Chapter 20 In Brief

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

Drivers and impacts of changes in aquatic ecosystems

Philip M. Fearnside[a], Dolors Armenteras[b], Erika Berenguer[c], Fabrice Duponchelle[d], Federico Mosquera Guerra[e], Clinton N. Jenkins[f], Paulette Byone[g], Roosevelt García-Villacorta[h], Adalberto Luis Val[a], Vera Maria Fonseca de Almeida-Val[a]

Key Messages & Recommendations

1) Over the last four decades, and especially over the last two, many Amazonian aquatic ecosystems have become less connected and more polluted. Urgent attention should be given to creating aquatic protected areas, as most existing protected areas were designed to safeguard terrestrial ecosystems and generally do little to conserve aquatic biota.
2) Prior to the massive impacts of dam construction over the past four decades, overexploitation of plant and animal species was the most significant driver of aquatic ecosystem degradation in the Amazon basin. This degradation continues to advance. Aquatic resources require cooperative arrangements to sustainably manage their use, including the exclusion of outside fishing vessels, and enforcement of restrictions on overharvesting.
3) Hydroelectric dams block fish migration and the transport of water, sediments and associated nutrients. They also alter river flows and oxygen levels. Dams with installed capacity greater than 10 MW should no longer be built. “Micro” dams, designed to power a single town or village, can be built with proper environmental licensing and risk-based approaches. In the meantime, energy policy should prioritize electricity conservation, halt exports of electricity-intensive products, and redirect investment to wind and solar generation.
4) Selected watersheds throughout the Amazon need to be preserved for research, long-term monitoring, and the protection of genetic and species diversity. These watersheds can also maintain ecological communities for recovery efforts.

Abstract Amazonian aquatic ecosystems are being destroyed and threats to their integrity are projected to grow in number and intensity. Here we present some of the main impacts on aquatic ecosystems triggered by infrastructure projects and predatory and illegal practices.

Introduction The Amazon River annually discharges 6.6 trillion m^3 of fresh water to the oceans, along with 600-800 million tons of suspended sediments[1]. The Amazon’s aquatic biodiversity is globally significant. So far, 2,406 fish species have been described[2] (see also Chapter 3), although the actual number is likely to be above 3,000 species[3]. Amazonian rivers and streams also connect distant parts of the vast Amazon basin, crucial for fish migration and sediment flow. However, these systems are fragile and impacts originating at any given location may be felt thousands of kilometers away. We list below some of the main threats faced by Amazonian aquatic ecosystems, along with their

[a] Instituto Nacional de Pesquisas da Amazônia (INPA), Av. André Araújo 2936, Petrópolis, Manaus AM 69067-375, Brazil, pmfearn@inpa.gov.br
[b] Ecología del Paisaje y Modelación de Ecosistemas ECOLMOD, Departamento de Biología, Facultad de Ciencias, Universidad Nacional de Colombia Sede Bogotá, Colombia
[c] Environmental Change Institute, School of Geography and the Environment, University of Oxford, OX1 3QY, Oxford, UK; Lancaster Environment Centre, Lancaster University, LA1 4YQ Lancaster, UK
[d] Institut de Recherche pour le Développement, 44 bd de Dunkerque, Immeuble Le Sextant CS 90009, F-13572 Marseille cedex 02, France
[e] Fundación Omacha, Carrera 20 N° 133 – 32, barrio La Calleja, Bogotá DC, Colombia
[f] Florida International University, 11200 SW 8th Street, Miami FL 33199, USA
[g] University of Guyana, Turkeyen Campus, Greater Georgetown, Guyana
[h] Centro Peruano para la Biodiversidad y Conservación (CPBC), Iquitos, Perú; Department of Ecology and Evolutionary Biology, Cornell University, E145 Corson Hall, Ithaca NY 14853, USA

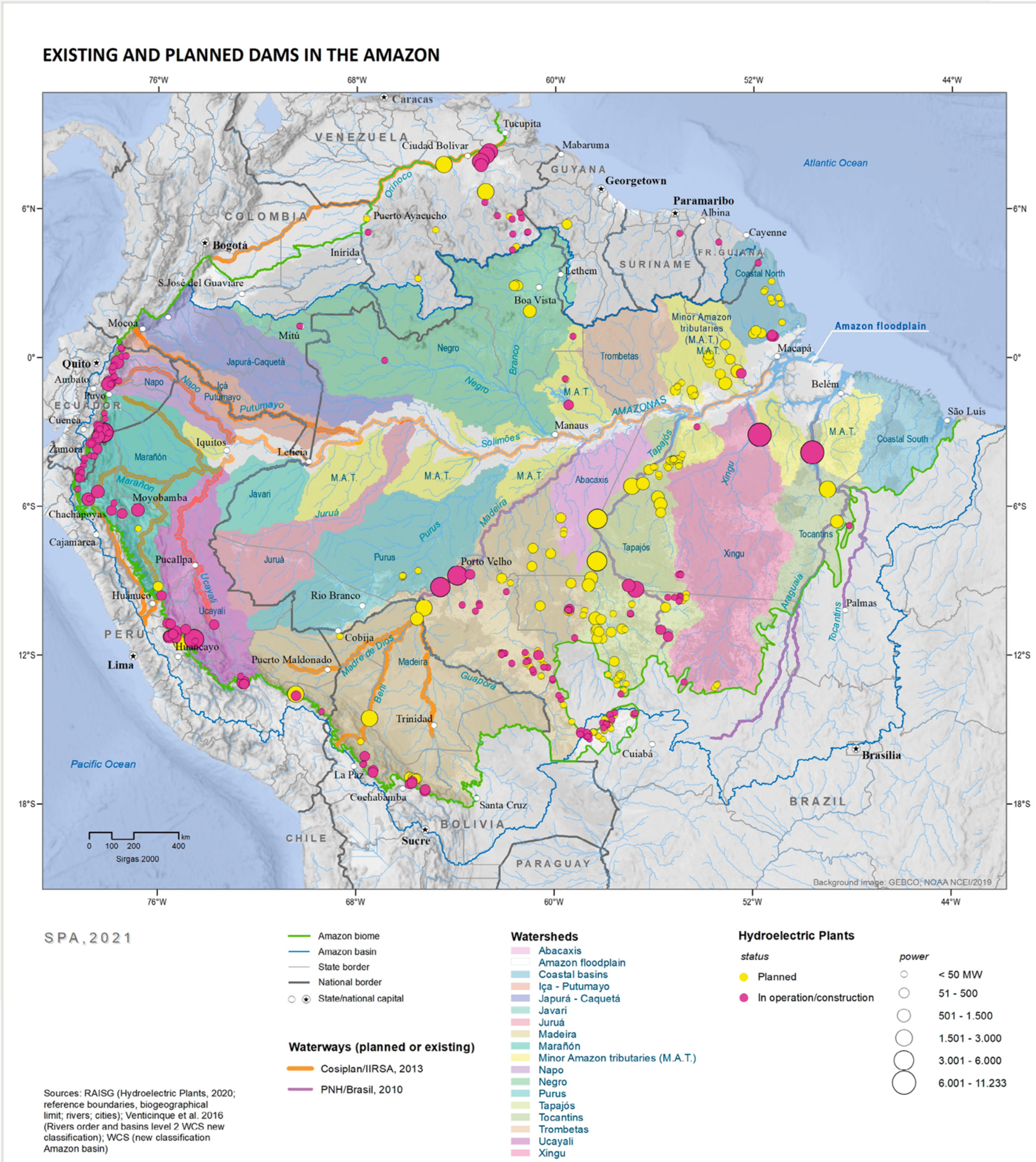

Figure 20.1 Existing and planned hydroelectric dams in the Amazon[5]

most important impacts. Across the Amazon there are 307 existing and 239 proposed hydroelectric dams, ranging from 1 MW installed capacity to some of the largest in the world, such as Belo Monte and Tucuruí (Figure 20.1)[4,5].

Dam impacts

Fish communities Hydroelectric dams negatively impact fish communities, both above and below the reservoir, due to habitat loss and disconnection, and severe changes in the hydrological regimes of flooded forests[6–9]. The conversion of a stretch of river from running water (lotic) to still water (lentic) eliminates or greatly reduces many species, few of which are adapted to the new environment[10]. Fish communities become structurally and functionally different from pre-dam baselines[11–13]. Amazonian dams and their ineffective fish passes have already seriously disrupted the migration routes of many fish species, such as the "giant catfish" of the Madeira River (*Brachyplatystoma* spp.).

Aquatic mammals, reptiles and insects Dams can fragment populations of dolphins, amphibians, and reptiles. This disrupts gene flow and can result in small, vulnerable populations[14,15]. A number of planned dams are particularly threatening to turtles[16], because the beaches on which turtles lay their eggs are commonly flooded by reservoirs or when dams alter downstream flows[17]. Dam impacts on aquatic insects vary; species that depend on fast-moving water decrease in abundance, while others that breed in standing water, such as mosquitos, can undergo population explosions[18,19].

Greenhouse-gas emissions Amazonian dams contribute to greenhouse gas emissions in two main ways; (1) methane is produced in stratified reservoirs, and (2) CO_2 is released by decaying trees killed by flooding[20–23]. The large amount of initial biomass lost 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[24]. Furthermore, trees near the edges of reservoirs suffer stress from higher water tables, causing additional mortality and CO_2 emissions[25–27].

Alteration of sediment flows Dams reduce sediment flows by trapping sediments in reservoirs[28] and by changing the natural hydrologic cycle. Downstream of dams, the reduced sediment load results in scouring, or increased erosion of riverbanks and bottoms[29,30]. Sediment reduction also deprives the river of nutrients downstream. In the Madeira River, sediment transport downstream of the Santo Antônio and Jirau Dams decreased by 20% compared to pre-dam quantities[31], which may have contributed to observed sharp declines in fish catches downstream of the dams[30,32]. Sediments, including suspended organic matter, form the base of aquatic food chains in the lower Amazon[33]; therefore, reductions in sediment loads below Andean dams are likely to have far-reaching consequences for fish along the entire length of the Madeira and Amazon Rivers[34].

Alteration of streamflow Dams can impact four hydrological parameters downstream; 1) the frequency and 2) duration of high and low water levels (flood pulses), and 3) the rate and 4) frequency of changes in water levels[35]. 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 Belo Monte Dam illustrates this effect; water flow is greatly reduced in a 130-km stretch known as the "big bend of the Xingu River" (*Volta Grande do Rio Xingu*), as 80% of the river's annual flow is diverted. Modifications in the hydrological regime directly impact aquatic biodiversity. Fish behavior, especially migration and reproduction, is attuned to changes in flow, and false signals caused by dams can induce fish to behave in ways that jeopardize their reproductive success[36–41].

Roads Dams are not the only type of infrastructure that degrade, or even destroy, aquatic systems in the Amazon; roads are also an important threat to these ecosystems. Amazonian roads are often built without adequate passages for water, such as culverts or bridges, fragmenting small tributaries and seasonal streams. Roads can act as dams, and their impact on seasonal streams is especially strong, causing ponding, blocking the passage of aquatic life, and disrupting stream connectivity.

Navigational waterways and river diversions The maintenance of navigational waterways can have severe impacts on aquatic ecosystems. Many endemic fish species could go extinct when rocky habitats are removed by dynamiting to allow barges to pass unimpeded[42]. In addition to removing rocky outcrops, the dredging of river channels deepens shallow zones and removes woody debris[43], destroying rich habitats for specific endemic fish fauna[44]. These populations are unlikely to recover. In the Peruvian Amazon, the recently contracted ~2,700-km *Hidrovía Amazónica*[45,46] could significantly alter river-channel morphology, impacting fish diversity and productivity on which local economies depend.

Fish harvested for human consumption Most large, high-valued fish species, such as the giant *pirarucu* or *paiche* (*Arapaima spp*.) and the large fruit-eating *tambaqui* or *gamitana,* are considered overfished in their natural ranges[47–50]. The same applies to several of the smaller Characiformes species, such as *Prochilodus nigricans* and *Psectrogaster spp*.[51–53]. Migratory fish are the most at risk from overfishing, accounting for over 90% of landings in the Amazon basin and generating over USD 400 million in income[54].

Ornamental fish The aquarium fish trade is a growing, multi-billion dollar industry[55,56]. Fish are one of the most popular pets in the world[57], and harvesting wild specimens for international trade is a major conservation issue[55,58,59]. The Amazon basin accounts for ~10% of the global trade in 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 about USD 17 million [60]. However, the effects of the ornamental fish trade on natural populations is poorly studied. Anecdotal information suggests population collapses or declines at some locations in the Rio Negro, such as for discus (*Symphysodon discus*)[61] and cardinal tetra (*Paracheirodon axelrodi*)[55,62]. In the Peruvian Amazon, exploitation has led to reductions of over 50% in ornamental species at study locations in terms of abundance, diversity, and biomass[63].

Invasive species In the Amazon, invasive species are used for farming, cultivation of ornamental species, and recreational fishing[64]. Fish introduced to lakes and reservoirs are often predatory species (*Cichla* spp., *Astronotus* spp. or *Pygocentrus nattereri*), feeding on and reducing the abundance of native species, with whole-ecosystem consequences including habitat loss, interruption of the life span of native fish (many invasive species eat the eggs of native fish), and competition for food, leading to changes in species composition and entire food-webs[65–69]. In the Andean waters of Bolivia and Peru, the introduction of predatory rainbow trout (*Oncorhynchus mykiss)* resulted in local extirpation or greatly reduced abundance of native *Astroblepus spp.*[70,71].

Deforestation Forest loss usually results in increased rainfall runoff and discharge. For example, deforestation induced a 25% increase in discharge in large river systems such as the Tocantins and Araguaia Rivers, with little change in precipitation[72]. Increased water runoff and sediment loads alters geomorphological and biochemical processes downstream, with consequences for soil erosion and the biological productivity of aquatic ecosystems[72–76]. Forest cover loss also results in direct sun exposure, reducing evapotranspirative cooling and sensible heat flux over land, leading to changes in the temperature, oxygen, and chemical content of watercourses, greatly affecting aquatic fauna[77]. For example, increased water temperatures and reduced oxygen during the dry period can be lethal for fish such as cardinal tetras[78,79].

Pollution

Agricultural chemicals Pesticides, herbicides, medicines, and other drugs are released into the environment, and their residence time is undetermined. Transition metals and other pollutants present in agricultural chemicals may affect local fish species differentially depending on their respiration, reproduction, trophic position, and metabolic characteristics[80,81]. The herbicide glyphosate (Roundup®) 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})[82,83]. The presence of pesticides has also been detected in Amazonian river dolphins[84,85] and turtles[86]. Expansion of soybean production in the southern Amazon is of particular concern to aquatic ecosystems due to the heavy use of herbicides, including glyphosate. Laboratory experiments on fish have shown that this and other herbicides cause damage to the liver and gills, as well as DNA breakage and increased risk of cancer[82,83,87].

Oil spills and toxic waste Contamination from crude oil and untreated toxic wastes from oil and gas exploitation are notorious in the Amazonian portions of Ecuador[88] and Peru[89,90]. In the Ecuadorian Amazon between 1972 and 1992, 73 billion liters of crude oil was discharged into the environment, nearly twice the amount released by the Exxon Valdez oil tanker in Alaska[91,92]. Over this period 43 billion liters of produced water (oilfield brine) was also released, containing salts that disrupt fish migrations[92]. Oil is toxic to fish[93], and oil-associated contamination can have far-reaching impacts on Amazonian aquatic communities because it can disperse widely, affecting the entire downstream network[90,94]. Hydrocarbon-related toxins have been found in Ecuadorian streams at concentrations up to 500 times higher than those allowed by European regulations[91].

Mining Gold mining is especially prevalent in Brazil and Peru, and the scale and impacts of this activity is projected to increase substantially if urgent action is not taken (Figure 20.2) [4,5,95]. It is estimated that the mercury shed by gold mining in the Brazilian Amazon totals more than 200,000 tons since the late 19th Century[96]. Gold mining has been estimated to account for 64% of the mercury entering Amazonian aquatic systems[97–100]. The remaining amount comes from natural deposits that are eroded by deforestation (33%) and from atmospheric deposition, with the original source being deforestation and forest fires (3%)[99,101]. At 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 or in thermally stratified natural lakes and rivers.

Methylmercury (MeHg) enters aquatic food webs and bio-accumulates with trophic levels[102,103]. Wildlife is exposed to MeHg through diet[103–105]. Mercury bioaccumulation causes concentrations to increase greatly in top predators such as large catfish, black caimans, otters, and dolphins[106–112]. Through fish consumption, humans also bioaccumulate mercury; Amazonian populations show some of the world's highest recorded mercury levels in human hair, along with associated health issues[113].

Urban sewage and plastic waste Urban sewage greatly affects aquatic invertebrates, reducing both abundance and species richness[114–118]. Large amounts of plastic are discarded in Amazonian rivers and streams and microplastics have been detected in river sediments[119] and in the sand of coastal beaches near the mouth of the Amazon[120]. Microplastics have also been found in fish species at all trophic levels, including 13 species from the Xingu River[121], and 14 from the Amazon estuary[122]. Micro- and nano-plastics affect aquatic ecosystems, and further serve as carriers for persistent organic pollutants (POPs)[123] and other chemicals that can provoke hepatic stress in fish[124].

Interactions among drivers The text above discusses drivers of degradation separately; however, several are highly correlated and often interacting, and aquatic organisms will have to cope with com-

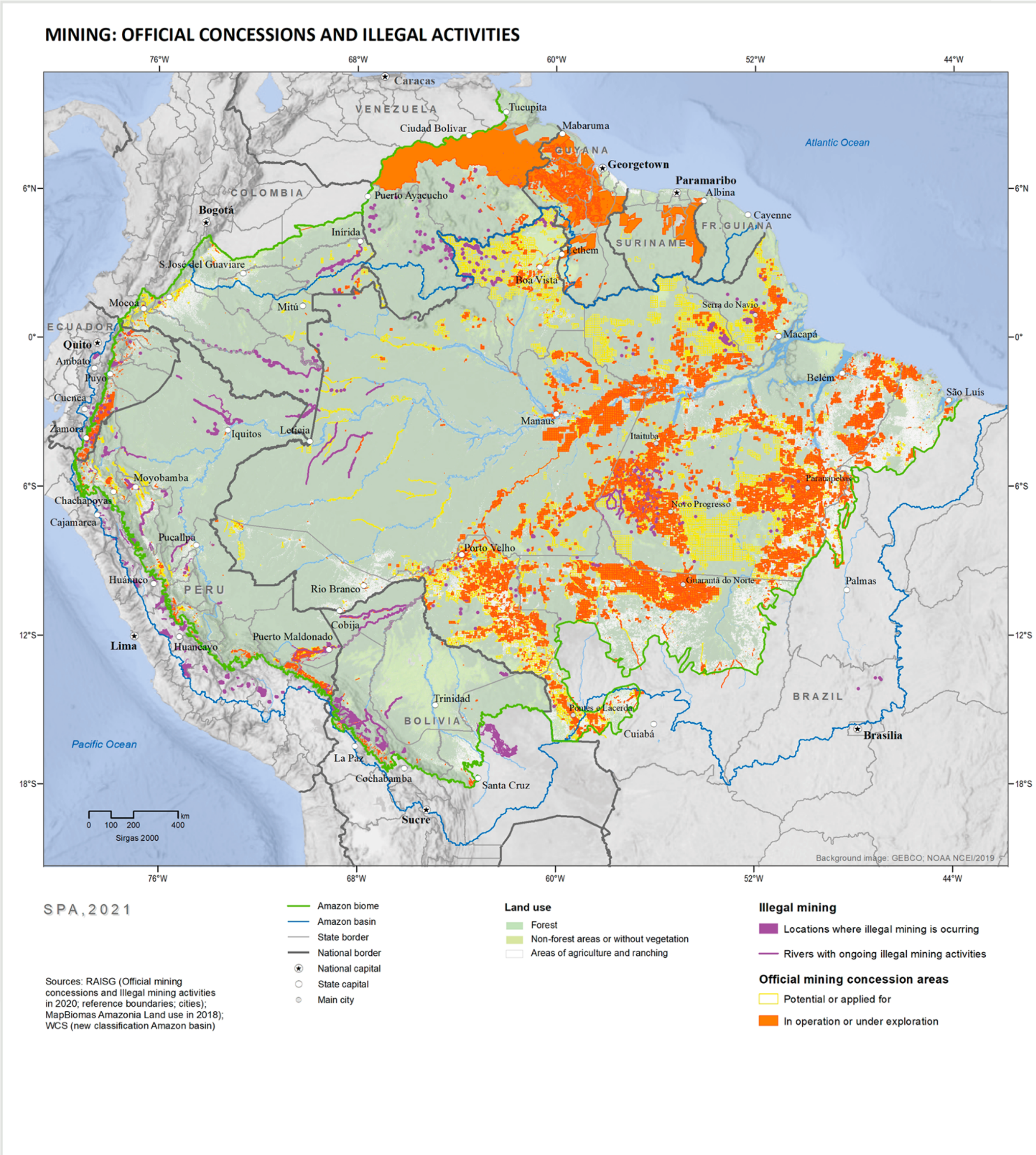

Figure 20.2 Official mining concessions and illegal activities[5]

binations of these drivers. For example, hydroelectric dams induce road construction, which in turn leads to increased deforestation and agriculture[34,45,125–127]. As already explained, interruptions to the hydrological cycle by dams isolates large portions of floodplains, which will likely then be exploited for agriculture, further increasing deforestation[34].

Similarly, the waterway in the Tapajós sub-basin is likely to encourage further deforestation directly through increased soy production in Mato Grosso. Runoff from soy plantations delivers fertilizers, herbicides, pesticides, and sediments from soil erosion to aquatic ecosystems. Waterways reduce transportation costs and encourage the transition from livestock to soy, resulting in indirect land-use change, as cattle ranchers sell their land to soy farmers and clear new parts of the Amazon for pasture[128,129].

One impact of waterways is that they justify hydroelectric dams regardless of how severe the negative impacts may be. Without a complete set of dams and locks on a river, barges cannot pass. They rely on reservoirs to eliminate rapids and waterfalls. The Tocantins/Araguaia waterway[130] and the Tapajós waterway[128] both serve as examples. In the case of the Madeira River, a plan for 4,000 km of waterways in the Amazonian portion of Bolivia, intended to transport soybeans, was used as an argument to support the viability of Brazil's Santo Antônio and Jirau Dams[131,132].

Exploitation of new sources of energy, such as oil, usually require road construction, hence deforestation[45,133]. Oil exploitation also has strong combined effects with dams, devastating aquatic biota where these drivers intersect[134]. In the Peruvian Amazon, the Interoceanic highway has had a dual impact on the rivers and associated terrestrial ecosystems; this road has promoted land-use change due to agriculture expansion in the north, while at the same time contributing to gold extraction in the Malinowsky and Inambari Rivers[135,136].

Conclusions The Amazon's aquatic ecosystems are impacted by human actions, especially infrastructure such as hydroelectric dams, roads, and oil and gas exploitation. These impacts have been intensified by increases in deforestation, pollution by agrochemicals, urban and industrial waste, and illegal mining. The synergistic effects of these impacts can compromise the functioning of ecosystems, leading to imbalances in food chains, decreases in species abundance, and extinction; this, in turn, has important effects on human health and ways of life.

References

1. Filizola, N. & Guyot, J. L. Fluxo de sedimentos em suspensão nos rios da Amazônia. *Rev. Bras. Geociências* 41, 566–576 (2011).
2. Jézéquel, C. *et al.* Freshwater fish diversity hotspots for conservation priorities in the Amazon Basin. *Conserv. Biol.* 34, 956–965 (2020).
3. Val, A. L. Fishes of the Amazon: diversity and beyond. *An. Acad. Bras. Cienc.* 91, (2019).
4. Venticinque, E. *et al.* An explicit GIS-based river basin framework for aquatic ecosystem conservation in the Amazon. *Earth Syst Sci Data* 651–661 https://knb.ecoinformatics.org/view/doi%3A10.5063%2FF1BG2KX8#snapp_computing.6.1 (2016).
5. RAISG. Amazonian Network of Georeferenced Socio-Environmental Information. https://www.amazoniasocioambiental.org/en/ (2020).
6. Ribeiro, M. & Petrere, M. Viagem de reconhecimento ao rio Tocantins e baixo rio Araguaia entre 20/11/88 e 8/12/88. *Consult. Rep. to UNDP/ELETRONORTE, Bras. (DF)(mimeographed report)* (1988).
7. Ribeiro, M. C. L. de B., Petrere Junior, M. & Juras, A. A. Ecological integrity and fisheries ecology of the Araguaia—Tocantins River Basin, Brazil. *Regul. Rivers Res. Manag.* 11, 325–350 (1995).
8. Santos, G. M. dos. Impactos da hidrelétrica Samuel sobre as comunidades de peixes do rio Jamari (Rondônia, Brasil). *Vol. 25, Número 3-4, Pags. 247-280* (1995).
9. Santos, R. E., Pinto-Coelho, R. M., Fonseca, R., Simões, N. R. & Zanchi, F. B. The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin. *Fish. Manag. Ecol.* 25, 380–391 (2018).
10. Agostinho, A. A., Gomes, L. C., Santos, N. C. L., Ortega, J. C. G. & Pelicice, F. M. Fish assemblages in Neotropical reservoirs: Colonization patterns, impacts and management. *Fish. Res.* 173, 26–36 (2016).
11. Araújo, E. S. *et al.* Changes in distance decay relationships after river regulation: similarity among fish assemblages in a large Amazonian river. *Ecol. Freshw. Fish* 22, 543–552 (2013).
12. Arantes, C. C., Fitzgerald, D. B., Hoeinghaus, D. J. & Winemiller, K. O. Impacts of hydroelectric dams on fishes

and fisheries in tropical rivers through the lens of functional traits. *Curr. Opin. Environ. Sustain.* 37, 28–40 (2019).
13. Arantes, C. C. *et al.* Floodplain land cover affects biomass distribution of fish functional diversity in the Amazon River. *Sci. Rep.* 9, 16684 (2019).
14. Gravena, W., Farias, I. P., da Silva, M. N. F., da Silva, V. M. F. & Hrbek, T. Looking to the past and the future: were the Madeira River rapids a geographical barrier to the boto (Cetacea: Iniidae)? *Conserv. Genet.* 15, 619–629 (2014).
15. Paschoalini, M. *et al.* On the brink of isolation: Population estimates of the Araguaian river dolphin in a human-impacted region in Brazil. *PLoS One* 15, e0231224 (2020).
16. Gonzales, J. Amazon's giant South American river turtle holding its own, but risks abound. *Mongabay Series: Amazon Conservation* (2019).
17. Norris, D., Michalski, F. & Gibbs, J. P. Beyond harm's reach? Submersion of river turtle nesting areas and implications for restoration actions after Amazon hydropower development. *PeerJ* 6, e4228 (2018).
18. Tavares de Lima, I. B., Novo, E. M. L. M., Ballester, M. V. R. & Ometto, J. P. Role of the macrophyte community in CH4 production and emission in the tropical reservoir of Tucuruí, Pará State, Brazil. *SIL Proceedings, 1922-2010* 27, 1437–1440 (2000).
19. Fearnside, P. M. Environmental Impacts of Brazil's Tucuruí Dam: Unlearned Lessons for Hydroelectric Development in Amazonia. *Environ. Manage.* 27, 377–396 (2001).
20. Fearnside, P. M. & Postal, C. Hydroelectric dams in the Brazilian Amazonia as sources of greenhouse gases. *Environ. Conserv.* 22, 7–19 (1995).
21. Fearnside, P. M. Greenhouse gas emissions from a hydroelectric reservoir (Brazil's Tucuruí Dam) and the energy policy implications. *Water. Air. Soil Pollut.* 133, 69–96 (2002).
22. Fearnside, P. M. Brazil's Samuel Dam: Lessons for hydroelectric development policy and the environment in Amazonia. *Environ. Manage.* 35, 1–19 (2005).
23. Abril, G., Parize, M., Pérez, M. A. P. & Filizola, N. Wood decomposition in Amazonian hydropower reservoirs: An additional source of greenhouse gases. *J. South Am. Earth Sci.* 44, 104–107 (2013).
24. Barros, N. *et al.* Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nat. Geosci.* 4, 593–596 (2011).
25. Fearnside, P. M. As hidrelétricas de Belo Monte e Altamira (Babaquara) como fontes de gases de efeito estufa. *Novos Cad. NAEA* 12, (2009).
26. dos Santos Junior, U. M., de Carvalho Gonçalves, J. F. & Fearnside, P. M. Measuring the impact of flooding on Amazonian trees: photosynthetic response models for ten species flooded by hydroelectric dams. *Trees* 27, 193–210 (2013).
27. dos Santos Junior, U. M., Gonçalves, J. F. de C., Strasser, R. J. & Fearnside, P. M. 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 Physiol. Plant.* 37, 1–17 (2015).
28. Fearnside, P. M. Decision Making on Amazon Dams: Politics Trumps Uncertainty in the Madeira River Sediments Controversy. *Water Altern.* 6, 313–325 (2013).
29. Almeida, R. *et al.* Hydropeaking Operations of Two Run-of-River Mega-Dams Alter Downstream Hydrology of the Largest Amazon Tributary. in *Frontiers in Environmental Science* (2020).
30. Santos, R. E., Pinto-Coelho, R. M., Drumond, M. A., Fonseca, R. & Zanchi, F. B. Damming Amazon Rivers: Environmental impacts of hydroelectric dams on Brazil's Madeira River according to local fishers' perception. *Ambio* 49, 1612–1628 (2020).
31. Latrubesse, E. M. *et al.* Damming the rivers of the Amazon basin. *Nature* 546, 363–369 (2017).
32. Lima, M. A. L., Kaplan, D. A. & Rodrigues da Costa Doria, C. Hydrological controls of fisheries production in a major Amazonian tributary. *Ecohydrology* 10, e1899 (2017).
33. Arantes, C. C., Winemiller, K. O., Petrere, M. & Freitas, C. E. C. Spatial variation in aquatic food webs in the Amazon River floodplain. *Freshw. Sci.* 38, 213–228 (2019).
34. Forsberg, B. R. *et al.* The potential impact of new Andean dams on Amazon fluvial ecosystems. *PLoS One* 12, e0182254 (2017).
35. Timpe, K. & Kaplan, D. The changing hydrology of a dammed Amazon. *Sci. Adv.* 3, e1700611 (2017).
36. Agostinho, A. A., Gomes, L. C., Veríssimo, S. & K. Okada, E. 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* vol. 14 11–19 (2004).
37. Bailly, D., Agostinho, A. A. & Suzuki, H. I. 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, 1218–1229 (2008).
38. Carvalho Freitas, C. E. de *et al.* The Potential Impacts of Global Climatic Changes and Dams on Amazonian Fish and Their Fisheries. in *New Advances and Contributions to Fish Biology* (2012).
39. Vasconcelos, L. P., Alves, D. C. & Gomes, L. C. Fish reproductive guilds downstream of dams. *J. Fish Biol.* 85, 1489–1506 (2014).
40. Nunes, D. M. F. *et al.* 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, 317–324 (2015).
41. McIntyre, P. B. *et al.* Conservation of migratory fishes in freshwater ecosystems. in *Conservation of Freshwater Fishes* (eds. Closs, G. P. & Olden, J. D.) 324–360 (Cambridge University Press: Cambridge, 2016).
42. Zuanon, J. Ictiofauna. in *Uma avaliação crítica do Estudo e Relatório de Impacto Ambiental (EIA/RIMA) do Aproveitamento Hidrelétrico São Luiz do Tapajós.* (eds. Nitta, R. & Naka, L. N.) 67–74 (Greenpeace Brasil, 2015).
43. Castello, L. *et al.* The vulnerability of Amazon freshwater ecosystems. *Conserv. Lett.* 6, 217–229 (2013).

44. Hrbek, T., Meliciano, N. V, Zuanon, J. & Farias, I. P. Remarkable Geographic Structuring of Rheophilic Fishes of the Lower Araguaia River . *Frontiers in Genetics* vol. 9 295 (2018).
45. Anderson, E. P. *et al.* Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Sci. Adv.* 4, eaao1642 (2018).
46. Bodmer, R. *et al.* 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, 247–258 (2018).
47. Isaac, V. J. & Ruffino, M. L. Population dynamics of tambaqui, Colossoma macropomum Cuvier, in the Lower Amazon, Brazil. *Fish. Manag. Ecol.* 3, 315–333 (1996).
48. Castello, L. & Stewart, D. J. Assessing CITES non-detriment findings procedures for Arapaima in Brazil. *J. Appl. Ichthyol.* 26, 49–56 (2010).
49. Campos, C. P., Costa Sousa, R. G., Catarino, M. F., de Albuquerque Costa, G. & Freitas, C. E. C. Population dynamics and stock assessment of Colossoma macropomum caught in the Manacapuru Lake system (Amazon Basin, Brazil). *Fish. Manag. Ecol.* 22, 400–406 (2015).
50. Castello, L., Arantes, C. C., Mcgrath, D. G., Stewart, D. J. & Sousa, F. S. De. Understanding fishing-induced extinctions in the Amazon. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 25, 587–598 (2015).
51. Catarino, M. F., Campos, C. P., Garcez, R. & Freitas, C. E. de C. Population dynamics of Prochilodus nigricans caught in Manacapuru Lake (Amazon basin, Brazil). *Bol. do Inst. Pesca* 40, 589–595 (2014).
52. García-Vásquez, A., Vargas, G., Sánchez, H., Tello, S. & Duponchelle, F. Periodic life history strategy of Psectrogaster rutiloides, Kner 1858, in the Iquitos region, Peruvian Amazon. *J. Appl. Ichthyol.* 31, 31–39 (2015).
53. Bonilla-Castillo, C. A., Córdoba, E. A., Gómez, G. & Duponchelle, F. Population dynamics of Prochilodus nigricans (Characiformes: Prochilodontidae) in the Putumayo River. *Neotrop. Ichthyol.* 16, e170139 (2018).
54. Duponchelle, F. *et al.* Conservation of migratory fishes in the Amazon basin. *Aquat. Conserv. Mar. Freshw. Ecosyst.*
55. Andrews, C. The ornamental fish trade and fish conservation. *J. Fish Biol.* 37, 53–59 (1990).
56. Stevens, C. H., Croft, D. P., Paull, G. C. & Tyler, C. R. Stress and welfare in ornamental fishes: what can be learned from aquaculture? *J. Fish Biol.* 91, 409–428 (2017).
57. Olivier, K. The ornamental fish market. *Globefish Res. Program.* 67, 99p (2001).
58. Chao, N. L. & Prang, G. Project Piaba -- towards a sustainable ornamental fishery in the Amazon. *Aquarium Sci. Conserv.* 1, 105–111 (1997).
59. Moreau, M.-A. & Coomes, O. T. Aquarium fish exploitation in western Amazonia: conservation issues in Peru. *Environ. Conserv.* 34, 12–22 (2007).
60. Monticini, P. *The Ornamental Fish Trade Production and Commerce of Ornamental Fish: technical-managerial and legislative aspects*. www.globefish.org (2010).
61. Crampton, W. G. R. 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 (1999).
62. Chao, N. L. & Prada-Pedreros, S. Diversity and habitat of ornamental fishes in the Rio Negro, Brazil: exploitation and conservation issues. in *Proceedings of World Fisheries Congress, Theme* vol. 3 241–261 (1995).
63. Gerstner, C. L., Ortega, H., Sanchez, H. & Graham, D. L. Effects of the freshwater aquarium trade on wild fish populations in differentially-fished areas of the Peruvian Amazon. *J. Fish Biol.* 68, 862–875 (2006).
64. Junior, D. P. L. *et al.* Aquaculture expansion in Brazilian freshwaters against the Aichi Biodiversity Targets. *Ambio* 47, 427–440 (2018).
65. Zaret, T. M. & Paine, R. T. Species Introduction in a Tropical Lake. *Science* 182, 449 LP – 455 (1973).
66. Latini, A. O. & Petrere Jr., M. Reduction of a native fish fauna by alien species: an example from Brazilian freshwater tropical lakes. *Fish. Manag. Ecol.* 11, 71–79 (2004).
67. Pelicice, F. M. & Agostinho, A. A. Fish fauna destruction after the introduction of a non-native predator (Cichla kelberi) in a Neotropical reservoir. *Biol. Invasions* 11, 1789–1801 (2009).
68. Fragoso-Moura, E. N., Oporto, L. T., Maia-Barbosa, P. M. & Barbosa, F. A. R. Loss of biodiversity in a conservation unit of the Brazilian Atlantic Forest: the effect of introducing non-native fish species. *Brazilian J. Biol.* 76, 18–27 (2016).
69. Pelicice, F. M., Latini, J. D. & Agostinho, A. A. Fish fauna disassembly after the introduction of a voracious predator: main drivers and the role of the invader's demography. *Hydrobiologia* 746, 271–283 (2015).
70. Ortega, H., Guerra, H. & Ramírez, R. The introduction of nonnative fishes into freshwater systems of Peru. in *Ecological and genetic implications of aquaculture activities* 247–278 (Springer, 2007).
71. Van Damme, P. A., Carvajal-Vallejos, F. M., Pouilly, M., Perez, T. & Carpio, J. M. Amenazas para los peces y las pesquerías de la Amazonía Boliviana. in *Los peces y delfines de la Amazonía boliviana: hábitats, potencialidades y amenazas. Editorial Inia, Cochabamba, Bolivia* (eds. Damme, P. A. Van, F. Carvajal-Vallejos & Carpio, J. M.) 327–365 (Editorial INIA, 2011).
72. Coe, M. T., Costa, M. H. & Soares-Filho, B. S. The influence of historical and potential future deforestation on the stream flow of the Amazon River – Land surface processes and atmospheric feedbacks. *J. Hydrol.* 369, 165–174 (2009).
73. Neill, C., Deegan, L. A., Thomas, S. M. & Cerri, C. C. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. *Ecol. Appl.* 11, 1817–1828 (2001).
74. Deegan, L. A. *et al.* Amazon deforestation alters small stream structure, nitrogen biogeochemistry and connectivity to larger rivers. *Biogeochemistry* 105, 53–74 (2011).
75. Iñiguez–Armijos, C., Leiva, A., Frede, H., Hampel, H. & Breuer, L. Deforestation and Benthic Indicators: How Much Vegetation Cover Is Needed to Sustain Healthy Andean Streams? *PLoS One* 9, e105869 (2014).

76. Ilha, P., Schiesari, L., Yanagawa, F. I., Jankowski, K. & Navas, C. A. Deforestation and stream warming affect body size of Amazonian fishes. *PLoS One* 13, e0196560 (2018).
77. da Silva Monteiro Júnior, C., Couceiro, S. R. M., Hamada, N. & Juen, L. Effect of vegetation removal for road building on richness and composition of Odonata communities in Amazonia, Brazil. *Int. J. Odonatol.* 16, 135–144 (2013).
78. Winemiller, K. O., Marrero, C. & Taphorn, D. C. Perturbaciones causadas por el hombre a las poblaciones de peces de los llanos y del piedemonte andino de Venezuela. *Biollania* 12, 13–48 (1996).
79. Gonçalves, L. M. F., Silva, M. de N. P. da, Val, A. L. & Almeida-Val, V. M. F. de. Differential survivorship of congeneric ornamental fishes under forecasted climate changes are related to anaerobic potential. *Genet. Mol. Biol.* 41, 107–118 (2018).
80. Duarte, R. M., Menezes, A. C. L., da Silveira Rodrigues, L., de Almeida-Val, V. M. F. & Val, A. L. Copper sensitivity of wild ornamental fish of the Amazon. *Ecotoxicol. Environ. Saf.* 72, 693–698 (2009).
81. Braz-Mota, S. *et al.* Exposure to waterborne copper and high temperature induces the formation of reactive oxygen species and causes mortality in the Amazonian fish Hoplosternum littorale. *Hydrobiologia* 789, 157–166 (2017).
82. Silva, G. S. da, Matos, L. V. de, Freitas, J. O. da S., Campos, D. F. de & Almeida e Val, V. M. F. de. Gene expression, genotoxicity, and physiological responses in an Amazonian fish, Colossoma macropomum (CUVIER 1818), exposed to Roundup® and subsequent acute hypoxia. *Comp. Biochem. Physiol. Part C Toxicol. Pharmacol.* 222, 49–58 (2019).
83. Silva de Souza, S. *et al.* Severe damages caused by Malathion exposure in Colossoma macropomum. *Ecotoxicol. Environ. Saf.* 205, 111340 (2020).
84. Lailson-Brito Jr, J. *et al.* Dolphins as indicators of micropollutant trophic flow in Amazon Basin. *Oecologia Bras.* 12, 12 (2008).
85. Torres, J. P. M. *et al.* Persistent toxic substances in the Brazilian Amazon: contamination of man and the environment. *J. Braz. Chem. Soc.* 20, 1175–1179 (2009).
86. Teófilo Pignati, M. *et al.* Levels of organochlorine pesticides in Amazon turtle (Podocnemis unifilis) in the Xingu River, Brazil. *J. Environ. Sci. Heal. Part B* 53, 810–816 (2018).
87. Braz-Mota, S., Sadauskas-Henrique, H., Duarte, R. M., Val, A. L. & Almeida-Val, V. M. F. Roundup® 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 (2015).
88. Jochnick, C., Norman, R. & Zaidi, S. Rights violations in the Ecuadorian Amazon: the human consequences of oil development. *Health Hum. Rights* 82–100 (1994).
89. Orta Martínez, M. *et al.* Impacts of petroleum activities for the Achuar people of the Peruvian Amazon: summary of existing evidence and research gaps. *Environ. Res. Lett.* 2, 45006 (2007).
90. Yusta-García, R., Orta-Martínez, M., Mayor, P., González-Crespo, C. & Rosell-Melé, A. Water contamination from oil extraction activities in Northern Peruvian Amazonian rivers. *Environ. Pollut.* 225, 370–380 (2017).
91. San Sebastián, M. & Karin Hurtig, A. Oil exploitation in the Amazon basin of Ecuador: a public health emergency. *Rev. Panam. salud pública* 15, 205–211 (2004).
92. Kimerling, J. Indigenous peoples and the oil frontier in Amazonia: The case of Ecuador, ChevronTexaco, and Aguinda v. Texaco. *NYUJ Int'l. L. Pol.* 38, 413 (2005).
93. Sadauskas-Henrique, H., Braz-Mota, S., Duarte, R. M. & de Almeida-Val, V. M. F. Influence of the natural Rio Negro water on the toxicological effects of a crude oil and its chemical dispersion to the Amazonian fish Colossoma macropomum. *Environ. Sci. Pollut. Res.* 23, 19764–19775 (2016).
94. Moquet, J.-S. *et al.* Cl and Na Fluxes in an Andean Foreland Basin of the Peruvian Amazon: An Anthropogenic Impact Evidence. *Aquat. Geochemistry* 20, 613–637 (2014).
95. MAPBIOMAS. Mapbiomas Amazonia. *Annual maps of land cover, land use and land use changes between 1985 to 2018 in the Pan-Amazon.* https://amazonia.mapbiomas.org/en (2020).
96. Bahia, M. de O. *et al.* Environmental biomonitoring using cytogenetic endpoints in a population exposed to mercury in the Brazilian Amazon. *Environ. Mol. Mutagen.* 44, 346–349 (2004).
97. Artaxo, P. *et al.* Large scale mercury and trace element measurements in the Amazon basin. *Atmos. Environ.* 34, 4085–4096 (2000).
98. de Cássia Guimarães Mesquita, R. Management of advanced regeneration in secondary forests of the Brazilian Amazon. *For. Ecol. Manage.* 130, 131–140 (2000).
99. Roulet, M. *et al.* Effects of recent human colonization on the presence of mercury in Amazonian ecosystems. *Water. Air. Soil Pollut.* 112, 297–313 (1999).
100. Roulet, M., Lucotte, M., Guimarães, J. R. D. & Rheault, I. Methylmercury in water, seston, and epiphyton of an Amazonian river and its floodplain, Tapajos River, Brazil. *Sci. Total Environ.* 261, 43–59 (2000).
101. Souza-Araujo, J., Giarrizzo, T., Lima, M. O. & Souza, M. B. G. Mercury and methyl mercury in fishes from Bacaja River (Brazilian Amazon): evidence for bioaccumulation and biomagnification. *J. Fish Biol.* 89, 249–263 (2016).
102. Morel, F. M. M., Kraepiel, A. M. L. & Amyot, M. The Chemical Cycle and Bioaccumulation Of Mercury. *Annu. Rev. Ecol. Syst.* 29, 543–566 (1998).
103. Ullrich, S. M., Tanton, T. W. & Abdrashitova, S. A. Mercury in the Aquatic Environment: A Review of Factors Affecting Methylation. *Crit. Rev. Environ. Sci. Technol.* 31, 241–293 (2001).
104. Sarica, J. *et al.* Mercury transfer from fish carcasses to scavengers in boreal lakes: the use of stable isotopes of mercury. *Environ. Pollut.* 134, 13–22 (2005).
105. de Moura, J. F. *et al.* Mercury Status of the Amazon Continental Shelf: Guiana Dolphins (Sotalia guianensis, Van Benédén 1864) as a Bioindicator. *Bull. Environ. Contam. Toxicol.* 89, 412–418 (2012).
106. Markert, B. Definitions and principles for bioindication and biomonitoring of trace metals in the environment. *J. Trace Elem. Med. Biol.* 21, 77–82 (2007).
107. Molina, C. I. *et al.* Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of

the Beni River, Bolivian Amazonia. *Sci. Total Environ.* 408, 3382–3391 (2010).
108. Bossart, G. D. Marine mammals as sentinel species for oceans and human health. *Vet. Pathol.* 48, 676–690 (2011).
109. Salinas, C., Cubillos, J. C., Gómez, R., Trujillo, F. & Caballero, S. "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 (2014).
110. Nuñez-Avellaneda, M., Agudelo Córdoba, E. & Gil-Manrique, B. D. Un análisis descriptivo de la presencia de mercurio en agua, sedimento y peces de interés socioeconómico en la Amazonia Colombiana. *Rev. Colomb. Amaz.* 7, 149–159 (2014).
111. Mosquera-Guerra, F., Trujillo, F., Díaz-Granados, M. C. & Mantilla-Meluk, H. Conservación de delfines de río (Inia geoffrensis y Sotalia fluviatilis) en los ecosistemas acuáticos de la Amazonia y Orinoquia en Colombia. *Momentos Cienc.* 12, 77–86 (2015).
112. Mosquera-Guerra, F. *et al.* Mercury in populations of River Dolphins of the Amazon and Orinoco Basins. *Ecohealth* 16, 743–758 (2019).
113. Passos, C. J. S. & Mergler, D. Human mercury exposure and adverse health effects in the Amazon: a review. *Cad. Saude Publica* 24, s503–s520 (2008).
114. Couceiro, S. R. M., Forsberg, B. R., Hamada, N. & Ferreira, R. L. M. Effects of an oil spill and discharge of domestic sewage on the insect fauna of Cururu stream, Manaus, AM, Brazil. *Brazilian J. Biol.* 66, 35–44 (2006).
115. Couceiro, S. R. M., Hamada, N., Ferreira, R. L. M., Forsberg, B. R. & da Silva, J. O. Domestic sewage and oil spills in streams: effects on edaphic invertebrates in flooded forest, Manaus, Amazonas, Brazil. *Water. Air. Soil Pollut.* 180, 249–259 (2007).
116. Couceiro, S. R. M., Hamada, N., Luz, S. L. B., Forsberg, B. R. & Pimentel, T. P. Deforestation and sewage effects on aquatic macroinvertebrates in urban streams in Manaus, Amazonas, Brazil. *Hydrobiologia* 575, 271–284 (2007).
117. Couceiro, S. R. M., Hamada, N., Forsberg, B. R. & Padovesi-Fonseca, C. Trophic structure of macroinvertebrates in Amazonian streams impacted by anthropogenic siltation. *Austral Ecol.* 36, 628–637 (2011).
118. Martins, R. T., Couceiro, S. R. M., Melo, A. S., Moreira, M. P. & Hamada, N. Effects of urbanization on stream benthic invertebrate communities in Central Amazon. *Ecol. Indic.* 73, 480–491 (2017).
119. Gerolin, C. R. *et al.* Microplastics in sediments from Amazon rivers, Brazil. *Sci. Total Environ.* 749, 141604 (2020).
120. Martinelli Filho, J. E. & Monteiro, R. C. P. Widespread microplastics distribution at an Amazon macrotidal sandy beach. *Mar. Pollut. Bull.* 145, 219–223 (2019).
121. Andrade, M. C. *et al.* 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. Pollut.* 244, 766–773 (2019).
122. Pegado, T. de S. e S. *et al.* First evidence of microplastic ingestion by fishes from the Amazon River estuary. *Mar. Pollut. Bull.* 133, 814–821 (2018).
123. Besseling, E., Redondo-Hasselerharm, P., Foekema, E. M. & Koelmans, A. A. Quantifying ecological risks of aquatic micro- and nanoplastic. *Crit. Rev. Environ. Sci. Technol.* 49, 32–80 (2019).
124. Rochman, C. M., Hoh, E., Kurobe, T. & Teh, S. J. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Sci. Rep.* 3, 3263 (2013).
125. Finer, M. & Jenkins, C. N. Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes-Amazon connectivity. *PLoS One* 7, e35126 (2012).
126. Chen, G., Powers, R. P., de Carvalho, L. M. T. & Mora, B. Spatiotemporal patterns of tropical deforestation and forest degradation in response to the operation of the Tucuruí hydroelectric dam in the Amazon basin. *Appl. Geogr.* 63, 1–8 (2015).
127. Lees, A. C., Peres, C. A., Fearnside, P. M., Schneider, M. & Zuanon, J. A. S. Hydropower and the future of Amazonian biodiversity. *Biodivers. Conserv.* 25, 451–466 (2016).
128. Fearnside, P. M. Amazon dams and waterways: Brazil's Tapajós Basin plans. *Ambio* 44, 426–439 (2015).
129. Arima, E. Y., Richards, P., Walker, R. & Caldas, M. M. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environ. Res. Lett.* 6, 24010 (2011).
130. Fearnside, P. M. Avança Brasil: Environmental and social consequences of Brazil's planned infrastructure in Amazonia. *Environ. Manage.* 30, 735–747 (2002).
131. Fearnside, P. Brazil's Madeira River dams: A setback for environmental policy in Amazonian development. *Water Altern.* 7, 235–255 (2014).
132. Fearnside, P. M. Impacts of Brazil's Madeira River Dams: Unlearned lessons for hydroelectric development in Amazonia. *Environ. Sci. Policy* 38, 164–172 (2014).
133. Fearnside, P. Brazil's Bem Querer dam: An impending Amazon disaster (commentary). *Mongabay Series: Amazon Conservation* (2020).
134. Anderson, E. P. *et al.* Energy development reveals blind spots for ecosystem conservation in the Amazon Basin. *Front. Ecol. Environ.* 17, 521–529 (2019).
135. Sánchez-Cuervo, A. M. *et al.* Twenty years of land cover change in the southeastern Peruvian Amazon: implications for biodiversity conservation. *Reg. Environ. Chang.* 20, 8 (2020).
136. Finer, M., Villa, L. & Mamani, N. Gold mining continues to ravage the Peruvian Amazon. *Amazon Conservation* (2018).