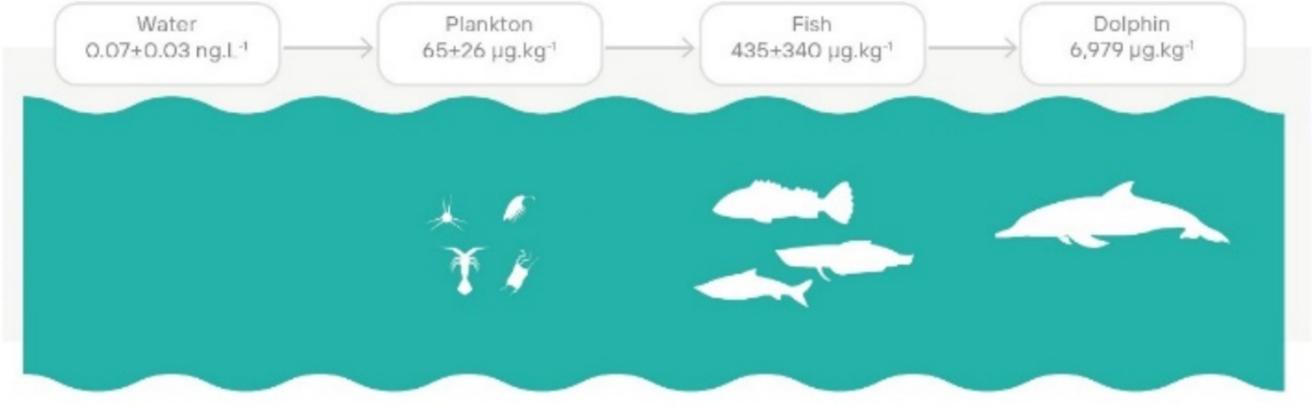


Figure 20.14 Bioaccumulation of mercury in the Rio Negro. Adapted from Kasper (2018).

gold from two open-pit mines beside the *Volta Grande* (Big Bend) stretch of the river that is already heavily impacted by reduced water flow due to the Belo Monte complex. Risks include tailings dams, cyanide use, and demand for large amounts water from the already insufficient flow of the *Volta Grande* (Emerman 2020). The 44 m high tailings dam will remain indefinitely, although the mine is estimated to be exhausted after 17 years of operation. Were the tailings dame to rupture, it could provoke a catastrophe equal to the 2015 Mariana disaster on the Rio Doce in Minas Gerais (Tófoli *et al*. 2017), and release over 35 million m^3 of tailings containing cyanide (Emerman 2020).

Bauxite mining and the processing of ore to produce alumina and then aluminum can release fine toxic particles known as "red mud" into aquatic ecosystems. At the Mineração Rio do Norte bauxite mine on the Trombetas River in Pará, a large lake (the Lago Batata) was completely filled with 24 million tons of this mud in the 1980s, killing virtually all aquatic life (Soares 2015; Borges and Branford 2020). In 2018, a holding pond for red mud burst at the Norsk Hydro alumina plant in Barcarena, Pará (Fearnside 2019). Water was contaminated as far away as Abaetetuba, 48 km from the alumina plant (Barbosa 2018).

20.11 Urban sewage and plastic waste

Urban sewage greatly affects aquatic invertebrates, reducing both abundance and species richness, as shown by a series of studies in 20 streams in the Manaus area (Couceiro *et al*. 2006, 2007a,b, 2011; Martins *et al*. 2017). The effect varies by taxonomic group, which allowed an index of pollution severity to be developed using aquatic insects as bioindicators (Couceiro *et al*. 2012). Streams in Manaus are also contaminated with a variety of hydrocarbons both from biomass burning and petroleum (de Melo *et al*. 2020).

Streams in Manaus have been found to contain human pharmaceuticals, as well as traces of cocaine, but these are diluted below detection limits after entering the major rivers (Thomas *et al*. 2014; de Melo *et al*. 2019). Pollution with pharmaceutical compounds can affect fish (dos Santos *et al*. 2020) and macrophytes (Otomo *et al*. 2021). Pharmaceutical pollution is a growing threat to aquatic environments throughout Latin America, including Amazonian countries (Valdez-Carrillo *et al*. 2020). Samples taken at 40 sites along the Amazon River and major tributaries in Brazil found 30-40 compounds near major cities and 1-7 compounds in the Amazon River far from cities (Fabregat-Safont *et al*. 2021). A different survey at 40 sampling sites along the Amazon River, three tributaries (Negro, Tapajós and Tocantins Rivers), and four cities found that chemical pollution can cause long-term effects in 50–80% of aquatic species near urban areas (Rico *et al*. 2021).

Large amounts of plastic are discarded in Amazonian rivers and streams (Figure 20.15), and the presence of microplastics has now been detected in river sediments (Gerolin *et al*. 2020), in the sand of a beach on the coast of the Amazon region, and in a river beach in the Ecuadorian Amazon (Lucas-Solis *et al.* 2021; Martinelli Filho and Monteiro 2019). Microplastics have also been found in fish species from all trophic levels, including 13 species from the Xingu River (Andrade *et al*. 2019) and 14 from the Amazon estuary (Pegado *et al*. 2018). Micro- and nanoplastics have impacts on aquatic ecosystems, including serving as carriers for persistent organic pollutants (POPs) (Besseling *et al*. 2019) and transferring chemicals that can provoke hepatic stress in fish (Rochman *et al*. 2013). They can also affect mammals (Rubio *et al*. 2020). Many cities, towns, and municipalities across the basin do not have plastic and waste management in place, and this remains as an important challenge to be tackled by policy makers for the conservation of healthy freshwater ecosystems in the region. The Amazon River is estimated to discharge 32,000-64,000 tons of plastic into the Atlantic Ocean annually (Lebreton *et al*. 2017). The Amazon River has also been identified as a major source of organic plastic additives in the water of the tropical North Atlantic (Schmidt *et al*. 2019).

20.12 Interactions among drivers

Although most drivers of degradation in aquatic ecosystems have been discussed separately, several are highly correlated, often interacting, and aquatic organisms will have to cope with some combination of these drivers. The impacts of land-cover change, global climate change, dams, and mining have interactions that are causing large-scale degradation of the Amazon's freshwater

Figure 20.15 Plastic waste discarded in a stream in Manaus in 2021. Source: Rodrigo Duarte/Greenpeace.

ecosystems, and current development trends imply dramatic increases in these impacts (Castello and Macedo 2016).

Several of the drivers discussed here can directly or indirectly promote deforestation. Hydropower dams induce road construction, which in turn lead to increased deforestation and agriculture, which often also result in more deforestation (Finer and Jenkins 2012; Chen *et al.* 2015; Lees *et al.* 2016; Forsberg *et al.* 2017; Anderson *et al.* 2018). As already explained, regulation of hydrological cycles by dams will isolate large portions of floodplains, which will likely be exploited for agriculture, further increasing deforestation (Forsberg *et al.* 2017).

Similarly, the planned waterway in the Tapajós sub-basin is likely to encourage further deforestation directly through increased soy production in Mato Grosso. Soy plantations cause aquatic ecosystems to receive runoff containing fertilizers, herbicides, pesticides, and sediment from soil erosion (Section 20.6.1). Waterways also reduce transportation costs and induce replacement of pasture by soy, resulting in indirect land-use change, where cattle ranchers sell their land to soy farmers and move to other parts of the Amazon, clearing forest for cattle pasture (Arima *et al.* 2011; Fearnside 2015c) (see Chapters 14 and 15).

One impact of waterways is that they serve to justify hydroelectric dams regardless of how severe the impacts may be. Without a complete sequence of dams on a river, the entire waterway would cease to function because barges cannot pass rapids and waterfalls, which are eliminated by reservoirs. The Tocantins/Araguaia waterway (Fearnside 2002b) and the Tapajós waterway (Fearnside 2015c) both serve as examples. In the case of the Madeira River, a plan for 4,000 km of waterways in the Amazon portion of Bolivia, intended to transport soybeans, was used as an argument in the viability study for Brazil's Santo Antônio and Jirau Dams (Fearnside 2014a,b).

Exploitation of new sources of energy, such as oil, usually require road construction, hence deforestation (Anderson *et al.* 2018; Fearnside 2020b). Oil exploitation also has strong combined effects with dams, devastating aquatic biota where these drivers intersect (Anderson *et al.* 2019). Indirect effects of oil exploitation, such as road building and consequent deforestation, can lead to fragmentation of aquatic connectivity or habitat loss for migratory species, further aggravating the effects of dams and waterways. In the Peruvian Amazon, the Interoceanic Highway has had a dual impact on the rivers and associated terrestrial ecosystems. As shown by satellite imagery, this road promoted land-use change due to agricultural expansion in the north, while at the same time facilitating access to previously pristine forests along the Malinowsky and Inambari Rivers for the extraction of alluvial gold (Finer *et al.* 2018; Sánchez-Cuervo *et al.* 2020).

Climate-induced increases in the severity of droughts and lengthening dry seasons will lead to further deforestation and fires (Malhi *et al.* 2009). The effects of climate change will also interact with other anthropogenic impacts. Warming trends will increase water temperatures, increasing the toxicity of pollutants to organisms and bioaccumulation of mercury in aquatic food webs (Ficke *et al.* 2007; Val 2019). The expected trend of declining discharges in the Amazon Basin, except in the western part (Sorribas *et al.* 2016; Farinosi *et al.* 2019), could result in fish biodiversity loss of up to 12% in the Amazon Basin and 23% in the Tocantins Basin (Xenopoulos *et al.* 2005). Droughts and decreased river discharge are also expected to impact fish community composition, population size and structure, reproduction, and recruitment (Poff *et al.* 2001; Lake 2003; Freitas *et al.* 2013; Frederico *et al.* 2016).

Increased temperatures and reduced oxygen concentrations resulting from reduced water volumes are expected to be detrimental for many aquatic organisms, including fish (Lake 2003; Ficke *et al.* 2007; Frederico *et al.* 2016; Nelson and Val 2016; Gonçalves *et al.* 2018; Lapointe *et al.*

2018; Campos *et al.* 2019). In adult organisms, energy is allocated to growth, reproduction, and maintenance metabolism (Val and Almeida-Val 1995; Almeida-Val *et al.* 2006; Wootton 1998). The surplus energy spent in compensating for increased thermal conditions will therefore come at the expense of growth and reproduction, and it is likely to increase susceptibility to disease (Ficke *et al.* 2007; Freitas *et al.* 2012; Oliveira and Val 2017; Costa and Val 2020). Higher temperatures are also expected to favor eutrophic conditions and to stimulate macrophyte development in floodplain lakes, modifying food-web dynamics and affecting the fish that depend on them (Ficke *et al.* 2007).

Global warming and reduced oxygen availability result in shrinking body size in many organisms (Sheridan and Bickford 2011), and this is also expected in fishes (Cheung *et al.* 2013; Oliveira and Val 2017; Pauly and Cheung 2018; Almeida-Silva *et al.* 2020), which could impact fisheries across the region. Declining body sizes under global warming could lead to ecosystem alteration through a trophic cascade for predatory species (Estes *et al.* 2011), or through disruption of carbon flows for detritivorous species (Taylor *et al.* 2006) and consequent decreased recruitment because reproductive output is proportional to body size in most fishes. Expected climate-driven reductions of fish size will also further accelerate the fishing-induced size decreases that have already been observed for commercial species.

Fragmentation of river networks by hydroelectric dams and other infrastructure will constrain potential range shifts of aquatic species to cope with expected temperature rise under climate change (Myers *et al.* 2017). Range shifts of fish to higher altitudes as a result of climate change have already been documented, and river fragmentation by dams will block this form of adaptation (Herrera-R *et al.* 2020). Andean aquatic species will likely be particularly impacted because most dams have been built or are planned on Andean tributaries (Forsberg *et al.* 2017; Anderson *et al.* 2018; Tognelli *et al.* 2019).

20.12 Conclusions

Rivers provide connections between widely separated aquatic and terrestrial ecosystems through flows of water, sediment, and nutrients, and through fish migrations. Fragmenting rivers therefore has consequences that are far-reaching (and often international).

Clean, free-flowing rivers and their interacting floodplain ecosystems generate ecosystem services that are important at local, regional, and global scales (e.g., fisheries for food security, sediment transport, and carbon sequestration).

Aquatic ecosystems are particularly prone to cumulative or synergistic impacts. These include the effects of multiple dams on rivers and the combined impacts of changes in river flows, oxygen levels, water temperatures, and levels of pollution.

20.13 Recommendations

- Dams with installed capacity ≥10 MW should not be built in the Amazon. Dams with installed capacity <10 MW which would power a single town or village can be built with the proper environmental licensing and using a risk-based approach. Rather than building Amazonian dams, energy policy should prioritize electricity conservation, halt exports of energy-intensive products, and redirect investment in new electricity generation to wind and solar sources.
- Dams with installed capacity <10 MW have significant impacts and should not be built to feed national or regional grids. The severe cumulative effect of blocking multiple tributaries with these dams should also be considered.
- Decision making processes on infrastructure projects should be reformed such that direct and indirect environmental and social impacts are compiled and democratically debated before decisions are made.
- Selected watersheds throughout the Amazon need to be preserved for research, long-term monitoring, and protection of genetic and species diversity. These watersheds will also

maintain ecological communities that can be needed for recovery efforts.

- Rivers and streams should be protected by an adequate forest border when surrounding land is converted to other uses.
- Better regulation and monitoring of exotic species is needed, especially for fish culture. Interbasin water diversion projects, which inevitably lead to introduction of exotic species, should be avoided.
- Adequate controls are needed on urban sewage, plastic pollution, mercury and other heavy metals, and on the use of agro-chemicals.
- Control of sediments and waste from mining is needed.
- Alluvial mining must be banned across the Amazon Basin to preserve aquatic biodiversity, floodplain forests, and human health.
- Regional governments and municipalities must prioritize the cleaning of sewage water in order to preserve the health of aquatic biota and human populations.
- Because aquatic resources are not private property, they require cooperative arrangements to manage their use (including the exclusion of outside fishing vessels) and enforcement of restrictions on overharvesting.
- Proper accounting of the greenhouse-gas emissions of Amazonian dams is needed.

20.14 References

Abril G, Guérin F, Richard S, et al. 2005. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem Cycles 19: GB4007.

Agostinho AA, Agostinho CS, Pelicice FM, and Marques EE. 2012. Fish ladders: safe fish passage or hotspot for predation? Neotrop Ichthyol 10: 687–96.

Agostinho AA, Gomes LC, Santos NCL, et al. 2016. Fish assemblages in Neotropical reservoirs: Colonization patterns, impacts and management. Fish Res 173: 26–36.

Agostinho AA, Gomes LC, Veríssimo S, and K. Okada E. 2004. Flood regime, dam regulation and fish in the Upper Paraná River: effects on assemblage attributes, reproduction and recruitment. In: Reviews in Fish Biology and Fisheries 14: 11–9

Agostinho AA, Marques EE, Agostinho CS, et al. 2007. Fish ladder of Lajeado Dam: migrations on one-way routes? Neotrop Ichthyol 5: 121–30.

Agostinho AA, Pelicice FM, and Gomes LC. 2008. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. Brazilian J Biol 68: 1119–32.

Albuquerque AF, Ribeiro JS, Kummrow F, Nogueira AJA, Montagner CC, and Umbuzeiro GA. 2016. Pesticides in Brazilian freshwaters: A critical review. Environ Sci: Processes & Impacts, 18: 779-87.

Alho CJR. 2011. Environmental effects of hydropower reservoirs on wild mammals and freshwater turtles in Amazonia: a review. Oecologia Aust 15: 593–604.

Almeida-Silva J, Campos DF, and Almeida-Val VMF. 2020. Metabolic adjustment of Pyrrhulina aff. Brevis exposed to different climate change scenarios. J Therm Biol 92: 102657.

Almeida R, Hamilton S, Rosi E, et al. 2020. Hydropeaking Operations of Two Run-of-River Mega-Dams Alter Downstream Hydrology of the Largest Amazon Tributary. Frontiers in Environ Sci 8: 120.

Almeida-Val VMF, Chippari-Gomes AR, and Lopes NP. 2006. Metabolic and physiological adjustments to low oxygen and high temperature in fish of the Amazon, In: The Physiology of Tropical Fishes. London, UK: Elsevier, pp. 443-500.

Albuquerque AF, Ribeiro JS, Kummrow F, Nogueira AJA, Montagner CC, and Umbuzeiro GA. 2016. Pesticides in Brazilian freshwaters: A critical review. Environ Sci: Processes & Impacts 18: 779-87.

Almeida RM, Shi Q, Gomes-Selman JM, et al. 2019. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nat Commun 10: 4281.

Alonso JC and Pirker LEM. 2005. Dinâmica populacional e estado atual de exploração de Piramutaba e de Dourada. O manejo da pesca dos Grandes bagres migradores Piramutaba e Dourada no eixo Solimoes--Amazonas. Manaus, AM, Brazil: IBAMA, ProVárzea, pp. 21–28. https://bityl.co/4jSQ

Anderson EP, Jenkins CN, Heilpern S, et al. 2018. Fragmentation of Andes-to-Amazon connectivity by hydropower dams. Sci Adv 4: eaao1642.

Anderson EP, and Maldonado-Ocampo JA. 2011. A regional perspective on the diversity and conservation of tropical Andean fishes. Conserv Biol 25: 30-39.

Anderson EP, Osborne T, Maldonado-Ocampo JA, Mills-Novoa M, Castello L, Montoya M, Encalada AC, and Jenkins CN. 2019. Energy development reveals blind spots for ecosystem conservation in the Amazon Basin. Front Ecol Environ 17: 521–9.

Andrade MC, Winemiller KO, Barbosa PS, Fortunati A, Chelazzi D, and Giarrizzo T. 2019. First account of plastic pollution impacting freshwater fishes in the Amazon: Ingestion of plastic debris by piranhas and other serrasalmids with diverse feeding habits. Environ Pollution 244: 766-77.

Andrews C. 1990. The ornamental fish trade and fish conservation. J Fish Biol 37: 53–9.

Anjos HDB, Amorim RMS, Siqueira JA, and Anjos CR. 2018. Ornamental fish export of the State of Amazonas, Amazon Basin, Brazil. Bol do Inst Pesca 35: 259–74.

Anjos NA, Schulze T, Brack W, et al. 2011. Identification and evaluation of cyp1a transcript expression in fish as molecular biomarker for petroleum contamination in tropical fresh water ecosystems. Aquat Toxicol 103: 46–52.

Arantes CC, Fitzgerald DB, Hoeinghaus DJ, and Winemiller KO. 2019a. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. Curr Opin Environ Sustain 37: 28–40.

Arantes CC, Winemiller KO, Asher A, et al. 2019b. Floodplain land cover affects biomass distribution of fish functional diversity in the Amazon River. Sci Rep 9: 16684.

Arantes CC, Winemiller KO, Petrere M, and Freitas CEC. 2019c. Spatial variation in aquatic food webs in the Amazon River floodplain. Freshw Sci 38: 213–28.

Arantes CC, Winemiller KO, Petrere M, et al. 2018. Relationships between forest cover and fish diversity in the amazon river floodplain. Jour Applied Ecol 55: 386-395.

Araújo ES, Marques EE, Freitas IS, et al. 2013. Changes in distance decay relationships after river regulation: similarity among fish assemblages in a large Amazonian river. Ecol Freshw Fish 22: 543–52.

Araújo CC, and Wang JY. 2015. The dammed river dolphins of Brazil: Impacts and conservation. Oryx 49:17-24.

Araújo-Lima C, and Goulding M. 1998. So Fruitful a Fish: Ecology, Conservation and Aquaculture of the Amazon's Tambaqui. New York, NY, USA: Columbia University Press. 191 pp.

Arima EY, Richards P, Walker R, and Caldas MM. 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. Environ Res Lett 6: 024010.

Arsenault C. 2021. Canadian firm's proposed gold mine in Amazon rainforest a step closer to reality, CEO says. CBC News, 28 March 2021. https://bityl.co/6Kz4

Artaxo P, de Campos RC, Fernandes T., et al. 2000. Large scale mercury and trace element measurements in the Amazon basin. Atmos Environ 34: 4085-4096.

Assahira C, Piedade MTF, Trumbore SE, et al. 2017. Tree mortality of a flood-adapted species in response of hydrographic changes caused by an Amazonian river dam. For Ecol Manage 396: 113–23.

Athayde S, Mathews M, Bohlman S, et al. 2019. Mapping research on hydropower and sustainability in the Brazilian Amazon: advances, gaps in knowledge and future directions. Curr Opin Environ Sustain 37: 50–69.

Augier H, Benkoël L, Chamlian A, Park WK, and Ronneau C. 1993. Mercury, zinc and selenium bioaccumulation in tissues and organs of Mediterranean striped dolphins Stenella coeruleoalba meyen. Toxicological result of their interaction. Cell Mol Biol (Noisy-le-grand) 39(6):621-34.

Bahía-Oliveira M, Corvelo CC, Mergler D, et al. 2004. Environmental biomonitoring using cytogenetic endpoints in a population exposed to mercury in Brazilian Amazon. Environ Molecular Mutagenesis 44: 346-9.

Bailly D, Agostinho AA, and Suzuki HI. 2008. Influence of the flood regime on the reproduction of fish species with different reproductive strategies in the Cuiabá River, Upper Pantanal, Brazil. River Res Appl 24: 1218–29.

Barbosa AC, and Dorea JG. 1998. Indices of mercury contamination during breast feeding in the Amazon Basin. Environ Toxicol Pharmacol 6: 71–9.

Barbosa C. 2018. Lama vermelha da Hydro também contaminou mananciais em Abaetetuba, diz IEC. Amazônia Real, 29 March 2018. https://amz.run/4TEn

Barletta M, Jaureguizar AJ, Baigun C, et al. 2010. Jour Fish Biol 76: 2118-76.

Barros N, Cole JJ, Tranvik LJ, et al. 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat Geosci 4: 593–6.

Barthem R, and Goulding M. 2007. Un ecosistema inesperado: la Amazônia revelada por la pesca Belém, PA, Brazil: Museu Paraense Emilio Goeldi, and Lima, Peru: Amazon Conservation Association (ACA).

Batista VS, Inhamuns AJ, Freitas CEC, and Freire-Brasil D. 1998. Characterization of the fishery in river communities in the low-Solimões/high-Amazon region. Fish Manag Ecol 5: 419–35.

Bayley PB. 1995. Understanding large river: floodplain ecosystems. Bioscience 45: 153–8.

Bayley PB. 1998. Aquatic biodiversity and fisheries management in the Amazon. Washington, DC, USA: World Bank.

Bayley PB, Castello L, Batista VS, and Fabré NN. 2018. Response of Prochilodus nigricans to flood pulse variation in the central Amazon. R Soc Open Sci 5: 172232.

Bertassoli Jr DJ, Sawakuchi HO, Araújo KR de, et al. 2021. How green can Amazon hydropower be? Net carbon emission from the largest hydropower plant in Amazonia. Sci Adv 7: eabe1470.

Besseling E, Hasselerharm PR, Foekema EM, and Koelmans AA. 2019. Quantifying ecological risks of aquatic micro- and nanoplastic. Critical Reviews in Environ Sci and Technol 49: 32-80.

Bodmer R, Meléndez PP, Henderson P, et al. 2018. Modelamiento de las consecuencias previsibles del dragado de los principales ríos amazónicos sobre la fauna silvestre y la gente de los bosques inundados de Loreto, Perú. Folia Amaz 27: 247–58.

Bonilla-Castillo CA, Córdoba EA, Gómez G, and Duponchelle F. 2018. Population dynamics of Prochilodus nigricans (Characiformes: Prochilodontidae) in the Putumayo River. Neotrop Ichthyol 16: e170139.

Borges T, and Branford S. 2020. Mina de bauxita deixa legado de pobreza e poluição em quilombo do Pará. Mongabay, 8 June 2020. https://bityl.co/6MG6

Bossart, G.D. 2011. Marine mammals as sentinel species for oceans and human health. Veterinary Pathol 48: 676-90.

Branford S, and Torres M. 2019. Brazil to open indigenous reserves to mining without indigenous consent. Mongabay, 14 March 2019. https://bit.ly/3jzBEwb

Brazil. 2004. Comunicação Nacional Inicial do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Brasília, DF, Brazil: Coordenadoria Geral de Mudanças Globais do Clima, Ministério da Ciência e Tecnologia (MCT), 276 pp. https://bit.ly/3M4gkes

Braz-Mota S, Fé LML, de Lunardo FAC, et al. 2017. Exposure to waterborne copper and high temperature induces the formation of reactive oxygen species and causes mortality in the Amazon fish Hoplosternum littorale. Hydrobiologia 789: 157–66.

Braz-Mota S, Sadauskas-Henrique H., Duarte RM, et al. 2015. Roundup-R exposure promotes gills and liver impairments, DNA damage and inhibition of brain cholinergic activity in the Amazon teleost fish Colossoma macropomum.

Chemosphere 135: 53-60.

Brito JG, Roque FO, Martins RT, et al. 2020. Small forest losses degrade stream macroinvertebrate assemblages in the eastern Brazilian Amazon. Biol Conserv 241: 108263.

Brum SM, Silva VMF da, Rossoni F, and Castello L. 2015. Use of dolphins and caimans as bait for Calophysus macropterus (Lichtenstein, 1819)(Siluriforme: Pimelodidae) in the Amazon. J Appl Ichthyol 31: 675–80.

Campos CP, Costa Sousa RG, Catarino MF, et al. 2015. Population dynamics and stock assessment of Colossoma macropomum caught in the Manacapuru Lake system (Amazon Basin, Brazil). Fish Manag Ecol 22: 400–6.

Campos DF, Braz-Mota S, Val AL, and Almeida-Val VMF. 2019. Predicting thermal sensitivity of three Amazon fishes exposed to climate change scenarios. Ecol Indic 101: 533–40.

Campos DF, Jesus TF, Kochhann D, et al. 2017. Metabolic rate and thermal tolerance in two congeneric Amazon fishes: Paracheirodon axelrodi Schultz, 1956 and Paracheirodon simulans Géry, 1963 (Characidae). Hydrobiologia 789: 133–42.

Campos DF, Val AL, and Almeida-Val VMF. 2018. The influence of lifestyle and swimming behavior on metabolic rate and thermal tolerance of twelve Amazon forest stream fish species. Jour Thermal Biol 72: 148-54.

Cardellicchio N, Decataldo A, Di Leo A, and Giandomenico S. 2002. Trace elements in organs and tissues of striped dolphins (Stenella coeruleoalba) from the Mediterranean Sea (Southern Italy). Chemosphere 49: 85-90.

Castello L, Arantes CC, Mcgrath DG, et al. 2015. Understanding fishing-induced extinctions in the Amazon. Aquat Conserv Mar Freshw Ecosyst 25: 587–98.

Castello L, Hess LL, Thapa R, et al. 2018. Fishery yields vary with land cover on the Amazon River floodplain. Fish Fish 19: 431-440.

Castello L, Isaac VJ, and Thapa R. 2015a. Flood pulse effects on multispecies fishery yields in the lower Amazon. Roy Soc Open Sci 2(11): 150299.

Castello L, and Macedo MN. 2016. Large-scale degradation of Amazonian freshwater ecosystems. Glob Change Biol 22: 990–1007.

Castello L, McGrath DG, and Beck PSA. 2011. Resource sustainability in small-scale fisheries in the Lower Amazon floodplains. Fish Res 110: 356–64.

Castello L, McGrath DG, Arantes CC, and Almeida OT. 2013a. Accounting for heterogeneity in small-scale fisheries management: The Amazon case. Mar Policy 38: 557–65.

Castello L, McGrath DG, Hess LL, et al. 2013b. The vulnerability of Amazon freshwater ecosystems. Conserv Lett 6: 217–29.

Castello L and Stewart DJ. 2010. Assessing CITES nondetriment findings procedures for Arapaima in Brazil. J Appl Ichthyol 26: 49–56.

Castro DMP, Hugles RM, and Callisto M. 2013. Influence of peak flow changes on the macroinvertebrate drift downstream of a Brazilian hydroelectric dam. Braz Jour Biol, 73: 775-82.

Catarino MF, Campos CP, Garcez R, and Freitas CE de C. 2014. Population dynamics of Prochilodus nigricans caught in Manacapuru Lake (Amazon basin, Brazil). Bol do Inst Pesca 40: 589–95.

Centro de Investigación y Tecnologia del Agua CITA. 2019. Mejores prácticas para el estudio de los ríos amazónicos frente al desarrollo de infraestructura. Caso EIA-d Hidrovía Amazónica. Boletín CITA No. 2. Lima, Peru: CITA-UTEC. 20 pp. https://ggle.io/3g0l

Chan FT, Beatty SJ, Gilles Jr AS, et al. 2019. Leaving the fish bowl: the ornamental trade as a global vector for freshwater fish invasions. Aquat Ecosyst Health Manag 22: 417–39.

Chao NL and Prada-Pedreros S. 1995. Diversity and habitat of ornamental fishes in the Rio Negro, Brazil: exploitation and conservation issues. In: Proceedings of World Fisheries Congress, (Theme 3). Lebanon, VA, USA: Science Publishers, pp. 241-60.

Chao NL and Prang G. 1997. Project Piaba -- towards a sustainable ornamental fishery in the Amazon. Aquarium Sci Conserv 1:105–11.

Charvet P, Occhi TVT, Faria, L, et al. 2021. Tilapia farming threatens Brazilian waters. Science 371: 356.

Chen G, Powers RP, de Carvalho LMT, and Mora B. 2015. Spatiotemporal patterns of tropical deforestation and forest degradation in response to the operation of the Tucuruí hydroelectric dam in the Amazon basin. Applied Geog 63: 1-8.

Cheung WWL, Sarmiento JL, Dunne J et al. 2013. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat Climate Change 3: 254-58.

Cintra IHA. 2009. A pesca no reservatório da Usina Hidrelétrica de Tucuruí, Estado do Pará, Brasil. PhD thesis in fisheries engineering, Universidade Federal do Ceará, Fortaleza, CE, Brazil. 190 pp. https://bit.ly/3M7bHR3

Coe MT, Costa MH, and Soares-Filho BS. 2009. The influence of historical and potential future deforestation on the stream flow of the Amazon River – land surface processes and atmospheric feedbacks. Jour Hydrol 369: 165-74.

Constantine JA, Dunne T, Ahmed J, et al. 2014. Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin. Nat Geosci 7: 899–903.

Córdoba EA, León ÁVJ, Bonilla-Castillo CA, et al. 2013. Breeding, growth and exploitation of Brachyplatystoma rousseauxii Castelnau, 1855 in the Caqueta River, Colombia. Neotrop Ichthyol 11: 637–47.

Correa SB, Costa-Pereira R, Fleming T, et al. 2015a. Neotropical fish-fruit interactions: Eco-evolutionary dynamics and conservation. Biol Rev 90: 1263–78.

Correa SB, Costa-Pereira R, Fleming T, Goulding M, and Anderson JT. 2015b. Neotropical fish–fruit interactions: eco-evolutionary dynamics and conservation. Biol Reviews Cambridge Philosophical Soc 90(4): 1263-1278.

Costa F, Damazio J, Raupp I, et al. 2011. Hydropower inventory studies of river basins in Brazil. Int J Hydropower Dams 2: 31–36.

Costa JC, and Val AL. 2020. Extreme climate scenario and parasitism affect the Amazon fish Colossoma macropomum. Sci Total Environ 726: 138628.

Couceiro SEM, Forsberg BR, Hamada N, and Ferreira RLM. 2006. Effects of an oil spill and discharge of domestic sewage on the insect fauna of Cururu stream, Manaus, AM, Brazil. Braz Jour Biol 66(1a): 35-44.

Couceiro SRM, Hamada N, Ferreira RLM, et al. 2007a. Domestic sewage and oil spills in streams: effects on edaphic invertebrates in flooded forest, Manaus, Amazonas, Brazil. Water Air Soil Pollut 180: 249–59.

Couceiro SRM, Hamada N, Forsberg BR, and Padovesi-Fonseca C. 2011. Trophic structure of macroinvertebrates in Amazonian streams impacted by anthropogenic siltation. Austral Ecol 36: 628–37.

Couceiro SRM, Hamada N, Luz SLB, et al. 2007b. Deforestation and sewage effects on aquatic macroinvertebrates in urban streams in Manaus, Amazonas, Brazil. Hydrobiologia 575: 271–84.

Couceiro SRM, Hamada N, Forsberg BR, et al. 2012. A macroinvertebrate multimetric index to evaluate the biological condition of streams in the Central Amazon region of Brazil. Ecol Indicators 18: 118-25.

Couto TBA, and Olden JD. 2018. Global proliferation of small hydropower plants–science and policy. Front Ecol Environ 16: 91–100.

Crampton WGR. 1999. The impact of the ornamental fish trade on the discus Symphysodon aequifasciatus: A case study from the floodplain forests of Estação Ecológica Mamirauá. Adv Econ Bot 13: 29–44.

Crampton WGR, Castello L, and Viana JP. 2004. Fisheries in the Amazon várzea: Historical trends, current status, and factors affecting sustainability. In: People in Nature: Wildlife Conservation in South and Central America. New York, USA: Columbia University Press. pp. 76-95.

Daga VS, Azevedo-Santos VM, Pelicice FM, et al. 2020. Water diversion in Brazil threatens biodiversity. Ambio 49: 165–72.

Dala'corte RBM, Siqueira AS, Bini T, et al. 2020. Thresholds of freshwater biodiversity in response to riparian vegetation loss in the Neotropical region. Journ Applied Ecol 57: 1391-402.

Dayrell JS, Magnusson WE, Bobrowiec PED, and Lima AP. 2021. Impacts of an Amazonian hydroelectric dam on frog assemblages. PLoS One 16: e0244580.

Deegan L. Neill C, Haupert CL, et al. 2011. Amazon deforestation alters small stream structure, nitrogen biogeochemistry and connectivity to larger rivers. Biogeochem 105: 53–74.

Deines AM, Marion E, Wittmann JMD et al. 2016. Tradeoffs among ecosystem services associated with global tilapia introductions. Reviews in Fisheries Sci & Aquacult 24: 178-191.

Delmas R, Galy-Lacaux C, and Richard S. 2001. Emissions of greenhouse gases from the tropical hydroelectric reservoir of Petit Saut (French Guiana) compared with emissions from thermal alternatives. Global Biogeochem Cycles 15: 993–1003.

de Melo MG; da Silva BA, Costa GS, et al. 2019. Sewage contamination of Amazon streams crossing Manaus (Brazil) by sterols biomarkers. Environ Pollution 244: 818-26.

de Melo MG, de Castro LG, Reis LA, et al. 2020. Metals, n-alkanes, hopanes, and polycyclic aromatic hydrocarbon in sediments from three Amazon streams crossing Manaus (Brazil). Chemistry 2: 274-92.

de Moura JF, Emin-Lima R, Hacon SS et al. 2012. Mercury Status of the Amazon Continental Shelf: Guiana Dolphins (Sotalia guianensis, Van Benédén 1864) as a Bioindicator. Bull Contamination and Toxicol 89: 412–8.

de Paula FR, Leal CG, Leitão RP, et al. 2021. The role of secondary riparian forests for conserving fish assemblages in eastern Amazon streams. Hydrobiologia, https://doi.org/10.1007/s10750-020-04507-4

Dias Fonseca FR, Malm O, and Waldemarin HF. 2005. Mercury levels in tissues of giant otters (Pteronura brasiliensis) from the Rio Negro, Pantanal, Brazil. Environmental Research 98: 368–71.

Doria CRC, dos Santos Catâneo DTB, Torrente-Vilara G, et al. 2020. Is there a future for artisanal fishing in the Amazon? The case of Arapaima gigas. Manage of Biol Invasions 11(1): 1-8.

Doria CRC, Agudelo E, Akama, A et al. 2021. The silent threat of non-native fish in the Amazon biome. Front Ecol Evol, 9: 646702.

dos Santos LSN, Müller RCS, Sarkis JES, et al. 2000. Evaluation of total mercury concentrations in fish consumed in the municipality of Itaituba, Tapajós River basin, Pará, Brazil. Sci Total Environ 26: 1-8.

dos Santos PRO, Costa MJ, dos Santos ACA, ECM Silva-Zacarín, and Nunes, B. 2020. Neurotoxic and respiratory effects of human use drugs on a Neotropical fish species, Phalloceros harpagos. Compar BiochemPhysiol Part C: Toxicol & Pharmacol 230: 108683.

dos Santos Júnior UM, Gonçalves JFC, and Fearnside PM. 2013. Measuring the impact of flooding on Amazon trees: photosynthetic response models for ten species flooded by hydroelectric dams. Trees-Struct Funct 27: 193-210.

dos Santos Junior UM, Gonçalves, JFC, Strasser RJ and Fearnside PM. 2015. Flooding of tropical forests in central Amazonia: What do the effects on the photosynthetic apparatus of trees tell us about species suitability for reforestation in extreme environments created by hydroelectric dams? Acta Physiologiae Plantarum 37: 166.

Duarte RM, Menezes ACL, Rodrigues L et al. 2009. Copper sensitivity of wild ornamental fish of the Amazon. Ecotoxicol and Environ Safety 72: 693-8.

Dumestre JF, Guézennec J, Galy-Lacaux C, et al. 1999. Influence of light intensity on methanotrophic bacterial activity in Petit Saut Reservoir, French Guiana. Appl Environ Microbiol 65: 534–9.

Dunne T, Mertes LAK, Meade RH, et al. 1998. Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. Geol Soc Am Bull 110: 450–67.

Duponchelle F, Isaac VJ, Doria CRDC, et al. 2021. Conservation of migratory fishes in the Amazon basin. Aquat Conserv Mar Freshw Ecosyst 31: 1087–105.

Emerman SH. 2020. Evaluation of the tailings dam, cyanide use and water consumption at the proposed Volta Grande gold project, Pará, northern Brazil. Spanish Fork, Utah, USA: Malach Consulting. 40 pp. https://bityl.co/5g8Q

Estes JA, Terborgh J, Brashares JS, et al. 2011. Trophic downgrading of planet Earth. Science 333: 301-6.

Estivals G, Duponchelle F, Römer U, et al. 2020. The Amazonian dwarf cichlid Apistogramma agassizii (Steindachner, 1875) is a geographic mosaic of potentially tens of species: Conservation implications. Aquat Conserv Mar Freshw Ecosyst 30: 1521–39.

Fabré NN, Castello L, Isaac VJ, and Batista VS. 2017. Fishing and drought effects on fish assemblages of the central Amazon Basin. Fish Res 188: 157–65.

Fabregat-Safont D, Ibáñez M, Bijlsma L, et al. 2021. Wide-scope screening of pharmaceuticals, illicit drugs and their metabolites in the Amazon River. Water Research 200: 117251.

Farinosi F, Arias ME, Lee E, et al. 2019. Future climate and land use change impacts on river flows in the Tapajós Basin in the Brazilian Amazon. Earth's Future 7: 993–1017.

Fearnside PM. 1989. Brazil's Balbina Dam: Environment versus the legacy of the pharaohs in Amazonia. Environ Manage 13: 401–23.

Fearnside PM. 1995. Hydroelectric dams in the Brazilian Amazon as sources of 'greenhouse' gases. Environ Conserv 22: 7-19.

Fearnside PM. 1999. Social Impacts of Brazil's Tucururí Dam. Environ Manage 24: 483–95.

Fearnside PM. 2001. Environmental impacts of Brazil's Tucuruí Dam: Unlearned lessons for hydroelectric development in Amazonia. Environ Manage 27: 377–96.

Fearnside PM. 2002a. Greenhouse gas emissions from a hydroelectric reservoir (Brazil's Tucuruí Dam) and the energy policy implications. Water Air Soil Pollut 133: 69–96.

Fearnside PM. 2002b. Avança Brasil: Environmental and social consequences of Brazil's planned infrastructure in Amazonia. Environ Manage 30: 735–47.

Fearnside PM. 2005. Brazil's Samuel Dam: Lessons for hydroelectric development policy and the environment in Amazonia. Environ Manage 35: 1–19.

Fearnside PM. 2009. As hidrelétricas de Belo Monte e Altamira (Babaquara) como fontes de gases de efeito estufa. Novos Cadernos NAEA 12(2): 5-56. English translation available at: https://bit.ly/3PlI1C5

Fearnside PM. 2013a. Credit for climate mitigation by Amazonian dams: Loopholes and impacts illustrated by Brazil's Jirau Hydroelectric Project. Carbon Manag 4: 681–96.

Fearnside PM. 2013b. Carbon credit for hydroelectric dams as a source of greenhouse-gas emissions: The example of Brazil's Teles Pires Dam. Mitig Adapt Strateg Glob Chang 18: 691–9.

Fearnside PM. 2013c. Decision Making on Amazon Dams: Politics Trumps Uncertainty in the Madeira River Sediments Controversy. Water Altern 6: 313–25.

Fearnside PM. 2014a. Impacts of Brazil's Madeira River Dams: Unlearned lessons for hydroelectric development in Amazonia. Environ Sci Policy 38. 164172.

Fearnside, P.M. 2014b. Brazil's Madeira River dams: A setback for environmental policy in Amazon development. Water Altern 7: 156-69.

Fearnside PM. 2015a. Tropical hydropower in the clean development mechanism: Brazil's Santo Antônio Dam as an example of the need for change. Clim Change 131: 575–89.

Fearnside PM. 2015b. Emissions from tropical hydropower and the IPCC. Environ Sci Policy 50: 225–39.

Fearnside PM. 2015c. Amazon dams and waterways: Brazil's Tapajós Basin plans. Ambio 44: 426-39.

Fearnside PM. 2016. Greenhouse gas emissions from hydroelectric dams in tropical forests. In: Alternative Energy and Shale Gas Encyclopedia. New York, USA: Wiley. pp. 428-38.

Fearnside PM. 2017a. Planned disinformation: The example of the Belo Monte Dam as a source of greenhouse gases. In: Brazil in the Anthropocene: Conflicts between Predatory Development and Environmental Policies. New York, USA: Routledge, pp. 125-142.

Fearnside PM. 2017. Dams with big reservoirs: Brazil's hydroelectric plans threaten its Paris climate commitments. The Globalist, 29 January 2017. https://bit.ly/3jyVc3S

Fearnside PM. 2019. Exploração mineral na Amazônia brasileira: O custo ambiental. In: Dossiê Desastres e Crimes da Mineração em Barcarena, Mariana e Brumadinho. Belém, Pará, Brazil: Editora do Núcleo de Altos Estudos Amazônicos (NAEA), Universidade Federal do Pará (UFPA). pp. 35-42.

Fearnside PM. 2020a. Brazil's Bem Querer dam: An impending Amazon disaster (commentary). Mongabay, 16 November 2020. https://bit.ly/3O3HDHP

Fearnside PM. 2020b. Oil and gas project threatens Brazil's last great block of Amazon forest (commentary). 9 March 2020. https://bit.ly/3ELLZxt

Fearnside PM. 2020c. The danger of Brazil's Amazon plans for oil and gas: Response to EPE (commentary). Mongabay, 8 April 2020. https://bit.ly/37aSC1C

Fearnside PM, Ferrante L, Yanai AM, et al. 2020. Trans-Purus: Brazil's last intact Amazon forest at immediate risk (commentary) Mongabay, 24 November 2020. https://bit.ly/3IrTJH5

Fearnside PM, and Pueyo S. 2012. Greenhouse-gas emissions from tropical dams. Nat Clim Chang 2: 382–4.

Fé-Gonçalves LM, Paula-Silva MN, Val A., Almeida-Val VMF, 2018. Differential survivorship of congeneric ornamental fishes under forecasted climate changes are related to anaerobic potential. Genetics and Molecular Biol 41:107-18.

Ferrante L, and Fearnside PM. 2019. Brazil's new president and "ruralists" threaten Amazonia's environment, traditional peoples and the global climate. Environ Conserv 46: 261-3.

Ferrante L, and Fearnside PM. 2020. Evidence of mutagenic and lethal effects of herbicides on Amazon frogs. Acta Amazonica 50: 363-6.

Ferrante, L, and Fearnside PM. 2021. Brazilian government violates Indigenous rights: What could induce a change? Die Erde 152: 200-11.

Ficke AD, Myrick CA, and Hansen LJ. 2007. Potential impacts of global climate change on freshwater fisheries. Reviews in Fish Biol and Fisheries 17: 581-613.

Filizola N, and Guyot JL. 2009. Suspended sediment yields in the Amazon basin: an assessment using the Brazilian national data set. Hydrol Process An Int J 23: 3207–15.

Filizola N, and Guyot JL. 2011. Fluxo de sedimentos em suspensão nos rios da Amazônia. Rev Bras Geociências 41: 566–76.

Finer M, and Jenkins CN. 2012. Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes-Amazon connectivity. PLoS One 7: e35126.

Flecker AS. 1996. Ecosystem engineering by a dominant detritivore in a diverse tropical stream. Ecology 77: 1845-54.

Forero-Medina G, Ferrara CR, Vogt RC, et al. 2021. On the future of the giant South American river turtle Podocnemis expansa. Oryx 55: 73–80.

Forsberg BR, Melack JM, Dunne T, et al. 2017. The potential impact of new Andean dams on Amazon fluvial ecosystems. PLoS One 12: e0182254.

Fragoso-Moura EM, Oporto LT., Maia-Barbosa PM, and Barbosa FAR. 2016. Loss of biodiversity in a conservation unit of the Brazilian Atlantic Forest: The effect of introducing nonnative fish species. Braz Jourf Biol 76: 18-27.

Frankham R, Ballou SEJD, Briscoe DA et al. 2010. Introduction to Conservation Genetics, 2nd ed. Cambridge, UK: Cambridge University Press.

Fraser B. 2014. Amazon oil spill has killed tons of fish, sickened native people. Environ Health News https://bit.ly/3uGI2s5

Freeman MC, Pringle CM, Greathouse EA, and Freeman BJ. 2003. Ecosystem-level consequences of migratory faunal depletion caused by dams. In: Biodiversity and Conservation of Shads Worldwide, American Fisheries Society Symposium 5: 255–66. https://bit.ly/3O7gd3H

Freitas CE de, F. Rivas AA, Pereira C, et al. 2012. The potential impacts of global climatic changes and dams on Amazonian fish and their fisheries. In: New Advances and Contributions to Fish Biology. London, UK: Intech. pp. 175–195.

Freitas CEC, Siqueira-Souza FK, Humston R, et al. 2013. An initial assessment of drought sensitivity in Amazon fish communities. Hydrobiologia 705: 159-71.

Garcia A, Tello S, Vargas G, and Duponchelle F. 2009. Patterns of commercial fish landings in the Loreto region (Peruvian Amazon) between 1984 and 2006. Fish Physiol Biochem 35(1): 53.

García-Vásquez A, Vargas G, Sánchez H, et al. 2015. Periodic life history strategy of Psectrogaster rutiloides, Kner 1858, in the Iquitos region, Peruvian Amazon. J Appl Ichthyol 31: 31–9.

García-Villacorta R. 2019. Impacts of the Hidrovía Amazónica on the fisheries resources of Loreto, Peruvian Amazon. Lima, Peru: Wildlife Conservation Society (WCS). 19 pp. https://bit.ly/3OcfxKe

Gerolin C, Pupim F, Sawakuchi A, et al. 2020. Microplastics in sediments from Amazon rivers, Brazil. Sci Total Environ 749: 141604.

Gerstner CL, Ortega H, Sanchez H, and Graham DL. 2006. Effects of the freshwater aquarium trade on wild fish populations in differentially-fished areas of the Peruvian Amazon. J Fish Biol 68: 862–75.

Gippet JMW and Bertelsmeier C. 2021. Invasiveness is linked to greater commercial success in the global pet trade. Proc Natl Acad Sci USA 118: e2016337118.

Gonçalves AP. 2011. Ecologia e etnoecologia de Hypancistrus zebra (Siluriformes: Loricariidae) no rio Xingu, Amazônia brasileira. Master's dissertation in aquatic ecology and fisheries, Universidade Federal do Pará, Belém, Pará. 133 pp. https://bityl.co/4XLC

Gonçalves L, Paula-Silva MN, Val AL, et al. 2018. Differential survivorship of congeneric ornamental fishes under forecasted climate changes are related to anaerobic potential. Genetics Molecul Biol 41: 107-18.

Gonzales J. 2019. Amazon's giant South American river turtle holding its own, but risks abound. Mongabay , 6 December 2019. https://bityl.co/55Vq

Goulding M, Venticinque, E, Ribeiro MLB, Barthem RB, Leite RG et al. 2019. Ecosystem-based management of Amazon fisheries and wetlands. Fish and Fisheries 20(1): 138-58.

Gravena W, Farias IP, Silva MNF da, et al. 2014. Looking to the past and the future: were the Madeira River rapids a geographical barrier to the boto (Cetacea: Iniidae)? Conserv Genet 15: 619–29.

Guerrero JVR, Escobar-Silva E V, Chaves MED, et al. 2020. Assessing land use and land cover changes in the direct influence zone of the Braço Norte Hydropower Complex, Brazilian Amazonia. Forests 11: 988.

Guimarães JRD. 2020. Mercury in the Amazon: Problem or opportunity? A commentary on 30 years of research on the subject. Elementa Sci of the Anthopocene 8(1): 032.

Guimarães JRD, Meili M, Hylander LD, et al. 2000. Mercury net methylation in five tropical flood plain regions of Brazil: High in the root zone of floating macrophyte mats but low in surface sediments and flooded soils. Sci Total Environ 261: 99-107.

Gutiérrez FDPE, Lasso CA, Baptiste MPE et al. 2012. Catálogo de la Biodiversidad Acuática Exótica y Trasplantada en Colombia: Moluscos, Crustáceos, Peces, Anfibios, Reptiles y Aves (No. Doc. 26072) CO-BAC Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Hacon S, Barrocas PRG, de Vasconcellos ACS, et al. 2008. An overview of mercury contamination research in the Amazon basin with an emphasis on Brazil. Cadern Saúde Pública 24: 1479-92.

Hauser M, Doria CRC, Santos R V, et al. 2019. Shedding light on the migratory patterns of the Amazonian goliath catfish, Brachyplatystoma platynemum, using otolith 87Sr/86Sr analyses. Aquat Conserv Mar Freshw Ecosyst 29: 397–408.

Herrera-R GA, Oberdorff T, Anderson EP et al. 2020. The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. Global Change Biol 26: 5509-23.

Higgins T. 2020. Brazil could dynamite Amazon dolphin, turtle habitat for industrial waterway. Mongabay, 2 July 2020. https://bit.ly/3jyW4Wc

Hrbek T, Meliciano N V, Zuanon J, and Farias IP. 2018. Remarkable Geographic Structuring of Rheophilic Fishes of the Lower Araguaia River. Front Genet 9: 295.

Hurd LE, Sousa RGC, Siqueira-Souza FK, et al. 2016. Amazon floodplain fish communities: Habitat connectivity and conservation in a rapidly deteriorating environment. Biol Conserv 195: 118–27.

IBAMA (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis). 2012. Normativa interministerial n_01/2012. Ministério da Pesca e Aquicultura. https://bit.ly/3jTNwcR

IDSM (Instituto de Desenvolvimento Sustentável Mamirauá). 2021. Programa de manejo de pesca. Tefé, Amazonas, Brasil: IDSM. https://bit.ly/3EchL82

Ilha P, Schiesari L, Yanagawa FI, et al. 2018. Deforestation and stream warming affect body size of Amazon fishes. PLoS ONE, 13: e0196560.

Iñiguez–Armijos C, Leiva A, Frede HG, et al. 2014. Deforestation and benthic indicators: How much vegetation cover is needed to sustain healthy Andean streams? PLoS ONE, 9(8): e105869.

Isaac VJ, and Ruffino ML. 1996. Population dynamics of tambaqui, Colossoma macropomum Cuvier, in the Lower Amazon, Brazil. Fish Manag Ecol 3: 315–33.

Isaac VJ, Ruffino ML, and McGrath D. 1998. In search of a new approach to fisheries management in the middle Amazon region. Alaska Sea Grant Coll Progr: 1–98.

Jézéquel C, Tedesco PA, Bigorne R, et al. 2020. A database of freshwater fish species of the Amazon Basin. Sci Data 7: 1–9.

Jochnick C, Norman R, and Zaidi S. 1994. Rights violations in the Ecuadorian Amazon: The human consequences of oil development. Health and Human Rights, 1: 82-100.

Junk WJ, Bayley PB, Sparks RE, and others. 1989. The flood pulse concept in river-floodplain systems. Can Spec Publ Fish Aquat Sci 106: 110–27.

Kasper D, Forsberg BR, Kehrig HA, et al. 2018. Mercury in blackwaters of the Amazon. In: Igapó (black water flooded forests) of the Amazon Basin. Amsterdam, The Netherlands: Springer. pp. 39-56.

Kemenes A, Forsberg BR, and Melack JM. 2007. Methane release below a tropical hydroelectric dam. Geophys Res Lett 34: L12809.

Kemenes A, Forsberg BR, and Melack JM. 2011. CO2 emissions from a tropical hydroelectric reservoir (Balbina, Brazil). J Geophys Res Biogeosciences 116: G03004.

Kemenes A, Forsberg BR, and Melack JM. 2016. Downstream emissions of CH4 and CO2 from hydroelectric reservoirs (Tucuruí, Samuel, and Curuá-Una) in the Amazon basin. Inl Waters 6: 295–302.

Kennedy TA, Muehlbauer JD, Yackulic CB, et al. 2016. Flow management for hydropower extirpates aquatic insects, undermining river food webs. Bioscience 66: 561–75.

Killeen TJ. 2007. A Perfect Storm in the Amazon Wilderness: Development and Conservation in the Context of the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA). Arlington, VA, USA: Conservation International. 98 pp.

Kimerling J. 2006. Indigenous people and the oil frontier in Amazonia: The case of Ecuador, Chevron Texaco and Aguinda vs Texaco International. International Law and Politics 38: 413–664.

King TA. 2019. Wild caught ornamental fish: a perspective from the UK ornamental aquatic industry on the sustainability of aquatic organisms and livelihoods. J Fish Biol 94: 925–36.

Kirkland M, Eisenberg C, Bicerra A, Bodmer RE, Mayor P, and Axmacher JC. 2020. Sustainable wildlife extraction and the impacts of socio-economic change among the Kukama-Kukamilla people of the Pacaya-Samiria National Reserve, Peru. Oryx 54: 260–9.

Krusche AV, Ballester MVR, Victoria RL, et al. 2005. As mudanças no uso da terra e a biogeoquímica dos corpos d'água na Amazônia. Acta Amazonica 35: 197-205.

Lacerda LD. 1997. Evolution of mercury contamination in Brazil. Water Air Soil Pollut 97: 247-55.

Lacerda LD, and Salomons W. 1998. Mercury from gold and silver mining: A chemical time bomb? Heidelberg, Germany: Springer-Verlag. 168 pp.

Lailson-Brito Jr. J, Dorneles PR, da Silva VMF, et al. 2008. Dolphins as indicators of micropollutant trophic flow in Amazon basin. Oecologia Brasiliensis 12: 531-41. https://bityl.co/6MPZ

Lake PS. 2003. Ecological effects of perturbation by drought in flowing waters. Freshw Biol 48: 1161-1172.

Lapointe D, Cooperman MS, Chapman LJ, et al. 2018. Predicted impacts of climate warming on aerobic performance and upper thermal tolerance of six tropical freshwater fishes spanning three continents. Conserv Physiol 6(1): coy056.

Latini AO, and Petrere Junior M. 2004. Reduction of native fish fauna by alien species: an example from Brazilian freshwater tropical lakes. Fisheries Manage Ecol 11: 71-9.

Latrubesse EM, Arima EY, Dunne T, et al. 2017. Damming the rivers of the Amazon basin. Nature 546: 363–9.

Lebreton LCM, van der Zwet J, Damsteeg J-W, et al. 2017. River plastic emissions to the world's oceans. Nature Commun 8: 15611.

Lees AC, Peres CA, Fearnside PM, et al. 2016. Hydropower and the future of Amazonian biodiversity. Biodivers Conserv 25: 451–66.

Liew JH, Tan HH, and Yeo DJC. 2016. Dammed rivers: Impoundments facilitate fish invasions. Freshw Biol 61: 1421-9.

Lima IBT de. 2002. Emissão de metano por reservatórios hidrelétricos amazônicos através de leis de potência. Ph.D. thesis in nuclear energy, Centro de Energia Nuclear na Agricultura (CENA), Universidade de São Paulo, Piracicaba, São Paulo. 108 pp

Lima IBT, Novo EMLM, Ballester MVR, et al. 2000. Macrophyte community in the CH4 production and emission in the tropical reservoir of Tucuruí, Pará state, Brazil. Verhandlungen Internationale Vereinigung für Limnologie 27: 1437-440.

Lima MAL, Kaplan DA, and Doria CRC. 2017. Hydrological controls of fisheries production in a major Amazonian tributary. Ecohydrology 10: e1899.

Lima AC and Prang G. 2008. Demandas para o manejo e conservação do aruanã branco, Osteoglossum bicirrhosum (Cuvier, 1829), na região do médio rio Solimões. In: Biologia, Conservação e manejo dos Aruanãs na Amazôni Brasileira. Téfé, Amazonas, Brasil: Instituto de Desenvolvimento Sustentável de Mamirauá, pp. 15-26. https://bit.ly/3viTf12

Lima-Junior DP, Magalhães ALB, Pelicice FM et al. 2018. Aquaculture expansion in Brazilian freshwaters against the Aichi Biodiversity Targets. Ambio 47: 427–40.

Lobón-Cerviá J, Hess L, Melack J, et al. 2015. The importance of forest cover for fish richness and abundance on the Amazon floodplain. Hydrobiologia 750: 245-55.

Lucas-Solis OGM, Moulatlet J, Guamangallo N, et al. 2021. Preliminary assessment of plastic litter and microplastic contamination in freshwater depositional areas: The case study of Puerto Misahualli, Ecuadorian Amazonia. Bull Environ Contamin Toxicol 107: 45–51.

Lytle DA, and Poff NL. 2004. Adaptation to natural flow regimes. Trends Ecol Evol 19: 94–100.

Maia LMS. 2012. BR 319: Impacto da Estrada na Qualidade Ambiental dos Cursos d'Água. PhD thesis in forestry engineering. Lávras, Minas Gerais, Brazil: Universidade Federal de Lávras (UFLA). 119 pp. https://bityl.co/6rpf

Malhi Y, Aragão LEOC, Galbraith D et al. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. Proc Nat Acad Sci USA 106: 20610-5.

Markert B. 2007. Definitions and principles for bioindication and biomonitoring of trace metals in the environment. Journ Trace Elements Medicine Biol, Suppl, 1: 77-82.

Mariac C, Renno J-F, Garcia-Davila C, et al. 2022. Species-level ichthyoplankton dynamics for 97 fishes in two major river basins of the Amazon using quantitative metabarcoding. Molecular Ecol 31: 1627-48.

Marshall B, Forsberg B, Hess L. et al. 2011. Water temperature differences in interfluvial palm swamp habitats of Paracheirodon axelrodi and P. simulans (Osteichthyes: Characidae) in the middle Rio Negro, Brazil. Ichthyolog Explor Freshwaters 22: 377-83. https://bit.ly/3O9nCzz

Marshall BG, Forsberg BR, Thomé-Souza M, et al. 2016. Evidence of mercury biomagnification in the food chain of the cardinal tetra Paracheirodon axelrodi (Osteichthyes: Characidae) in the Rio Negro, central Amazon, Brazil. Journ Fish Biol 89. https://doi.org/10.1111/jfb.12952,

Martinelli LA, Ferreira JR, Forsberg BR et al. 1988. Mercury contamination in the Amazon – a gold rush consequence. Ambio 17: 252-4. https://bit.ly/3jC81dG

Martinelli Filho JE, and Monteiro RCP. 2019. Widespread microplastics distribution at an Amazon macrotidal sandy beach. Marine Pollut Bull 145: 219-23.

Martins RT, Couceiro SEM, Melo AS et al. 2017. Effects of urbanization on stream benthic invertebrate communities in Central Amazon. Ecol Indicators 73: 480-91.

McClain ME, and Naiman RJ. 2008. Andean influences on the biogeochemistry and ecology of the Amazon River. Bioscience 58: 325–38.

McIntyre PB, Reidy Liermann C, Childress E, et al. 2016. Conservation of migratory fishes in freshwater ecosystems. In: Conservation of Freshwater Fishes. Cambridge, UK: Cambridge University Press.

Meade RH. 2007. Transcontinental moving and storage: the Orinoco and Amazon Rivers transfer the Andes to the Atlantic. In: Large Rivers Geomorphology and Management. New York, USA: Wiley, pp. 45–64.

Mendes RDA, Lopes AS, Souza LC, et al. 2016. DDT concentration in fish from the Tapajós River in the Amazon region, Brazil. Chemosphere 153: 340-45.

Miranda-Chumacero G, Wallace R, Calderón H, et al. 2012. Distribution of arapaima (Arapaima gigas) (Pisces: Arapaimatidae) in Bolivia: Implications in the control and management of a non-native population. BioInvasions Records 1: 129–38.

Mojica JIE, Usma Oviedo JUE, Alvarez León RE, and Lasso CA. 2012. Libro rojo de peces dulceacuícolas de Colombia. Universidad Nacional de Colombia and Ministério del Médio Ambiente, Bogotá, Colombia.

Molina CI, Gibon FM, Duprey JL et al. 2010. Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of the Beni River, Bolivian Amazonia. Sci Total Environ 408:3382-91.

Monteiro Jr CS, Couceiro SEM, Hamada N, et al. 2013. Effect of vegetation removal for road building on richness and composition of Odonata communities in Amazonia, Brazil. Internat Journ Odonatology 16: 135-44.

Monticini P. 2010. The Ornamental Fish Trade Production and Commerce of Ornamental Fish: Technical, Managerial and Legislative Aspects. GLOBEFISH Research Programme, Vol. 102. Rome, Italy: FAO. 134 pp. https://bit.ly/37ITbiW

Moquet J-S, Maurice L, Crave A, et al. 2014. Cl and Na fluxes in an Andean foreland basin of the Peruvian Amazon: An anthropogenic impact evidence. Aquatic Geochem 20: 613-37.

Moreau M-A, and Coomes OT. 2006. Potential threat of the international aquarium fish trade to silver arawana Osteoglossum bicirrhosum in the Peruvian Amazon. Oryx 40: 152–60.

Moreau M-A, and Coomes OT. 2007. Aquarium fish exploitation in western Amazonia: conservation issues in Peru. Environ Conserv 34: 12–22.

Mosquera-Guerra F, Trujillo F, Caicedo-Herrera D, and Martínez-Callejas S. 2015. Indicios de biomagnificación de Mercurio total (Hg) en las especies del género Inia (Cetartiodactyla: Iniidae) en los ríos Amazonas y Orinoco (Colombia). Momentos Cienc 12: 77–86.

Myers BJE, Lynch AJ, Bunnell DB et al. 2017. Global synthesis of the documented and projected effects of climate change on inland fishes. Reviews Fish Biol Fisheries 27: 339-61.

Myhre G, Shindell D, Bréon F-M, et al. 2013. Anthropogenic and natural radiative forcing. In: Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. pp. 661-740.

Nascimento SP do. 2002. Observações sobre o comportamento de nidificação de três espécies de Podocnemis Wagler (Testudinata, Pelomedusidae) no Baixo Rio Branco, Roraima, Brasil. Rev Bras Zool 19: 201–4.

Neill C, Deegan LA, Thomas SM, et al. 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazon streams. Ecol Applicat 11: 1817-28.

Neill C, Deegan LA, Thomas SM, et al. 2006. Deforestation alters the hydraulic and biogeochemical characteristics of small lowland Amazon streams. Hydrolog Processes 20: 2563-80.

Nelson J, and Val AL. 2016. From the equator to the poles, a physiology section perspective on climate change. Fisheries 41: 409-11.

Nilsson C, and Berggren K. 2000. Alterations of riparian ecosystems caused by river regulation. Bioscience 50: 783–92.

Norris D, Michalski F, and Gibbs JP. 2018. Beyond harm's reach? Submersion of river turtle nesting areas and implications for restoration actions after Amazon hydropower development. PeerJ 6: e4228.

Nunes DMF, Magalhães ALB, Weber AA, et al. 2015. Influence of a large dam and importance of an undammed tributary on the reproductive ecology of the threatened fish matrinxã Brycon orthotaenia Günther, 1864 (Characiformes: Bryconidae) in southeastern Brazil. Neotrop Ichthyol 13: 317–24.

Odinetz Collart O. 1987. La pêche crevettière de Macrobrachium amazonicum (Palaemonidae) dans le Bas-Tocantins après fermeture du barrage de Tucurui (Brésil). Rev d'hydrobiologie Trop 20: 131–44.

Oliveira AM de, and Val AL. 2017. Effects of climate scenarios on the growth and physiology of the Amazonian fish tambaqui (Colossoma macropomum) (Characiformes: Serrasalmidae). Hydrobiologia 789: 167–78.

Oliveira WL, Medeiros MB, Moser P, and Simon MF. 2021. Megadams and extreme rainfall: Disentangling the drivers of extensive impacts of a large flooding event on Amazon Forests. PLoS One 16: e0245991.

Olivier K. 2001. The ornamental fish market. Roma, Italia: Food and Agriculture Organization of the United Nations (FAO). https://bit.ly/38IIJZb

Orta Martínez M, Napolitano DA, MacLennan GJ, et al. 2007. Impacts of petroleum activities for the Achuar people of the Peruvian Amazon: summary of existing evidence and research gaps. Environ Res Lett 2: 45006.

Ortega Lara A, Cruz-Quintana Y, and Puentes Granada V. 2015. Dinámica de la Actividad Pesquera de los Peces Ornamentales Continentales de Colombia. In: Ecological and Genetic Implications of Aquaculture Activities. Dordrecht: The Netherlands: Springer. pp. 247-278. https://bit.ly/3JDMJak

Otomo JI, de Jesus TA, Coelho LHG, et al. 2021. Effect of eight common Brazilian drugs on Lemna minor and Salvinia auriculata growth. Environ Sci Pollution Res 28: 43747–62.

Paschoalini M, Almeida RM, Trujillo F, et al. 2020. On the brink of isolation: Population estimates of the Araguaian river dolphin in a human-impacted region in Brazil. PLoS One 15: e0231224.

Passos C, and Mergler D. 2008. Human mercury exposure and adverse health effects in the Amazon: A review. Cadern Saúde Pública 24: S503–20.

Patterson RJ and Smokorowski KE. 2011. Assessing the benefit of flow constraints on the drifting invertebrate community of a regulated river. River Res Appl 27: 99–112.

Pauly D, and Cheung WWL. 2018. Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. Global Change Biol 24: e15-e26.

Pauly D, Christensen V, Dalsgaard J, et al. 1998. Fishing down marine food webs. Science 279: 860–3.

Pegado TSS, Schmid K, Winemiller KO et al. 2018. First evidence of microplastic ingestion by fishes from the Amazon River estuary. Marine Pollution Bull 133: 814-21.

Pelicice FM and Agostinho AA. 2008. Fish-passage facilities as ecological traps in large neotropical rivers. Conserv Biol 22: 180–8.

Pelicice FM and Agostinho AA. 2009. Fish fauna destruction after the introduction of a non-native predator (Cichla kelberi) in a neotropical reservoir. Biolog Invasions 11: 1789-801

Pelicice FM, Pompeu PS, and Agostinho AA. 2015a. Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. Fish Fish 16: 697–715.

Pelicice FM, Latini JD, and Agostinho AA. 2015b. Fish fauna disassembly after the introduction of a voracious predator: main drivers and the role of the invader's demography. Hydrobiologia 746: 271–83.

Petrere Junior M, Barthem RB, Córdoba EA, and Gómez BC. 2004. Review of the large catfish fisheries in the upper Amazon and the stock depletion of piraíba (Brachyplatystoma filamentosum Lichtenstein). Rev Fish Biol Fish 14: 403–14.

Piedade MTF, Parolin P, and Junk WJ. 2000. The flood pulse and photosynthetic response of trees in a white water floodplain (várzea) of the Central Amazon, Brazil. Verhandlungen - Internationale Vereinigung für Theoretische und Angewandte Limnologie 27: 1734-39.

Pignati MT, de Souza LC, Mendes RA, et al. 2018. Levels of organochlorine pesticides in Amazon turtle (Podocnemis unifilis) in the Xingu River, Brazil, Jour Environ Sci Health, Part B 53(12): 810-6.

Pires NL, Passos CJS, Morgado MGA et al. 2020. Determination of glyphosate, AMPA and glufosinate by high performance liquid chromatography with fluorescence detection in waters of the Santarem Plateau, Brazilian Amazon. Jour Environ Sci Health, Part B 55(9): 794-802.

Poff LN, Angermeier PL, Cooper SD, et al. 2001. Fish diversity in streams and rivers. In: Global biodiversity in a Changing Environment: Scenarios for the 21st Century. New York, USA: Springer. pp. 315-49. https://bit.ly/3JKyVKV

Pouilly M, Rejas D, Pérez T, et al. 2013. Trophic Structure and Mercury Biomagnification in Tropical Fish Assemblages, Itenez River, Bolivia. PLoS ONE 8(5): e65054.

Pringle CM, Freeman MC, and Freeman BJ. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. BioScience 50: 807–23.

Pueyo S, and Fearnside PM. 2011. Emissões de gases de efeito estufa dos reservatórios de hidrelétricas: Implicações de uma lei de potência. Oecologia Aust 15: 199–212.

Resende AF de, Schöngart J, Streher AS, et al. 2019. Massive tree mortality from flood pulse disturbances in Amazonian floodplain forests: The collateral effects of hydropower production. Sci Total Environ 659: 587–98.

Ribeiro M, and Petrere M. 1988. Viagem de reconhecimento ao rio Tocantins e baixo rio Araguaia entre 20/11/88 e 8/12/88. Consultant Report to UNDP/ELETRONORTE, Brasília (DF)(mimeographed report).

Ribeiro MCL de B, Petrere Junior M, and Juras AA. 1995. Ecological integrity and fisheries ecology of the Araguaia—Tocantins River Basin, Brazil. Regul Rivers Res Manag 11: 325–50.

Rico A, de Oliveira, R, Nunes GSS, et al. 2021. Pharmaceuticals and other urban contaminants threaten Amazon freshwater ecosystems. Environ Internat 155: 106702.

Roach K, Jacobsen N, Fiorello C, et al. 2013. Gold mining and mercury bioaccumulation in a floodplain lake and main channel of the Tambopata River, Perú. Jour Environ Protection 4: 51-60.

Rochman CM, Hoh E, Kurobe T, et al. 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Scient Rep 3: 3263.

Rosas FCW, and Lethi KK. 1996. Nutritional and mercury content of milk of the Amazon river dolphin, Inia geoffrensis. Compar Biochem Physiol 115A(2): 117-9.

Roulet M, Lucotte M, Farella N, et al. 1999. Effects of recent human colonization on the presence of mercury in Amazonian ecosystems. Water Air Soil Pollut 112: 297–313.

Roulet M, Lucotte M, Guimarães JRD, and Rheault I. 2000. Methylmercury in water, seston, and epiphyton of an Amazonian river and its floodplain, Tapajos River, Brazil. Sci Total Environ 261: 43–59.

Rubio L, Marcos R, and Hernández A. 2020. Potential adverse health effects of ingested micro- and nanoplastics on humans. Lessons learned from in vivo and in vitro mammalian models. Jourl Toxicol Environl Health, Part B, 23(2): 51-68.

Ruffino ML, and Isaac VJ. 1999. Dinâmica populacional do surubim-tigre, Pseudoplatystoma tigrinum (Valenciennes, 1840) no médio Amazonas (Siluriformes, Pimelodidae). Acta Amazonica 29: 463-76.

Sadauskas-Henrique H, Braz-Mota S, Duarte RM, et al. 2016. Influence of the natural Rio Negro water on the toxicological effects of a crude oil and its chemical dispersion to the Amazon fish Colossoma macropomum. Environ Sci Pollution Res 23: 19764-75.

Salinas C, Cubillos JC, Gómez R, et al. 2013. Pig in a poke (gato por liebre)'': The ''mota'' (Calophysus macropterus) Fishery, Molecular Evidence of Commercialization in Colombia and Toxicological Analyses. EcoHealth, 11: 197-206.

Salisbury C. 2015. Damming the Amazon: new hydropower projects put river dolphins at risk. Mongabay, 15 December 2015. https://bityl.co/56NP

Salisbury C. 2016. Amazon turtles imperiled by dams, mercury pollution and illegal trade. Mongabay, 12 July 2016. https://bityl.co/55Vy

Sánchez-Cuervo AM, de Lima LS, Dallmeier F, et al. 2020 Twenty years of land cover change in the southeastern Peruvian Amazon: Implications for biodiversity conservation. Regional Environ Change 20: 8.

Santos GM dos. 1995. Impactos da hidrelétrica Samuel sobre as comunidades de peixes do rio Jamari (Rondônia, Brasil). Acta Amazonica 25: 247-80.

Santos RE, Pinto-Coelho RM, Drumond MA, et al. 2020. Damming Amazon rivers: Environmental impacts of hydroelectric dams on Brazil's Madeira River according to local fishers' perception. Ambio 49: 1612–28.

Santos RE, Pinto-Coelho RM, Fonseca R, et al. 2018. The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin. Fish Manag Ecol 25: 380–91.

Sá-Oliveira JC, Hawes JE, Isaac-Nahum VJ, et al. 2015a. Upstream and downstream responses of fish assemblages to an eastern Amazonian hydroelectric dam. Freshwater Biol 60: 2037–50.

Sá-Oliveira JC, Isaac VJ, and Ferrari SF. 2015b. Fish community structure as an indicator of the longterm effects of the damming of an Amazonian river. Environ Biol Fishes 98: 273–86.

Sarica S, Amyot M, Hare L, et al. 2005. Mercury transfer from fish carcasses to scavengers in boreal lakes: the use of stable isotopes of mercury. Environ Pollution 134: 13–22.

Schmidt N, Fauvelle V, Ody A, et al. 2019. The Amazon River: A major source of organic plastic additives to the tropical North Atlantic? Environ Sci Technol 53: 7513–21.

Schöngart J, Wittmann F, Faria de Resende A, et al. 2021. The shadow of the Balbina Dam: A synthesis of over 35 years of downstream impacts on floodplain forests in central Amazonia. Aquat Conserv Mar Freshw Ecosyst 31: 1117–35.

Sebastian SM, and Hurtig AK. 2004. Oil exploitation in the Amazon basin of Ecuador: A public health emergency. Pan Amer Jour Pub Health 3: 205-11. https://bityl.co/6MQa

Sheridan JA, and Bickford D. 2011. Shrinking body size as an ecological response to climate change. Nature Climate Change 1: 401–6.

Silva G, Matos L, Freitas J, et al. 2019. Gene expression, genotoxicity, and physiological responses in an Amazonian fish, Colossoma macropomum (CUVIER 1818), exposed to Roundup® and subsequent acute hypoxia. Compar Biochem Physiol 222: 49-58.

Sioli H. 1984. The Amazon and its main affluents: hydrography, morphology of the river courses, and river types. In: The Amazon. Dordrecht, The Netherlands: Springer. pp. 127-65.

Soares BE. 2015. O Assoreamento por Rejeito de Bauxita e sua Relação com a Diversidade Taxonômica e Filogenética: Um Estudo da Ictiofauna de um Lago da Amazônia Central (Lago Batata, PA). Master's dissertation in ecology, Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, RJ, Brazil. 127 pp. https://bityl.co/6MLH

Soares MGM, Menezes NA, and Junk WJ. 2006. Adaptations of fish species to oxygen depletion in a central Amazon floodplain lake. Hydrobiologia 68: 353–367.

Sorribas MV, Paiva RCD, Melack JM, et al. 2016. Projections of climate change effects on discharge and inundation in the Amazon basin. Climatic Change 136: 555–70.

Souza-Araújo J, Giarrizzo T, Lima MO, et al. 2016. Mercury and methyl mercury in fishes from Bacajá River (Brazilian Amazon): Evidence for bioaccumulation and biomagnification. Jour Fish Biol 89: 249-263.

Souza S, Machado R, Costa J, Campos D, Silva G and Almeida-Val VMF. 2020. Severe damages caused by Malathion exposure in Colossoma macropomum. Ecotoxicology and Environmental Safety 205: 111340.

Starling F, Lazzaro X, Cavalcanti C, et al. 2002. Contribution of omnivorous tilapia to eutrophication of a shallow tropical reservoir: Evidence from a fish kill. Freshwater Biol 47: 2443–52.

Stegmann LF, Leitão RP, Zuanon J, and Magnusson WE. 2019. Distance to large rivers affects fish diversity patterns in highly dynamic streams of Central Amazonia. PLoS One 14: e0223880.

Stevens CH, Croft DP, Paull GC, and Tyler CR. 2017. Stress and welfare in ornamental fishes: what can be learned from aquaculture? J Fish Biol 91: 409–28.

Tadei WP, Scarpassa VM, Rodrigues IB, and Moura R. 1991. Evolução das populações de Anopheles e de Mansonia, na área de influência da UHE de Tucuruí (Pará). Ciência e Cultura 43(7) (supl.): 639–40.

Taylor BW, Flecker AS, and Hall RO. 2006. Loss of a harvested fish species disrupts carbon flow in a diverse tropical river. Science 313: 833-6.

The Intercept. 2019. Plano de desenvolvimento da Amazônia. The Intercept. 12 September 2019. https://bit.ly/3yl5ygk.

Thomas KV, da Silva FMA, Langford KH et al. 2014. Screening for selected human pharmaceuticals and cocaine in the urban streams of Manaus, Amazonas, Brazil. Jour Amer Water Resour Assoc 50: 302-8.

Timpe K, and Kaplan D. 2017. The changing hydrology of a dammed Amazon. Sci Adv 3: e1700611.

Tófoli RM, Dias RM, Alves GHZ et al. 2017. Gold at what cost? Another megaproject threatens biodiversity in the Amazon. Perspect Ecol Conserv, 15: 129–31.

Tognelli MF, Anderson EP, Jiménez-Segura LF et al. 2019. Assessing conservation priorities of endemic freshwater fishes in the tropical Andes region. Aquat Conserv: Marine and Freshw Ecosyst, 29: 1123-32.

Torres JPM, Lailson-Brito J, Saldanha GC, et al. 2009. Persistent toxic substances in the Brazilian Amazon: Contamination of man and the environment. Jour Braz Chem Soc, 20: 1175-9.

Toussaint A, Charpin N, Brosse S, and Villéger S. 2016a. Global functional diversity of freshwater fish is concentrated in the Neotropics while functional vulnerability is widespread. Sci Rep 6: 1–9.

Toussaint A, Beauchard O, Oberdorff T, et al. 2016b. Worldwide freshwater fish homogenization is driven by a few widespread non-native species. Biol Invasions 18: 1295–304.

Tregidgo DJ, Barlow J, Pompeu PS, et al. 2017. Rainforest metropolis casts 1,000-km defaunation shadow. Proc Natl Acad Sci USA 114: 8655–9.

Ullrich SM, Tanton TW, and Abdrashitova SA. 2001. Mercury in the aquatic environment: A review of factors affecting methylation. Critl Reviews Environl Sci Technol 31: 241–93.

Val AL. 2019. Fishes of the Amazon: diversity and beyond. An Acad Bras Cienc 91(supl 3): e20190260.

Val, A.L., and Almeida-Val, V.M.F., 1995. Fishes of the Amazon and their environments. Physiological and biochemical features. Heidelberg, Germany: Springer Verlag.

Val AL, Almeida-Val VMF de, and Randall DJ. 2006. Fish physiology: The Physiology of Tropical Fishes. London, UK: Elsevier.

Val AL, and Almeida-Val VMF. 1999. Effects of crude oil on respiratory aspects of some fish species of the Amazon. In: Biology of Tropical Fish. Manaus, Amazonas, Brazil: Instituto Nacional de Pesquisas da Amazônia (INPA). pp. 277–91.

Val AL, Silva MNP, and Almeida-Val VMF. 1998. Hypoxia adaptation in fish of the Amazon: A never-ending task, South African Jour Zool 33: 107-14.

Valdez-Carrillo J, Abrell L, Ramírez-Hernández J, Reyes-López JA, et al. 2020. Pharmaceuticals as emerging contaminants in the aquatic environment of Latin America: A review. Environ Sci Pollution Res, 27: 44863–91. https://doi.org/10.1007/s11356-020-10842-9

Van Damme PA, Carvajal-Vallejos F, Sarmiento J, Barrera S, Osinaga K and Miranda-Chumacero G. 2009. Peces. In Libro rojo de la fauna Silvestre de vertebrados de Bolivia. La Paz, Bolivia: Ministerio de Medio Ambiente y Agua. pp. 25–90. https://bit.ly/3M5V2Ns

Van Damme PA, Carvajal-Vallejos F, Pouilly M, et al. 2011. Amenazas para los peces y las pesquerías en la Amazonía Boliviana. In: Los peces y delfines de la Amazonía Boliviana - Hábitats, potencialidades y amenazas. Cochabamba, Bolivia: Editorial INIA. pp. 327-366. https://bit.ly/3JKzy7f

Vasconcelos LP, Alves DC, and Gomes LC. 2014. Fish reproductive guilds downstream of dams. J Fish Biol 85: 1489–506.

Villéger S, Blanchet S, Beauchard O, et al. 2011. Homogenization patterns of the world's freshwater fish faunas. Proc Nat Acadf Sci USA 108: 18003-8.

Villén-Pérez S, Moutinho P, Nóbrega CC, et al. 2020. Brazilian Amazon gold: Indigenous land rights under risk. Elementa Sci Anthropocene 8: 31.

Wang J, Ding C, Heino J, et al. 2020. What explains the variation in dam impacts on riverine macroinvertebrates? A global quantitative synthesis. Environ Res Lett 15: 124028.

Watts J. 2019. Poorly planned Amazon dam project 'poses serious threat to life'. The Guardian, 8 November 2019. https://bityl.co/55W8

Welcomme RL. 1995. Relationships between fisheries and the integrity of river systems. Regul Rivers Res Manag 11: 121–36.

Welcomme RL. 1999. A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. Fish Manag Ecol 6: 1–19.

Williams MR, Fisher TR, and Melack JM. 1997. Solute dynamics in soil water and groundwater in a central Amazon catchment undergoing deforestation. Biogeochem 38: 303-35.

Winemiller KO, Marrero C, and Taphorn DC. 1996. Perturbaciones causadas por el hombre a las poblaciones de peces de los llanos y del piedemonte andino de Venezuela. Biollania (Venezuela) 12: 13-48. https://bit.ly/36eLD7e

Wittmann F, Schöngart J, Montero JC, et al. 2006. Tree species composition and diversity gradients in whitewater forests across the Amazon Basin. J Biogeogr 33: 1334–47.

Wootton RJ. 1998. The Ecology of Teleost Fishes, second edition. Dordrecht, The Netherlands: Kluwer. 386 pp.

Wright JP, and Flecker AS. 2004. Deforesting the riverscape: The effects of wood on fish diversity in a Venezuelan piedmont stream. Biol Conserv 120: 443–51.

Xenopoulos MA, Lodge DM, Alcamo J, et al. 2005. Scenarios of freshwater fish extinctions from climate change and water withdrawal. Global Change Biol 11: 1557-64.

Yusta-García R, Orta-Martínez M, Mayor P, et al. 2017. Water contamination from oil extraction activities in northern Peruvian Amazon rivers. Environ Pollution 225: 370-80.

Zaret TM, and Paine RT. 1973. Species introduction into a tropical lake. Science 182: 449-55.

Zehev BS, Vera A, Asher B, and Raimundo R. 2015. Ornamental fishery in Rio Negro (Amazon region), Brazil: combining social, economic and fishery analyses. Fish Aquac Jour 6: 1000143.

Zuanon JA, Py-Daniel LHR, Ferreira EJG., et al. 2005. Padrões de distribuição da ictiofauna na várzea do sistema Solimões-Amazonas, entre Tabatinga (AM) e Santana (AP). In: Projeto de Manejo dos Recursos Naturais da Várzea. Provárzea - Estudos Estratégicos. Bases Científicas para a Conservação da Várzea - Identificação e Caracterização de Regiões Biogeográficas. Manaus, Amazonas, Brazil: EMBRAPA/ProVárzea. pp. 237-85.

Zuanon J. 2015. Ictiofauna. In: Uma avaliação crítica do Estudo e Relatório de Impacto Ambiental (EIA/RIMA) do Aproveitamento Hidrelétrico São Luiz do Tapajós. São Paulo, SP, Brasil: Greenpeace Brasil. pp. 67-74. https://bit.ly/3jGAizG

Zwink W, and Young PS. 1990. Desova e eclosão de Podocnemis expansa (Schweigger 1812)(Chelonia: Pelomedusidae) no Rio Trombetas, Pará, Brasil. In: FOREST 90: First International Symposium on Environmental Studies. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, RJ, Brazil. pp. 34--5.

CONTACT INFORMATION

SPA Technical-Scientific Secretariat New York
475 Riverside Drive, Suite 530
New York NY 10115
USA
+1 (212) 870-3920
spa@unsdsn.org

SPA Technical-Scientific Secretariat South America
Av. Ironman Victor Garrido, 623
São José dos Campos – São Paulo
Brazil
spasouthamerica@unsdsn.org

WEBSITE theamazonwewant.org
INSTAGRAM @theamazonwewant
TWITTER @theamazonwewant