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REVIEW

Translating science into actions to conserve Amazonian freshwaters

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Abstract

Despite the importance of freshwater ecosystems to social-ecological systems of the Amazon, conservation in the region historically has focused on terrestrial ecosystems. Moreover, current information on pressing management and conservation needs specific to freshwaters is scattered across multiple disciplines and generally focused on particular threats, habitats, and taxa. This disparateness of information limits the ability of researchers and practitioners to set priorities and implement actions that comprehensively address challenges faced by freshwater ecosystems. To reduce this research-implementation gap, we reviewed the scientific literature on Amazon freshwater conservation to identify pressing actions to be taken and potential directions for their implementation. We identified 63 actions gleaned from 174 publications. These were classified into six major themes: (i) implement environmental flows, (ii) improve water quality, (iii) protect and restore critical habitats, (iv) manage exploitation of freshwater organisms, (v) prevent and control invasive species,

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and (vi) safeguard and restore freshwater connectivity. Although each action may face different implementation challenges, we propose three guiding principles to support action planning and decisions on-the-ground. We conclude with a reflection on potential future directions to place freshwaters into the center of policies and agreements that target the conservation of the Amazon.

KEYWORDS

Amazon Basin, aquatic ecosystems, conservation actions, conservation planning, freshwater biodiversity

1 | INTRODUCTION

Conserving the Amazon, the largest river basin and tropical forest in the world, is a global priority in the endeavors to mitigate climate change and biodiversity loss (Dinerstein et al., 2019; Lapola et al., 2023). Maintaining functional and biodiverse freshwater ecosystems is central to these efforts. Freshwaters of the Amazon are among the most biodiverse and productive on Earth, hosting nearly 15% of global freshwater fish biodiversity and hundreds of other aquatic and semi-aquatic life forms (Jézéquel et al., 2020a; Lessmann et al., 2016; Winemiller et al., 2016). Moreover, Amazonian freshwaters sustain local economies and food supplies, underpin livelihoods, and signify sociocultural connections to the environment for approximately 47 million people that live in the Amazon Basin (Athayde et al., 2021; RAISG, 2020). Key ecosystem services like inland fisheries, transportation, soil fertility, and clean water are provided by freshwater environments (Jackson et al., 2022; Lopes et al., 2021). Consequently, promoting more sustainable practices in the region requires looking beyond the protection of terrestrial ecosystems and also supporting freshwater conservation (Anderson, Osborne, et al., 2019; Castello et al., 2013; Leal et al., 2020).

Growing threats to freshwater ecosystems are transforming the way Amazonian people live and interact with the environment (Castello et al., 2013; Castello & Macedo, 2016; Doria et al., 2018). Hundreds of hydropower dams have fragmented riverscapes, regulated water flows, and modified aquatic and terrestrial habitats, with many new hydropower projects under way (Flecker et al., 2022; Timpe & Kaplan, 2017). Expanding deforestation and agriculture have disturbed riparian ecosystems and decreased water quality, particularly around the arc of deforestation in the southeast Amazon (Dala-Corte et al., 2020; Macedo et al., 2013; Neill et al., 2013). Mining and oil drilling have expanded in different locations, eroding riverbanks, diverting water, and polluting soils and rivers (Anderson, Osborne, et al., 2019; Capparelli et al., 2021; Gerson et al., 2020). Overexploitation, habitat alteration, and species introductions have threatened freshwater organisms (Castello et al., 2013; Doria et al., 2021; Prestes et al., 2022), including river dolphins (*Inia geoffrensis* and *Sotalia fluviatilis*) and economically important fish species like the tambaqui (*Colossoma macropomum*) (Brum et al., 2021; Tregidgo et al., 2017). Climate change and increasingly common extreme hydrological events have already produced unprecedented humanitarian and environmental emergencies (Beveridge et al., 2024; Ottoni et al., 2023; Santos de Lima et al., 2024). All these impacts are expected to grow in the future, reinforcing the urgent need to strengthen conservation planning in the Amazon through the lens of freshwater ecosystems.

Many current conservation strategies for the Amazon focus on a protected areas approach applied to the terrestrial realm. These approaches do not necessarily result in commensurable conservation benefits for freshwater ecosystems (Anderson, Osborne, et al., 2019; Castello et al., 2013; Leal et al., 2020). For instance, few protected areas in the Amazon are designed to conserve floodplains and major river mainstems, fish spawning grounds and migratory corridors, or the geographic range of strictly freshwater species (Azevedo-Santos et al., 2019; Duponchelle et al., 2021; Frederico et al., 2018). Particularities of freshwater ecosystems make specific considerations necessary to produce solid conservation outcomes. Examples include the seasonality and directionality of water flows, the hierarchical spatial configuration of river networks, the confinement of aquatic biota to wet environments, and the strong reliance of people on riverine ecosystem services like food, water, and transportation (Anderson et al., 2019; Antunes et al., 2016; Azevedo-Santos et al., 2019; Tonkin et al., 2018). Without considering these needs, existing conservation portfolios will continue to miss the mark for freshwaters.

There have been efforts to set conservation priorities and plan strategies focused on freshwater ecosystems at the global level (Arthington, 2021; Darwall et al., 2018; Tickner et al., 2020). However, to avoid the "research-implementation gap" that is recurrent in conservation

(Knight et al., 2008), tailoring these priorities and strategies will require their adaptation to the unique context of the Amazon. We see three major challenges: First, the basin's size is enormous and encompasses a diversity of political, geographical, ecological, and social contexts. The Amazon Basin alone covers an area of 6,300,000 km^2—more than a third of the South American continent—and extends through part of seven different countries and a French territory across an elevation range of more than 6000 m (Encalada et al., 2019; Goulding, 2003; Venticinque et al., 2016). Second, published scientific information is limited for some topics and locations, where major gaps of basic ecological, taxonomic, and biogeographic information persist (Carvalho et al., 2023; Herrera-R et al., 2023; Jézéquel et al., 2020b). Third, the Amazon is amid rapid transformations. Deforestation, infrastructure development, and climate change are already well underway, with further widespread and irreversible impacts associated with new dams, roads, and changing land use expected in the coming decades (Castello et al., 2013; Flecker et al., 2022; Lapola et al., 2023). These impacts can forever change the Amazon as we know it, with widespread consequences for Earth's ecosystem functions and services.

Here, we explore conservation actions that are critical for the long-term persistence of freshwater ecosystems of the Amazon Basin. Through a comprehensive review of the scientific literature and inputs from all the authors (i.e., scientists and practitioners with many years of experience working in the Amazon), we (i) identified and mapped the most pressing problems threatening Amazonian freshwater ecosystems, actions needed, and actors and stakeholders involved, (ii) established three guiding principles for effective conservation planning that integrates across the Amazon's wide socio-ecological complexities, and (iii) examined practical outcomes of policies and interventions to highlight opportunities and momentum for freshwater conservation. These three components constitute initial steps toward broad spatial conservation planning focused on Amazon freshwaters (Tallis et al., 2021; Tickner et al., 2017).

2 | LESSONS FROM THE LITERATURE

2.1 | Identifying problems, defining actions, and mapping actors

We conducted a comprehensive review of the scientific literature on Amazon freshwater conservation to identify challenges to advancing environmental conservation and to map actions to address them. We created a shared library among a panel of scientists based on individual panelist searches and personal collections. This panel was initially composed of six researchers and then gradually expanded to include all co-authors of the present study—the final panel included ecologists, hydrologists, fishery scientists, and conservation practitioners with professional experience in the Amazon. This gradual expansion allowed for an iterative process where researchers with diverse backgrounds and research experiences could evaluate the scope of the shared library and contribute to it based on their own expertise. Scientific contributions that did not address practical conservation issues nor clearly articulate management implications were not part of the library. Although the shared library includes a few key reports from the gray literature and publications in Portuguese and Spanish, most of the literature examined was retrieved from peer-reviewed sources in English.

Based on the "Bending the Curve of Freshwater Biodiversity" framework (Arthington, 2021; Tickner et al., 2020), we categorized the scientific literature into six major themes for action: (i) implement environmental flows, (ii) improve water quality, (iii) protect and restore critical habitats, (iv) manage exploitation of freshwater biodiversity, (v) prevent and control invasive species, and (vi) safeguard and restore freshwater connectivity. This framework was developed as a global emergency recovery plan for freshwaters and represents the most up-to-date effort to organize conservation action needs. After categorizing the publications, we summarized the main findings and recommendations emerging from each paper. Based on these recommendations, we subsequently proposed a set of conservation actions and assigned potential actors and stakeholders involved in each. Actors are defined here as the parties responsible for designing and implementing a conservation action, while the stakeholders are the parties that can influence or be impacted by an action (Tallis et al., 2021). Actors and stakeholders were identified by our expert panel based on the readings and examples from practical experience.

This process resulted in a list of 63 conservation actions derived from 174 scientific publications, which were grouped into 17 overarching action categories (Tables 1 and S1, Supporting Information). The number of actions by theme ranged from five for the theme "prevent and control invasive species" to 15 for "protect and restore critical habitats." We also identified sets of actions that could simultaneously meet multiple conservation objectives and relate to more than one theme. For instance, 18 actions were directly linked to hydropower planning and operations, and another 11 were related to deforestation and riparian vegetation integrity. Also, throughout this exercise, we identified 15 different actors

TABLE 1 Examples of pressing conservation actions drawn from the scientific literature on Amazonian freshwater conservation and revised based on expert judgment.

Theme	Action category	Examples of conservation actions	References
(1) Implement environmental flows	Improve policies, regulations and guidelines on environmental flows (8)	• Strengthen policies and regulations on flow management with the support of the best science available	Benetti et al. (2004), Anderson et al. (2011), Santos and Cunha (2013), Pinto et al. (2016), and Timpe and Kaplan (2017)
		• Recognize and value local ecological knowledge to develop and assess environmental flow requirements	Hallwass et al. (2013), Santos et al. (2020), Doria, Dutka-Gianelli, et al. (2021), and Utsunomiya et al. (2024)
	Expand ecohydrologic monitoring (4)	• Improve hydrologic monitoring across the Amazon Basin through installation and maintenance of gauges	Latrubesse and Restrepo (2014), Timpe and Kaplan (2017), Siqueira et al. (2018), Fagundes et al. (2021), and Siddiqui et al. (2021)
		• Support continuous long-term hydroecological monitoring to better predict future impacts of flow alteration on biodiversity	Röpke et al. (2017) and Correa et al. (2022)
(2) Improve water quality	Manage urban waste (3)	• Expand the collection and treatment of sewage in large urban centers	Couceiro et al. (2007), Fabregat-Safont et al. (2021), and Rico et al. (2021)
		• Implement policies/regulations and initiatives of source control and removal of plastics	Pegado et al. (2018), Andrade et al. (2019), Giarrizzo et al. (2019), Gerolin et al. (2020), Ribeiro-Brasil et al. (2020), and Lucas-Solis et al. (2021)
	Regulate mining and oil exploration (3)	• Regulate gold mining activities, enforcing appropriate management, mitigation, and compensation of impacts	Swenson et al. (2011), Asner et al. (2013), Diele-Viegas et al. (2020), Gerson et al. (2020), Quijano-Vallejos et al. (2020), and Capparelli et al. (2021)
	Buffer negative effects of agriculture (3)	• Incentivize and enforce sustainable agriculture and soil management practices	Neill et al. (2001), Biggs et al. (2004), Biggs et al. (2006), Neill et al. (2017), and Riskin et al. (2017)
		• Improve regulations and measures of education, risk management, and contamination mitigation associated to pesticides	Waichman et al. (2002), Schiesari et al. (2013), Rico et al. (2022), Lima-Junior et al. (2024)
(3) Protect and restore critical habitats	Expand protected areas in critical locations (9)	• Improve the protection of endemic and threatened fish species, especially in upland regions where protected areas are insufficient	Frederico et al. (2018), Tognelli et al. (2019), Doria, Athayde, et al. (2020), Doria, Catâneo, et al. (2020), Jézéquel et al. (2020b), and Frederico et al. (2021)
		• Expand areas designated for community-based management across the Amazon lowlands	Fagundes et al. (2016), Campos-Silva et al. (2018), Norris et al. (2019), Freitas, Lopes, et al. (2020), Campos-Silva, Peres, Hawes, et al. (2021), and Lopes et al. (2021)
	Reduce riparian deforestation (3)	• Protect and restore riparian buffers in headwater streams to maintain functional freshwater ecosystems	Leal et al. (2018), Dala-Corte et al. (2020), and Martins et al. (2021)
	Strengthen regulations for protected areas (3)	• Prevent the downsizing, downgrading, and degazettement of protected areas fueled by mining, land use, and hydropower expansion	Pack et al. (2016), Anderson, Osborne, et al. (2019), and Mandai et al. (2024)
		• Increase recognition of indigenous cultures and territorial rights of Indigenous peoples, including subsurface mineral rights	Anderson, Osborne, et al. (2019)

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TABLE 1 (Continued)

Theme	Action category	Examples of conservation actions	References
(4) Manage exploitation of freshwater organisms	Manage fisheries at multiple levels of organization (5)	• Implement transnational cooperation agreements to manage fisheries at broad spatial scales	Maldonado et al. (2017), Goulding et al. (2019), Doria, Athayde, et al. (2020), and de Sousa et al. (2021)
		• Reinstate national and state-level leadership in assessing fishery stocks	Prestes et al. (2022)
		• Implement participatory governance and co-management agreements to advance social and conservation objectives	Almeida et al. (2009), Silvano et al. (2014), Campos-Silva and Peres (2016), Petersen et al. (2016), Campos-Silva et al. (2018), Campos-Silva et al. (2019), Freitas, Lopes, et al. (2020), Campos-Silva, Peres, Hawes, et al. (2021), Lopes et al. (2021), Medeiros-Leal et al. (2021), and Gurdak et al. (2022)
	Engage diverse stakeholders (3)	• Promote the consumption of well-managed wild fish species to advance human nutrition and food system sustainability	Freitas, Lopes, et al. (2020), Heilpern, DeFries, et al. (2021), and Heilpern, Fiorella, et al. (2021)
	Combat illegal exploitation and trade of endangered species (3)	• Enforce bans on use of river dolphin and caiman flesh for bait in piracatinga fisheries (*Calophysus macropterus*)	Brum et al. (2015) and Brum et al. (2021)
	Implement ecosystem-based management (3)	• Incorporate the synergetic impacts of exploitation with other ecological alterations into fisheries management (e.g., flow alteration, deforestation)	Doria et al. (2018), Fabré et al. (2012), Santos et al. (2018), Doria, Dutka-Gianelli, et al. (2021), Lopes et al. (2024)
(5) Prevent and control invasive species	Manage established invasives (2)	• Monitor and manage populations of *Arapaima gigas* on its invasion range in Northern Bolivia, Southern Peru, and Northwest Brazil (Rondônia State)	Miranda-Chumacero et al. (2012), Van Damme et al. (2015), Doria, Catâneo, et al. (2020), and Catâneo et al. (2022)
		• Assess and manage rainbow trout (*Oncorhynchus mykiss*) invasions in the Andean-Amazon	Ortega et al. (2007), Anderson and Maldonado-Ocampo (2011), Martín-Torrijos et al. (2016), Mouillet et al. (2018), and Carvajal-Vallejos et al. (2020)
	Regulate primary introduction pathways (3)	• Prevent new policies, decrees and regulations aiming to boost exotic fish farming	Pelicice et al. (2014), Padial et al. (2017), and Garcia et al. (2022)
		• Improve and enforce regulations on ballast water exchange	Uliano-Silva et al. (2013), Pereira et al. (2014), and Moutinho (2021)
(6) Safeguard and restore freshwater connectivity	Improve hydropower siting via strategic planning (1)	• Improve strategic planning for new dams, carefully balancing trade-offs between hydropower benefits and impacts on social-ecological systems	Finer and Jenkins (2012), Winemiller et al. (2016), Forsberg et al. (2017), Latrubesse et al. (2017), Anderson et al. (2018), Couto et al. (2021), Almeida et al. (2022), and Flecker et al. (2022)
	Mitigate impacts of existing infrastructure (4)	• Safeguard remaining free-flowing rivers that link the Andes and the Amazon lowlands	McClain and Naiman (2008), Finer and Jenkins (2012), Forsberg et al. (2017), Anderson et al. (2018), and Caldas et al. (2023)
		• Improve the efficiency and expand monitoring of fish passages	Hahn et al. (2019), Hauser et al. (2019), Van Damme et al. (2019), and Hahn et al. (2022)
	Oversee small artificial barriers (3)	• Strength policies and regulations on small hydropower to address their cumulative impacts on social-ecological systems	Athayde et al. (2019) and Couto et al. (2021)

(Continues)

TABLE 1 (Continued)

Theme	Action category	Examples of conservation actions	References
		• Restore river connectivity and mitigate the impacts of road-crossings with best engineering practices and appropriate culvert/bridge designs	Keller et al. (2015), Leal et al. (2016), Brejão et al. (2020), and Rosa et al. (2021)

Note: The actions were grouped in six different themes following Tickner et al. (2020). A total of 17 overarching action categories emerged from a list of 63 conservation actions derived from 174 scientific publications (number of conservation actions per category in parenthesis). The full list of actions is available in Table S1.

responsible for implementing the actions and an additional 36 categories of stakeholders that could be subjected to these actions (Table S1). The list of actors includes multiple levels of governmental agencies and regulatory/enforcement institutions, civil society organizations, and industry. Finally, we identified a diverse list of stakeholders that span from local communities to the private sector and consumers.

2.2 | Pressing problems and actions by theme

2.2.1 | Theme 1: Implement environmental flows

Environmental flows (or e-flows) are defined as "the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being" (Arthington et al., 2018). Eight of the 12 actions in this theme focused on advancing policies, regulations, and guidelines on e-flows (Tables 1 and S1). Despite existing evidence of major changes in river flows and floods in the Amazon Basin due to hydropower, deforestation, and climate change (Arias et al., 2020; Dalagnol et al., 2017; Timpe & Kaplan, 2017), policies and regulations in most Amazonian countries are just emerging to appropriately manage e-flows (Anderson et al., 2011; Timpe & Kaplan, 2017). There are differences in the legal and institutional frameworks among Amazonian countries, as well as in their capacity for implementation of e-flows (Anderson et al., 2011). For example, Colombia and Ecuador explicitly mention e-flows in their regulatory frameworks, yet practical standards and guidelines for e-flow assessments remain under development (Anderson et al., 2011; Boodoo et al., 2014; Rosero-López et al., 2019). Bolivia and Peru, in contrast, have water use laws that make no reference to e-flows, albeit new water agencies and initiatives were established to regulate flow management (ANA, 2019; Anderson et al., 2011). In Brazil, although the federal constitution and supplementary laws establish that water use must guarantee the integrity of ecosystems and should prioritize basic human needs, government agencies often have granted water use rights as percentages of residual flows (e.g., $Q_{7,10}$)—a method exclusively based on historical hydrological records that is unable to capture basic ecosystem needs (Benetti et al., 2004; Pinto et al., 2016; Santos & Cunha, 2013).

Limited recognition of e-flows can lead to negative consequences for ecosystems and conflicts with local communities in regulated rivers. Perhaps one of the most controversial cases involving deficient flow allocation strategies in the Amazon is the Belo Monte hydropower dam (11 gigawatts). It started operating in 2016, diverting water from a 100-km section of the mainstem Xingu River in the Volta Grande region, Brazil (Fearnside, 2017). Although the proposed allocation hydrographs are suggestively named as the "consensus hydrographs" by the operator, independent assessments conducted by and with the participation of local communities highlighted that they do not allocate enough flow to support ecosystems (e.g., fish and turtle reproduction), and the needs of Indigenous Peoples and Local Communities (e.g., fisheries, transportation) (Lopes et al., 2024; Utsunomiya et al., 2024; Zuanon et al., 2020). Stakeholder disagreement over the proposed compensation flows shown in the consensus hydrographs was the subject of a series of judicial battles until the beginning of 2021, when, after intense political pressure from the federal government, they were ultimately implemented. Residents of the Volta Grande witnessed an abrupt 85% flow reduction in the mainstem Xingu River to fuel Belo Monte operations, which resulted in unprecedented low flows and fish kills (Higgins, 2021; Moutinho, 2023). The future of Volta Grande is still uncertain, but many of these impacts can be mitigated with the implementation of e-flows, especially with the adoption of guidelines that incorporate human-flow relationships and local ecological knowledge (Anderson et al., 2019; Hallwass et al., 2013; Santos et al., 2020). As disputes around hydropower and e-flows are expected to escalate under future climate change scenarios (Almeida et al., 2021;

Arias et al., 2020), strong mitigation measures for water allocation become urgent. Ideally, the challenges and costs of these measures should be considered prior to new hydropower construction, preventing unfeasible projects (Flecker et al., 2022).

The need for better ecohydrological monitoring emerged explicitly in five actions along the e-flows theme (Tables 1 and S1), with the installation and maintenance of gauges being the most basic action to be taken for rivers across the Amazon (Krabbenhoft et al., 2022). Although recent research has expanded the coverage of hydrologic assessments in the Amazon, important areas are not being adequately monitored by stream gauges, adding uncertainties to hydrologic models (Fleischmann et al., 2022; Siddiqui et al., 2021; Siqueira et al., 2018; Vuille et al., 2008). In addition, most monitoring and management approaches tend to be restricted to surface waters with limited integration with other components of the water cycle like evapotranspiration, precipitation and groundwater (Bagheri et al., 2023; Beveridge et al., 2024; Heerspink et al., 2020). The monitoring of precipitation and glacier melting in the tropical Andes, for example, has received only limited attention by scientists and policy makers until recently, although evidence suggests that Andean glaciers have been retreating at an increasing rate since the 1970s and some may even disappear this century (Rabatel et al., 2013; Vuille et al., 2008). Another limitation in current monitoring efforts is the dearth of long-term biological information, in which existing data is rarely long enough to allow rigorous inferences on key ecohydrological relationships (but see Bayley et al., 2018; Castello et al., 2019; Röpke et al., 2017). The implementation of long-term ecosystem monitoring protocols is critical to better understand, model, and manage broad-scale flow-ecosystem relationships and should be considered a priority (Correa et al., 2022).

2.2.2 | Theme 2: Improve water quality

Actions for this theme fit within three primary categories: Manage urban waste, regulate mining activities, and buffer negative effects of agriculture (Tables 1 and S1). Expanding collection and treatment of sewage and implementing measures of source-control and removal of aquatic debris (e.g., plastics) are examples of actions that are essential to improve water quality in the Amazon, especially near rapidly urbanizing regions like Belém, Iquitos, and Manaus (Gerolin et al., 2020; Giarrizzo et al., 2019; Rico et al., 2021). Limited sewage systems and solid waste management are prevalent issues in urban centers of the Amazon. For instance, only 20%–50% of households in large urban areas in the Brazilian Amazon (e.g., Belém, Manaus, Macapá) are connected to a sewage system, and nearly 90% of the total wastewater produced in these areas is discharged untreated into freshwater ecosystems (Costa & Brondízio, 2011; KPMG/ABCON, 2020). Consequently, significant loads of human waste such as raw sewage, plastic debris, heavy metals, and pharmaceuticals have been detected in Amazonian rivers (Fabregat-Safont et al., 2021; Gerolin et al., 2020; Rico et al., 2021). These pollutants have negative impacts on freshwater biodiversity and are detected across the whole basin, from the headwaters to the estuary (Andrade et al., 2019; Pegado et al., 2018; Rico et al., 2021). Advancing urban waste management in the Amazon involves considerable public and private investments and requires long-term planning that anticipates future urban development (Gauthier & Moran, 2018). Estimates indicate that nearly 6 billion US dollars would be required to universalize sewage systems just in the seven states of the North of Brazil by 2033 (KPMG/ABCON, 2020). This required investment underscores the economic challenges associated with managing pollution and waste in a rapidly urbanizing Amazon.

Three actions on implementing and enforcing regulations on mineral extraction emerged from our review (Tables 1 and S1). Mining and oil exploration pose threats to water quality and freshwater biodiversity due to contamination derived from poor tailing management and spills of raw materials and byproducts (Anderson, Osborne, et al., 2019; Azevedo-Santos et al., 2021; Finer et al., 2015). Actions for regulating widespread gold mining have a high priority. Legal and illegal gold mining have boomed across the Amazon (e.g., Madre de Dios, Peru) following increases in gold prices internationally and the deregulation of the sector (Asner et al., 2013; Diele-Viegas et al., 2020; Swenson et al., 2011). Estimates suggest that more than 500,000 people are actively engaged in artisanal and small-scale gold mining in the Amazon, often employing rudimentary techniques and working in poorly regulated conditions (Quijano-Vallejos et al., 2020). Water quality in gold mining areas is often poor, with high concentrations of Hg and other metals like Ag, Al, As, Cd, Cu, Fe, Mn, Pb, and Zn in water and V, B, and Cr in sediments (Capparelli et al., 2021; Gerson et al., 2020). Moreover, mercury contamination in fish and people has been reported in different locations, including among Indigenous people in remote areas, as a consequence of the ubiquitous nature of small-scale gold mining (Azevedo-Santos et al., 2021; da Silva & Lima, 2020; Martoredjo et al., 2024; Olivero-Verbel et al., 2016).

The impacts of mineral extraction on freshwater ecosystems are not restricted to small-scale activities, and the need for actions enforcing good practices for managing tailings and other mining wastes also applies to licensed mining operations. The Amazon contains world-class deposits of gold and other valuable minerals like bauxite, copper, tin, nickel, iron ore, manganese, oil, and gas, which are also explored and exported, often by large international corporations (Finer et al., 2015; Quijano-Vallejos et al., 2020; Tófoli et al., 2017). Although large-scale mining and oil-drilling operations occur in legal concessions and employ modern technologies, they do not necessarily follow the best practices of environmental management and mitigation (Anderson, Osborne, et al., 2019; Fearnside, 2016; Villén-Pérez et al., 2018). For instance, the western Amazon (e.g., Ecuador, Peru, Bolivia) has been subjected to intense oil exploration, and consequently, spills and pipeline leaks are commonplace in some areas, threatening freshwater ecosystems and affecting the livelihoods of Indigenous and local communities (Azevedo-Santos et al., 2016; Finer et al., 2008).

Expanding deforestation and agriculture are also sources of poor water quality in the Amazon, requiring actions to buffer their impacts in rural areas (Tables 1 and S1). Incentivizing and enforcing more sustainable land use practices are essential to safeguard the quality of water (Melack & Coe, 2021; Neill et al., 2013; Riskin et al., 2017). The conversion of native vegetation into pasture and crops increases erosive processes and siltation, reduces infiltration rates, and modifies concentrations of dissolved and particulate matter in streams (Biggs et al., 2004; Neill et al., 2001; Riskin et al., 2017). These effects are exacerbated by detrimental land use practices like hillslope and riparian deforestation and the lack of pasture rotation—common practices in the arc of deforestation where rural expansion follows a cycle of colonization of new areas and abandonment of old pastures (Biggs et al., 2006; Ferrante et al., 2021). In addition, there is a need for improving regulations and measures of education, risk management and contamination mitigation associated with pesticides, which involve governments, NGOs, industries, producers and consumers. Pesticides are often indiscriminately used throughout the Amazon, posing risks to the environment and human health due to overuse and inadequate manipulation (Rico et al., 2022; Schiesari et al., 2013; Waichman et al., 2002). Although this lack of control urges regulatory measures, recent policies and regulations are going in the opposite direction with hundreds of new pesticides being approved for use every year and their trade deregulated (Coelho et al., 2019). It is important to highlight that water quality issues can be manifested basinwide. For instance, nearly 10,000 small farm impoundments exist in the Upper Xingu, most of them located in pasture and soybean crop areas (Macedo et al., 2013). These aggregates of small impoundment were found to have major effects on water thermal regimes at the basin-level, with streams crossing crops and pastures being on average 3°C to 4°C warmer than forested streams. Conserving riparian buffers and properly managing stream flows are among the most effective actions to mitigate thermal and other types of water pollution in areas of intense land use (Ilha et al., 2018; Macedo et al., 2013; Nóbrega et al., 2020).

2.2.3 | Theme 3: Protect and restore critical habitats

Expanding the protection of areas in critical locations for biodiversity emerged in nine actions for this theme, which is then followed by limiting riparian deforestation and strengthening regulations for protected areas with three actions each (Tables 1 and S1). Although the Amazon stands out globally for its freshwater biodiversity and rich social-ecological systems linked to rivers, few protected areas were designed to specifically conserve freshwater ecosystems (Azevedo-Santos et al., 2019; Leal et al., 2020). Limitations of the current protected area network reflect the lack of congruence with areas of highest priority from the perspective of freshwater biodiversity. For instance, areas of greatest diversity and endemism of freshwater fish species remain largely unprotected, mainly at higher elevation riverscapes in the Andean Amazon (e.g., Upper Marañon) and the Brazilian Shield (e.g., Chapada dos Parecis, Serra do Cachimbo, Upper Tocantins) (Dagosta et al., 2021; Frederico et al., 2018; Jézéquel et al., 2020b; Tognelli et al., 2019). These regions coincide with hotspots of deforestation and hydropower proliferation, making actions to expand protected areas even more urgent (Dagosta et al., 2021; Flecker et al., 2022).

Fortress conservation models, that is, based on the exclusion of local people from protected areas, in some cases with violence and rights violations—have produced undesirable outcomes worldwide under the pretenses of promoting conservation (Domínguez & Luoma, 2020). Alternative models such as the ones based on community-based management have emerged as more appropriate governance designs for occupied areas of the Amazon, creating opportunities for expanding freshwater conservation led by and supported by local communities (Lopes et al., 2021). These models are centered on the co-management (i.e., collaborative management) of key natural resources (e.g., fisheries, fruits, nuts) with the guidance of ancestral knowledge and practices formalized in management plans of extractive reserves and Indigenous Territories. Actions to expand these models are promising to advance freshwater conservation in the

Amazon lowlands; areas that have been historically more densely populated and vulnerable to human impacts like deforestation and overexploitation, and still lack coverage in the current protected area network (Antunes et al., 2016; Costa & Brondízio, 2011; Norris et al., 2019). Evidence from the Juruá sub-basin indicates that community-based management can benefit not only the target species to be managed, but also entire ecosystems, meeting concomitantly multiple conservation and socio-economic goals (Campos-Silva et al., 2018; Campos-Silva, Peres, Amaral, et al., 2021; Campos-Silva, Peres, Hawes, et al., 2021).

Riparian and catchment vegetation plays a critical role in the maintenance of freshwater ecosystem functions and services in the Amazon, being directly linked to biodiversity conservation in streams (Brejão et al., 2018; Dala-Corte et al., 2020), and fisheries productivity in floodplains (Arantes et al., 2019; Castello et al., 2018). Actions aiming to protect and restore riparian buffers are among the most important to conserve freshwater ecosystems. Evidence suggests that even small levels of disturbance in catchment vegetation (natural vegetation coverage <80%) can result in detectable changes in freshwater ecosystems in low order streams (1st to 3rd) of the Amazon (Brejão et al., 2018; Dias et al., 2010; Leal et al., 2016, 2018). Riparian buffers of at least 50-m wide are required to provide the minimum levels of protection to biodiversity in these streams, with buffers larger than 100-m being highly desirable, particularly in less vegetated catchments (Dala-Corte et al., 2020). Although most Amazonian countries have regulations mandating the protection of riparian zones, poor enforcement and recent deregulation undermine riparian conservation (Durigan et al., 2013; Meli et al., 2019; Nunes et al., 2015). For instance, changes in the Brazilian Forest Code in 2012 reduced the minimum radius of riparian buffers with mandated protection and failed to regulate deforestation at the catchment-level (Leal et al., 2018). This is one case of a process described as the downsizing, downgrading and degazettement of protected areas (PADDD), which is often driven by activities that are directly linked to freshwater degradation such as hydropower, deforestation and mining (Anderson, Osborne, et al., 2019; Mandai et al., 2024; Pack et al., 2016). This case highlights the need for measures that go beyond expanding protected areas and focus on strengthening the legal backing to prevent PADDDs.

2.2.4 | Theme 4: Manage exploitation of freshwater organisms

There is evidence to state that overexploitation of freshwater species is widespread in the Amazon due to long-lasting periods of intense fishing, hunting and poaching pressure (Antunes et al., 2016; Heilpern et al., 2022; Prestes et al., 2022). For this theme, most actions focus on the need for managing fisheries at multiple levels of organization (i.e., local, national, international), although three other action categories emerged from the literature: Engage diverse stakeholders, combat illegal exploitation of endangered species, and advance ecosystem-based management (Tables 1 and S1). The vast extent of the Amazon Basin and the migratory behavior of most fish species of commercial importance pose difficulties to fisheries management (Goulding et al., 2019). At the higher level, actions to implement transnational cooperation agreements are crucial to properly manage shared fishery stocks and ornamental fisheries (de Sousa et al., 2021; Doria, Athayde, et al., 2020; Maldonado et al., 2017). For instance, one of the most profitable ornamental fisheries targets juveniles of the silver arowana (*Osteoglossum bicirrhosum*) in the tri-border region of Brazil, Colombia and Peru, which is often based on unsustainable practices that involve killing mouth-brooding adults to collect juveniles (Moreau & Coomes, 2006). Each one of these three countries has very distinct regulations and enforcement capabilities for the silver arowana fisheries, ranging from a complete ban in Brazil to closed seasons in Colombia and Peru (Maldonado et al., 2017). These regulatory differences and a lack of transboundary coordination favor illegal fisheries and trade near the borders, adding a false impression of legality to exports targeting international markets in Asia, Europe, and the United States. Although critical to advance fisheries management, the implementation of transnational agreements can be challenging given the complexity of actors and stakeholders involved, and the recent attempts have been characterized by having limited governmental and institutional support (Doria, Athayde, et al., 2020).

At local levels, initiatives employing community-based management have been successful in restoring fish stocks, especially those of higher monetary value and those that do not migrate long distances like the arapaima (*Arapaima* spp.) (Campos-Silva & Peres, 2016; Gurdak et al., 2022). Co-management experiences in several locations of the Amazon reported that stocks of *Arapaima gigas* shifted from depleted to well-managed in just a few years after being implemented (Castello et al., 2009; Campos-Silva & Peres, 2016; Petersen et al., 2016). These positive experiences indicate that actions to implement participatory governance and co-management agreements can successfully advance management objectives at local levels. In addition, by integrating local communities into conservation, co-management experiences can bring concrete economic and social benefits to local people and help to build trust between practitioners and community associations (Campos-Silva & Peres, 2016; Campos-Silva et al., 2018; Campos-Silva, Peres, Hawes, et al., 2021; Freitas, Espírito-Santo, et al., 2020). Although community-based management has been recognized as a promising strategy to improve fisheries and biodiversity management, expanding successful models to new areas of the Amazon will require substantial political will, especially when ensuring territorial collective rights to local Amazonian communities (Lopes et al., 2021).

At international, national, and state levels, evidence suggests that fisheries management in the Amazon has been deficient for many decades (Heilpern et al., 2022; Prestes et al., 2022). Indeed, our literature review failed to identify successful examples of large-scale fisheries management. This issue is particularly concerning for migratory species that depend on vast areas to complete their life cycle—areas that are hardly ever fully contained by single protected areas, communal reserves, or fishing zones (Duponchelle et al., 2021; Goulding et al., 2019; Herrera-R et al., 2024). In this context, measures to reinstate governmental leadership in assessing fishery stocks are necessary to centralize coordination and financing at regional scales (Prestes et al., 2022). Currently, common measures for fisheries management in the Amazon include restrictions of gear and mesh size, minimum fish length and fixed periods for fishing closures. These often fail to advance fisheries sustainability because of their limited scope, restricted adaptive capacity, low stakeholder adherence, and limited enforcement capabilities (Castello et al., 2015; Cavole et al., 2015; Isaac et al., 1998). To overcome these issues, fisheries management needs to cover larger spatiotemporal scales and shift toward more data-driven approaches (Heilpern et al., 2022; Prestes et al., 2022). The monitoring of fish landings and markets is critical to advance these two objectives, and cannot continue relying on monitoring efforts that have been ephemeral, restricted to few places, and often run by independent organizations (Doria et al., 2018; Garcia et al., 2009; Goulding et al., 2019). While governments still struggle to lead broad-scale fisheries monitoring programs, initiatives centered on citizen science and new conservation technologies emerge as promising strategies to centralize information flows in open-source databases and to engage with diverse stakeholders (Citizen Science Network for the Amazon, 2024).

2.2.5 | Theme 5: Prevent and control invasive species

Actions for this theme fit within two major categories: Manage established populations of invasive species and regulate primary introduction pathways (i.e., aquaculture, ballast water) (Tables 1 and S1). A recent inventory identified more than 1300 records of 41 exotic fish species in the Amazon, most of them released by activities related to aquaculture and ornamental trade (Doria et al., 2021; Doria, Agudelo, et al., 2021). Although not all these species may pose significant harm to the environment, there is evidence of social-ecological implications of some introductions, requiring measures of population assessments and control. For instance, *Arapaima gigas* was introduced in the Upper and Middle Madeira in Peru, Bolivia and Brazil (Catâneo et al., 2022; Miranda-Chumacero et al., 2012; Van Damme et al., 2015), likely from releases from local fish farms. This large predator has now expanded its range into parts of the Amazon where it was previously absent, which has led to changes in local fisheries composition, with *A. gigas* being now widely available in local fish markets (Doria, Catâneo, et al., 2020; Miranda-Chumacero et al., 2012; Van Damme et al., 2015). Rainbow trout (*Onchorynchus mykiss*) was introduced in high-elevation streams in the Andes in the 1920s and 1960s for fisheries and aquaculture (Crawford & Muir, 2008). This cold-water species is now widespread in streams and lakes above 1000 m in Colombia, Ecuador, Peru, and Bolivia (Anderson & Maldonado-Ocampo, 2011; Carvajal-Vallejos et al., 2020; Mouillet et al., 2018; Ortega et al., 2007), threatening endemic species of fish and frogs and disturbing aquatic food webs (Martín-Torrijos et al., 2016; Mouillet et al., 2018). Although necessary, managing problematic invasions alone is not effective without regulating primary introduction pathways. New political attempts to boost aquaculture of non-native fish species like the Nile tilapia (*Oreochromis niloticus*) in the Amazon have been escalating in the past years (Garcia et al., 2022; Padial et al., 2017; Pelicice et al., 2014). Actions to prevent these policies can substantially reduce the risk of new invasions.

Another concerning issue is the spread of exotic species through boats and vessels, primarily through ballast water (i.e., water held in tanks to stabilize ships). Ships from across the world travel throughout the Amazon to transport commodities and goods as far upstream as in Yurimaguas, Peru, and more than 100 major industrial ports operate in the Amazon (Andreoni, 2020). Evidence suggests that regulations and enforcement on ballast water exchange—a measure to gradually replace or dilute ballast water along the path—are currently limited in Amazonian ports, with high rates of misconduct and misreporting to port authorities (Pereira et al., 2014). In other South American basins like the Paraná-Paraguay, invasions of the golden mussel (*Limnoperna fortunei*) were linked to ballast water and resulted in major environmental and economic costs due to its capacity to engineer ecosystems, biofouling, and high tolerance to different environmental conditions (Moutinho, 2021; Uliano-Silva et al., 2013). The current invasion range of the golden mussel is just a few hundred kilometers from Amazon waters, and several rivers are potentially suitable for the establishment of the species (Uliano-Silva et al., 2013). Examples of invasions such as the golden mussel emphasize the urgent need to scale up and enforce regulations on ballast water exchange in the Amazon, particularly in major ports and waterways.

2.2.6 | Theme 6: Safeguard and restore freshwater connectivity

Water-mediated biophysical exchanges are critical determinants of ecological processes in freshwater ecosystems (e.g., sediment transport, fish migrations, floodplain productivity), making the maintenance of connected free-flowing rivers a priority (Grill et al., 2019; Pringle, 2003). Actions for this theme fit within three major categories: Improve hydropower siting via strategic planning, mitigate connectivity losses by existing infrastructure, and oversee the role of small artificial barriers on river fragmentation (Tables 1 and S1). Hydropower expansion is a primary threat to freshwater connectivity in the Amazon, especially in rivers draining from the Andean-Amazon and the Brazilian Shield (Anderson et al., 2018; Latrubesse et al., 2017; Winemiller et al., 2016). Studies have found that improving strategic planning for dam siting can considerably reduce future losses in river connectivity without hampering energy generation (Couto et al., 2021; Flecker et al., 2022). Traditionally, the selection of hydropower projects has been driven by economic and political criteria, with environmental repercussions of projects being assessed much later in the licensing process. Actions aiming to regulate and improve transparency over early stages of project selection have a great potential to prevent highly detrimental and needless sets of projects before large governmental and private investments are made (Almeida et al., 2022; Couto et al., 2021; Flecker et al., 2022). Although there is no prescriptive rule about which scales and conservation objectives should be addressed in a solid strategic planning (Almeida et al., 2022), previous research has highlighted the importance of considering broad spatial processes maintained by connected freshwaters like sediment transport, water flow, and species movement (Caldas et al., 2023; Flecker et al., 2022; Forsberg et al., 2017).

As hydropower and other large instream infrastructure (e.g., dams, canals) expand, actions to mitigate losses in freshwater connectivity become increasingly necessary (Tables 1 and S1). Maintaining free-flowing rivers is among the most effective mitigation measures, although specific legal mechanisms for protecting them still need development in most countries (Perry et al., 2021). Safeguarding remaining free-flowing rivers that link the Andes and the lowlands has been identified in the literature as a high priority (Anderson et al., 2018; Flecker et al., 2022; Forsberg et al., 2017). Sediments and nutrient-rich waters, mainly derived from Andean headwaters, play a critical role in shaping the geomorphology and supporting biological productivity in the floodplains of the Amazon lowlands (McClain & Naiman, 2008). Consequently, flow regulation and sediment trapping by instream infrastructure in Andean tributaries can affect fluvial processes, soil fertility, and fisheries yield much further downstream, impacting important ecosystems for both biodiversity and people (Forsberg et al., 2017).

Maintaining free-flowing tributaries is key for the long-term persistence of migratory fish that rely on connected freshwaters to complete their life cycle (Duponchelle et al., 2021; Herrera-R et al., 2024). In heavily fragmented basins like the Madeira, remaining free-flowing tributaries can sustain the reproductive needs of several migratory species, indicating a potential target for mitigation and compensation actions in the face of infrastructure development (Vasconcelos et al., 2020). The management toolbox for mitigating losses in freshwater connectivity also includes the implementation of e-flows (Theme 1), and the construction and maintenance of fish passage structures. Current evidence suggests that fish passage in the Amazon is costly and does not meet minimum standards of efficiency, still requiring research and considerable technical improvements to be considered an actual mitigation measure (Hahn et al., 2019, 2022; Hauser et al., 2019). Actions to improve efficiency and expand monitoring of fish passages can be considered a need. However, it is still uncertain the benefits these investments would return in the short and long term.

Another important topic that emerged in the literature is the underappreciated role of smaller infrastructure in river fragmentation (Tables 1 and S1), including small dams, road-crossings and aquaculture facilities (Athayde et al., 2019; Freitas et al., 2022; Macedo et al., 2013). For example, small hydropower plants (i.e., generation capacity up to 50 megawatts or less depending on the country's classification) are proliferating in the Amazon, causing important cumulative losses in river connectivity and threatening migratory fish (Anderson et al., 2018; Couto et al., 2021). The cumulative effects of small dams currently lack adequate impact assessments due to the general perception that "small" equates to low environmental impacts and the limited scope of regulations that tend to focus on individual projects (Athayde et al., 2019; Couto & Olden, 2018). Measures to scale up small hydropower impact assessments and licensing are needed to properly regulate their growing cumulative threat to river connectivity. Similarly, road-crossings are widespread but their effects on freshwater ecosystems are often disregarded in impact assessments of road infrastructure (Pocewicz & Garcia, 2016; Vilela et al., 2020). Poorly designed and maintained culverts and bridges alter local habitats, facilitate erosive processes and disconnect streams, which modify physical and chemical attributes of aquatic ecosystems and affect the composition of freshwater communities (Brejão et al., 2020; Leal et al., 2016; Rosa et al., 2021). There are unique challenges to infrastructure design and maintenance in the Amazon, but engineering practices (e.g., slope stabilization, appropriate culvert/bridge designs) tailored to the Amazon's conditions exist and can continue to be developed (Keller et al., 2015). Such practices should be integrated into conservation actions aiming to restore freshwater connectivity and mitigate the impacts of road-crossings.

3 | GUIDING PRINCIPLES TO ADVANCE FRESHWATER CONSERVATION

The implementation of actions reported by this compilation can be quite challenging. Therefore, learning from previous successes and failures can help advance practice. Through our review, we identified three key guiding principles for implementing freshwater-focused actions in the Amazon: (P1) Freshwater ecosystems of the Amazon are extraordinarily heterogeneous and the conservation value of one site is not necessarily replaceable by another. (P2) Freshwater ecosystems are interconnected spatially and temporally, and this connectivity should be maintained to conserve ecosystem functioning. (P3) Amazonian people are a critical, essential component of freshwater conservation. The rationale for each one of these is detailed below.

3.1 | P1: Freshwater ecosystems of the Amazon are extraordinarily heterogeneous

The Amazon Basin is a vast and highly heterogeneous system (Figure 1 and Table 2). It includes high-elevation mountainous Andean landscapes in the west, large fluvial islands and mangrove forests in the east, a mosaic of vegetation types including forests and savannas, and myriad freshwater ecosystems with distinct physical, chemical, and biological properties (Castello et al., 2013; Goulding, 2003). The recognition of these and other elements of heterogeneity for freshwater ecosystems is crucial to inform spatial prioritization efforts and to plan management interventions. For instance, rivers with distinct biogeochemical properties have long been recognized in the Amazon and classified according to their water colors—black, clear, or whitewater rivers (Bogotá-Gregory et al., 2020). These water types not only reflect particular habitat characteristics (e.g., transparency, acidity, nutrient content) but also represent important determinants of freshwater biodiversity composition and fisheries productivity (Bogotá-Gregory et al., 2020; Goulding et al., 2019). Different sub-basins of the Amazon are composed by unique blends of water colors in a wide range of spatial configurations and should be carefully examined in spatial prioritization (Ríos-Villamizar et al., 2020) (Table 2). Data limitation has been a major gap for mapping elements of riverscape heterogeneity to advance conservation planning in the Amazon (Thieme et al., 2007). However, recent advances in remote sensing and hydroecological modeling, coupled with more comprehensive biological datasets now available, provide renewed hope that freshwater-based conservation surrogates can support broad-scale spatial prioritizations (e.g., Fleischmann et al., 2022; Jézéquel et al., 2020a; Venticinque et al., 2016). Importantly, areas of potentially high biodiversity irreplaceability should be carefully examined in prioritization efforts, particularly when referring to unique freshwater habitats like patches of the Andean Páramos (Buytaert et al., 2006), cataracts and fluvial rocky outcrops (Lees et al., 2016), and the recently described freshwater mangroves (Bernardino et al., 2022).

3.2 | P2: Freshwater ecosystems are interconnected spatially and temporally

The distinct habitats and ecosystems described above are not isolated components of the landscape and their conservation requires maintaining connected freshwaters. For instance, the intense natural erosive processes happening in the high-elevation gradients of the Andean-Amazon form the most sediment-rich tributaries of the Basin (Table 2). Together, these tributaries supply nearly 90% of all sediment and most sediment-bound nutrients found in the Amazon River mainstem, even though representing just a small fraction of the Basin catchment (McClain & Naiman, 2008). Other ecosystem processes are mediated by the seasonal movement of aquatic animals such as fish that migrate hundreds or even thousands of kilometers to complete their life cycle (Duponchelle et al., 2021; Flecker et al., 2010). As frugivore and detritivore migratory fish are important for seed dispersal and aquatic metabolism in the Amazon, their exclusion by overfishing and artificial barriers like dams can have negative consequences for entire ecosystems

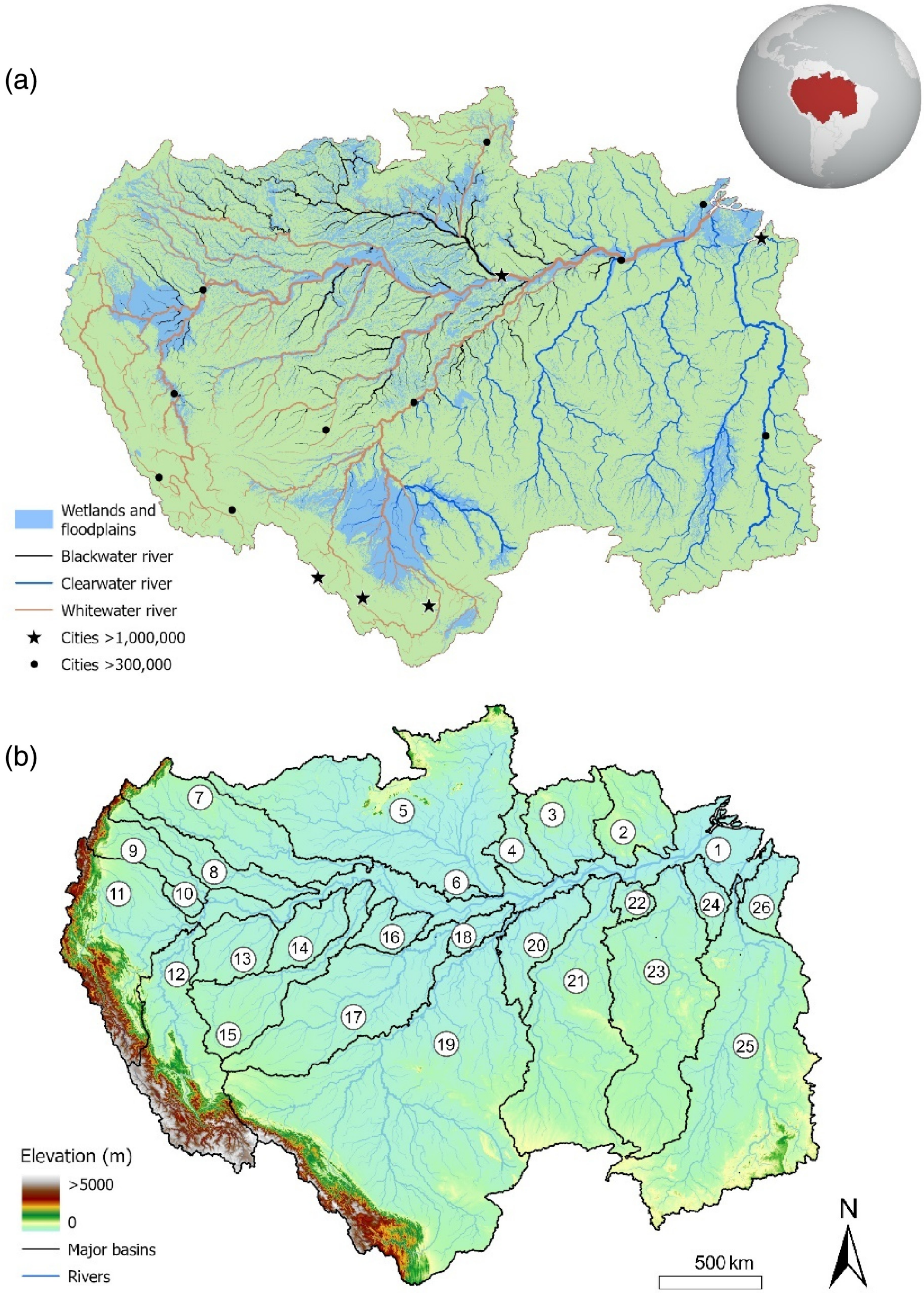

FIGURE 1 Maps depicting elements of environmental heterogeneity across freshwater ecosystems of the Amazon Basin, broadly referred here as all tributaries draining to the Amazon River delta (i.e., including Tocantins-Araguaia, Pacajá, and Guamá). (a) River networks represented by colored lines, and wetlands and floodplains by light blue areas. The three classes of river water color are differentiated: blackwater (black), clearwater (blue), and whitewater (brown). Black symbols represent the cities with populations larger than 1 million (stars) and 300,000 people (circles). (b) Elevation gradients (background color scale) and the 26 major river sub-basins (basin-level 2; Venticinque et al., 2016) that compose the Amazon Basin (black contours). Names and summary attributes for each sub-basin are presented in Table 2.

TABLE 2 Diversity of physical attributes of the different sub-basins of the Amazon Basin, including total sub-basin area (Area), percentage coverage of protected areas (PA), Indigenous territories (IT) and non-forest native vegetation (NFNV), percentage of area below 500 m (<500 m), between 500 and 3000 m (>500 and <3000 m) and above 3000 m (>3000 m), mean annual river discharge (Discharge), suspended sediment discharge (SSD), total river-network extent (TRE), and percentages of river kilometers composed by black, clear, and whitewaters.

Sub-basin	Area (km^2)[a]	PA (%)[b]	IT (%)[b]	NFNV (%)[c]	<500 m (%)[d]	>500 and <3000 m (%)[d]	>3000 (%)[d]	Discharge (m^3/s)[e]	SSD (Mt/year)[f]	TRE (km)[a]	Blackwater (%)[a]	Clearwater (%)[a]	Whitewater (%)[a]
(1) Amazon floodplain	405,172	0.9	6	7.4	100	0	0	207343	442.2	11,426	31	30	39
(2) Jari	133,503	27.2	24.7	0.9	95	5	0	2089	1.7	3012	0	100	0
(3) Trombetas	148,895	26.8	50.3	3.5	98	2	0	3573	1.5	3685	14	86	0
(4) Uatumã	67,273	14.1	30.7	0.3	99	1	0	1922	0.4	1617	100	0	0
(5) Negro	711,550	16.1	52.4	9.3	92	8	0	33,765	7.3	20,852	75	0	25
(6) Manacapuru	11,222	0	0.5	0.1	100	0	0	556	0	260	100	0	0
(7) Japurá-Caquetá	253,698	32.1	38.4	1.1	94	6	0	15,533	17.2	7356	61	0	39
(8) Içа-Putumayo	118,066	13	44.1	0.6	95	4	1	7515	14.8	3837	46	0	54
(9) Napo	99,928	0.5	37.2	3	82	13	5	7420	46.2	3123	24	0	76
(10) Nanay	16,719	0	14	0.8	100	0	0	822	0.1	301	100	0	0
(11) Marañón	362,390	3.1	35.2	12.1	47	39	14	25,570	358.3	8601	26	0	74
(12) Ucayali	353,086	7.4	32.9	23.9	45	23	32	9704	153.7	9123	19	0	81
(13) Javari	107,674	2.1	73.6	0	100	0	0	4380	0.6	2901	7	0	93
(14) Tefe-Coari	59,781	0	0.2	0.1	100	0	0	1437	0	1733	100	0	0
(15) Juruá	188,240	5.8	23.4	0.1	100	0	0	6513	22.1	5729	31	0	69
(16) Jutai	89,595	1.5	33.1	0	100	0	0	3733	0.3	2438	100	0	0
(17) Purus	369,104	12.7	22	0.6	100	0	0	11,655	19.7	11,040	62	0	38
(18) Madeirinha	37,581	17.5	13.6	1.6	100	0	0	1988	0.2	1254	100	0	0
(19) Madeira	1,315,036	7	24.3	15.4	83	13	4	27,291	217.1	36,548	7	47	47
(20) Abacaxis	127,494	24.2	15.3	0.4	100	0	0	336	0.4	3202	86	0	14
(21) Tapajós	493,030	7.5	18.1	2.9	91	9	0	15,970	3.7	10,639	4	96	0
(22) Curuá-una	30,536	0	8.3	0	100	0	0	1038	0.2	598	0	100	0
(23) Xingu	506,996	8.5	39.2	1.9	97	3	0	15,288	3.3	10,741	0	100	0
(24) Pacajá	48,606	0	1.3	0.1	100	0	0	2387	0.2	1274	0	100	0
(25) Tocantins	763,504	3.4	6.5	10.5	78	22	0	15,321	7.7	17,522	0	100	0

TABLE 2 (Continued)

Sub-basin	Area (km²)[a]	PA (%)[b]	IT (%)[b]	NFNV (%)[c]	<500 m (%)[d]	>500 and <3000 m (%)[d]	>3000 (%)[d]	Discharge (m³/s)[e]	SSD (Mt/year)[f]	TRE (km)[a]	Blackwater (%)[a]	Clearwater (%)[a]	Whitewater (%)[a]
(26) Guamá	71,322	0	0.9	0.1	100	0	0	3272	0.9	2026	0	100	0

Note: Sub-basins are represented at the basin-level 2 of the hierarchical basin-level framework proposed by Venticinque et al. (2016).
[a]Data source: Venticinque et al. (2016).
[b]Data source: RAISG (2020).
[c]Data source: MapBiomas (2022).
[d]Data source: Jarvis et al. (2008).
[e]Data source: Siqueira et al. (2018).
[f]Data source: Fagundes et al. (2021).

(Costa-Pereira et al., 2018; Flecker et al., 2010; Taylor et al., 2006). These examples reinforce that conservation planning should go beyond protecting specific locations but also requires maintaining connected freshwaters. From the management perspective, this involves identifying key interconnected hydrologic and ecological processes as well as the spatial and temporal scales that are relevant for maintaining them.

3.3 | P3: Amazonian people are a critical, essential component of freshwater conservation

Freshwater conservation in the Amazon is not possible without people. The notion of a "pristine" Amazon—untouched by humans—is simply unrealistic, with both archeological and ecological evidence indicating that people and the environment have been shaping each other for millennia (Levis et al., 2017). This human-environment dynamic is not restricted to land, with evidence of important pre-Columbian environmental modifications being found for freshwater ecosystems like the mounds, canals and reservoirs described for human settlements in seasonally flooded areas of Llanos de Moxos (Bolivia) and Marajó Island (Brazil) (de Fatima Rossetti et al., 2009; Prümers et al., 2022). Today, Amazonian people's lives and livelihoods continue to be intimately linked to freshwater ecosystems, which provide key sources of food and income, routes for transportation, and connections to biocultural heritage (Anderson et al., 2019; Harris, 1998; Heilpern, DeFries, et al., 2021; Heilpern, Fiorella, et al., 2021; Jackson et al., 2022). Successfully engaging with Amazonian people has proven to be not just desirable but also determinant to advance management objectives (Lopes et al., 2021; Nepstad et al., 2006). While bioeconomy models for the Amazon are still being conceptualized (Bergamo et al., 2022; Ferreira et al., 2024), practical experiences centered on freshwater governance and community-based management pinpoint potential directions for reconciling environmental protection, income generation, and social justice (Campos-Silva, Peres, Hawes, et al., 2021; Freitas, Espírito-Santo, et al., 2020; Lopes et al., 2021).

4 | FRESHWATERS AS A CENTERPIECE OF CONSERVATION

It is time for innovation in the evolution of conservation practices for the Amazon, where freshwater ecosystems become central in policies, regulations, and agreements. The Amazon Basin holds a massive amount of water that is critical to sustain the largest Earth's tropical forest, an unparalleled freshwater biodiversity, and the diverse needs of Amazonian people. Despite such importance, there are signs that freshwater ecosystems have been relegated to a sidelined role in current conservation practices (Anderson, Osborne, et al., 2019; Castello et al., 2013; Leal et al., 2020; Prestes et al., 2022). One example of this pattern is the lack of a clear mechanism to specifically protect free-flowing rivers, with current management options relying on conventional protected areas that are not necessarily suitable for long-lasting protection of rivers (Fernandes et al., 2023; Pecharroman, 2018; Perry et al., 2021). Hydropower and other impacts that are directly threatening freshwaters have been the spearhead of PADDDs in the Amazon, with many PADDD events being enacted to pave the way for the construction of new hydroelectric projects—like Jirau dam (Brazil) that was only possible after PADDD events in 14 protected areas (Pack et al., 2016). This situation of limited regulatory oversight is being permissive to a rapid deterioration of freshwater ecosystems.

For most conservation actions identified in this review, solid operational models for implementation are still to be developed. Therefore, assessing outcomes of current and prospective interventions is a critical step toward scaling up and adapting their implementation throughout the Amazon (Tallis et al., 2021). One example of an intervention that has been increasingly recognized as a successful model to advance conservation is the co-management of arapaima fisheries. This model was first implemented between 1999 and 2006 in the Sustainable Development Reserve of Mamirauá, being conceived as a Before-After-Control-Impact (BACI) experimental design and conducted with meticulous assessments (Castello et al., 2009). The socio-ecological benefits of co-management became evident and supported by data, which fueled the replication and adaptation of that same model throughout the Amazon lowlands (Campos-Silva & Peres, 2016; Gurdak et al., 2022; Petersen et al., 2016). As new research on *Arapaima* co-management flourish, new perspectives and improvements are gradually tested and incorporated into the model (Campos-Silva et al., 2018; Freitas, Espírito-Santo, et al., 2020; Freitas, Lopes, et al., 2020; Stokes et al., 2021). This example highlights not only how innovative approaches can become conservation models, but also the importance of assessing the effects of interventions to help balance the pros and cons of their implementation.

Despite the rapid pace of transformations of aquatic ecosystems in the Amazon, national and international freshwater conservation movements have built momentum to revert the global freshwater ecosystem crisis. High-level discussions on conservation priorities and regulatory mechanisms to specifically protect and restore freshwater ecosystems gained traction in the international debate (Perry et al., 2021; Reid et al., 2019; Tickner et al., 2020). Experiences from the Amazon have much to contribute to this evolving conversation as the diverse socio-ecological complexities found in the system can set the stage for experimenting innovative management solutions. Challenges for implementing broad-scale conservation actions in such a vast area cannot be minimized, but examples of interventions from the terrestrial realm inspire some optimism that ambitious outcomes can be accomplished. For instance, the soy moratorium—a voluntary zero-deforestation agreement implemented in the Brazilian Amazon—applied together with policies of satellite-based enforcement were quite successful in reducing deforestation rates after implementation (Gibbs et al., 2015). This effort required the support of key players from the supply chain and financing system, effective monitoring and enforcement protocols, and the active participation of NGOs and governmental agencies. While nothing comparable to this scale was designed and implemented specifically for freshwater ecosystems, the momentum and recognition of the global importance of the Amazon freshwaters indicate that it is time to think big (e.g., Beveridge et al., 2024).

5 | WHERE TO START?

The best set of conservation actions to be prioritized is still open for debate. A pragmatic assessment of action prioritization that balances expected costs and outcomes is necessary to inform optimal paths for future allocation of resources. Although this is beyond the scope of this study, we suggest a few key directions that emerged from our readings and discussions: (i) There is a clear need for improvement of regulations to specifically protect and restore flowing-water ecosystems (Fernandes et al., 2023; Pecharroman, 2018; Perry et al., 2021), and to strengthen the protection of riparian and catchment vegetation (Arias et al., 2020; Dala-Corte et al., 2020; Leal et al., 2018). Without the proper legal backing, managers, and practitioners will continue having a limited set of tools to operate (Caldas et al., 2023; Leal et al., 2020; Pack et al., 2016). (ii) There are successful conservation models from the Amazon (e.g., community-based management) that need to be expanded to new areas, integrated into management networks, and supported with public and private funds (Freitas, Lopes, et al., 2020; Lopes et al., 2021; Nepstad et al., 2006). Granting collective territorial rights, providing technical support to management decisions, and simplifying the supply chain of well-managed natural resources are examples of interventions that can help build more sustainable and inclusive economies in key areas for conservation (Anderson, Osborne, et al., 2019; Campos-Silva, Peres, Hawes, et al., 2021; Lopes et al., 2021). (iii) There is a need for expanding public awareness about freshwater conservation in the Amazon to bring new allies from politics, media, research, and the general public. Engaging with a broader public and publicizing the multiple relational values of freshwater ecosystems can make the difference for conservation. As evidence we can look to cases reported in the literature on the public scrutiny over infrastructure expansion (Tófoli et al., 2017), community and consumer support for sustainable extractivism (Evers et al., 2019; Freitas, Lopes, et al., 2020), and the global repercussion and emergency aid during the 2023 drought (Ottoni et al., 2023). Advancing in these three fronts could help scaling up freshwater conservation outcomes and transversally meeting multiple conservation objectives. Freshwaters of the Amazon are experiencing unprecedented changes, but decades of research and practice have produced a rich foundation for advancing solutions. As our approach is mostly limited to peer-reviewed publications, relevant findings from the gray literature might be missing and could be further explored in future assessments. Together, this collective knowledge constitutes the base for redeeming the proper place of freshwater ecosystems in efforts to conserve the Amazon.

AUTHOR CONTRIBUTIONS

Conceptualization and developing methods: TBAC, CFB, SAH, GAHR, NCP, MM, MV, SBC, MG, and EPA. *Library assembly, paper processing, and validation*: TBAC, CNJ, CFB, SAH, GAHR, NCP, CCL, JZ, CRCD, MM, MV, SBC, MG, and EPA. *Spatial data analysis*: TBAC, CNJ, and CFB. *Preparation of figures & tables*: TBAC, CNJ, and CFB. *Writing the first draft*: TBAC, CNJ, CFB, SAH, GAHR, NCP, and EPA. *Revising critically and editing subsequent drafts*: TBAC, CNJ, CFB, SAH, GAHR, NCP, CCL, JZ, CRCD, MM, MV, SBC, MG, and EPA.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data produced through the paper processing and references associated to it are available in the Supporting Information (Table S1).

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