Human impacts and the loss of Neotropical freshwater fish diversity

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Neotropical Ichthyology promotes the Special Issue (SI) "Human impacts and the loss of Neotropical freshwater fish diversity" with the purpose of publishing relevant scientific articles on the current biodiversity crisis and the loss of Neotropical freshwater fishes in the Anthropocene. The SI is composed of 22 publications, being two review articles and 20 original articles. A total of 107 researchers contributed to these papers, involving 44 institutions based in Brazil and six other countries. Published articles investigated main anthropic activities and their impacts on fish diversity, with special focus on river regulation, mining, land use changes, aquaculture, and fisheries. Studies provided evidence about the loss of fish diversity in the Neotropics, including fish kill events, demographic changes, contamination, changes in assemblage structure, loss of taxonomic and functional diversity, besides the degradation of ecosystem functions and services, and the lack of effective protection and conservation. Studies were conducted in rivers, streams, lakes, and reservoirs from different Neotropical systems. The studies published in this SI represent a relevant sample of the current worrisome situation of freshwater fishes in the Neotropical region and call for urgent revision in environmental policies, management and conservation initiatives, and socioeconomic priorities.

Keywords: Anthropocene, Biodiversity, Conservation, Environmental degradation, Special Issue.

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A revista Neotropical Ichthyology lança o Volume Especial (SI) "Human impacts and the loss of Neotropical freshwater fish diversity" com o objetivo de publicar artigos científicos relevantes sobre a atual crise da biodiversidade e a perda de diversidade de peixes de água doce Neotropicais no Antropoceno. O SI é composto por 22 publicações, sendo dois artigos de revisão e 20 artigos originais. Um total de 107 pesquisadores contribuíram com esses artigos, envolvendo 44 instituições sediadas no Brasil e em seis outros países. Os artigos publicados investigaram as principais atividades antrópicas e seus impactos sobre a diversidade de peixes, com foco especial na regulação dos rios, mineração, mudanças no uso do solo, aquicultura e pesca. Os estudos forneceram evidências sobre a perda de diversidade de peixes na região Neotropical, incluindo eventos de mortandade, alterações demográficas, contaminação, mudanças na estrutura das assembleias, perda de diversidade taxonômica e funcional, além da degradação de funções e serviços ecossistêmicos, e falta de ações efetivas de proteção e conservação. Os estudos foram conduzidos em rios, riachos, lagos e reservatórios de diferentes sistemas Neotropicais. Os estudos publicados neste SI representam uma amostra relevante da atual situação dos peixes de água doce na região Neotropical, reforçando a necessidade de revisão das políticas ambientais, ações de manejo e conservação, e prioridades socioeconômicas.

Palavras-chave: Antropoceno, Biodiversidade, Conservação, Degradação ambiental, Volume Especial.

INTRODUCTION

The Neotropical region houses a spectacular fish diversity, unparalleled to any other biogeographic region on the planet. More than 6,000 freshwater species have been formally described and cataloged (Albert *et al*., 2020), constituting a unique biological heritage. This number is certainly incomplete, as estimates indicate the existence of 8,000 to 9,000 species only in South America (Reis *et al*., 2016). Fish diversity is demonstrated in multiple dimensions, with a fabulous variety of morphologies, behaviors, life histories, historical/evolutionary relationships, and ecosystem functions (Winemiller, 1989; Reis *et al*., 2003; Toussaint *et al*., 2016; Vitule *et al*., 2017). The biogeography of the Neotropics is also remarkable, as its geological history provided a physiographic matrix of high environmental heterogeneity, allowing the evolution of a rich diversity of freshwater fishes, creating complex distribution patterns and endemism at different spatial scales (*e.g.*, Dagosta, de Pinna, 2019). The presence of large river systems and thousands of small independent drainages, with important geological events (*e.g.*, Andes uplift and evolution of separate shields), made the Neotropical region a vivid laboratory of evolution and diversification of unique biological lineages (Dagosta, de Pinna, 2017; Albert *et al*., 2018, 2020).

The Anthropocene, however, brought enormous challenges to the conservation of Earth's biodiversity. Particularly, Neotropical freshwater fishes (NFF) have been subjected to increasing, multiple and synergistic anthropogenic impacts (Barletta *et* *al*., 2010; Costa, Barletta, 2016; Reis *et al*., 2016; Torremorell *et al*., 2021). Hundreds of studies have reported the erosion of NFF diversity, depicted as changes in multiple organization levels (*i.e*., from organisms to communities), including changes in diversity patterns, demography, community structure, species richness or even extinction (*e.g*., Pelicice *et al*., 2017 and references). The expansion of human activities, particularly agriculture, construction of dams, aquaculture, urbanization, mining, and fishing, has transformed the structure, dynamics, history, and functioning of inland aquatic ecosystems. These activities have induced severe changes to fluvial hydrology, geomorphology, and connectivity, caused significant losses of riparian and aquatic habitats, changed land cover and carbon fluxes, favored invasive species, caused contamination by urban and agricultural pollutants, overfishing, among other disturbances (*e.g*., Araújo *et al*., 2009; Agostinho *et al*., 2016; Tregidgo *et al*., 2017; Brejão *et al*., 2018; Garcia *et al*., 2018; Loures, Pompeu, 2018; Pelicice *et al*., 2018; Moi *et al*., 2021). Currently, all aquatic ecoregions in the Neotropics are subjected to human stressors, and some drainages have been highly degraded (*e.g*., Doce, Paraíba do Sul, São Francisco, upper Paraná, and Tocantins-Araguaia basins). Environmental degradation has reached regions previously considered pristine, which concentrate high diversity and endemism, such as the Amazon basin and the Andes (Winemiller *et al*., 2016; Anderson *et al*., 2018; Duponchelle *et al*., 2021; Pelicice, Castello, 2021). This scenario shows that the current biodiversity crisis hovers over NFF; a process with planetary consequences.

Given the current scenario and the need to address this important environmental issue, Neotropical Ichthyology promoted this Special Issue (SI) "Human impacts and the loss of Neotropical freshwater fish diversity", with the purpose of publishing relevant scientific articles on the current biodiversity crisis and the loss of NFF. Several experts were invited to contribute to this issue, which resulted in the publication of 22 papers. These publications investigate different human stressors and impacts and show compelling evidence on the loss of fish diversity, epitomizing the current biodiversity crisis in the Neotropical region.

THE SPECIAL ISSUE

The SI is composed of 22 publications, being two review articles and 20 original articles. A total of 107 researchers contributed to these papers, 69.2% from Brazil and 30.8% from other countries. It involved 44 institutions (*i.e*., universities, research institutes, government agencies) based in Brazil (58.7%) and six other countries (41.3%), *i.e*., Argentina, Colombia, Czech Republic, Guyana, United Kingdom, and United States of America. Most authors are male; however, considering the first author of each publication, 54.5% are women (Fig. 1). Eight editors of Neotropical Ichthyology organized the SI and handled the submitted manuscripts.

Published articles investigated main anthropic activities and their impacts on fish diversity, *e.g*., dam construction, mining, land use change, aquaculture, and fisheries (Tab. 1). Studies provided evidence about the loss of fish diversity, including fish kill events, demographic changes, contamination, changes in the assemblage structure, loss of taxonomic and functional diversity, besides the degradation of ecosystem functions and services, and the lack of effective protection and conservation (Tab. 1). Studies were conducted in rivers, streams, lakes, and reservoirs from different Neotropical systems, *e.g.*, Uruguay, Paraná, Paraíba do Sul, Doce, São Francisco, Purus, Madeira, Essequibo, and Magdalena rivers, among others (Fig. 2).

The review articles published in this SI address original themes with high significance for the Neotropical region. Agostinho *et al.* (2021) examine the role of anoxia and gas supersaturation inducing fish mortality in areas affected by dams, exploring associated mechanisms and the occurrence of die-off events in different Neotropical systems. Mass mortality events have been recurrent in the region (Agostinho *et al.*, 2007; Loures, Godinho, 2016), but this topic had not been investigated accordingly, sometimes treated in secrecy or even omitted. The second review addresses multiple impacts emerging from mining activities (Azevedo-Santos *et al.*, 2021), including routine contamination by oils, metals, and other substances, besides the effects of

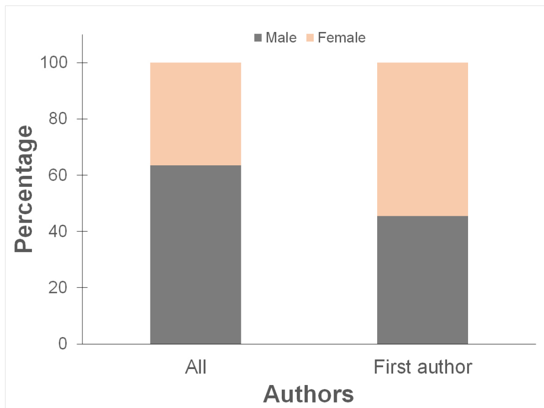

FIGURE 1 | Gender of authors in this Special Issue of Neotropical Ichthyology, considering all authors (n = 107) and the first author of each paper (n = 22).

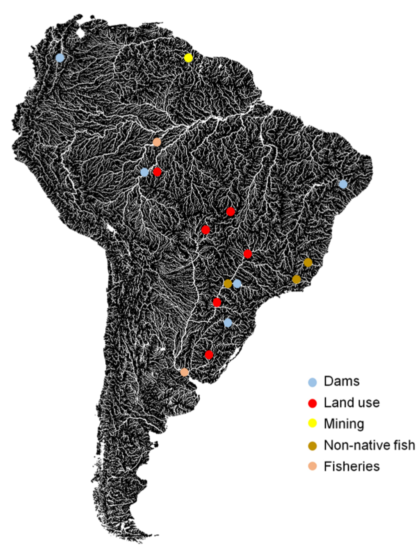

FIGURE 2 | Geographical distribution of studies published in this Special Issue of Neotropical Ichthyology. Colors indicate the type of impact. Five papers are not shown in the map, because they covered large spatial extents (*i.e.*, whole basins or the Neotropical region).

TABLE 1 | Studies included in this Special Issue (Human impacts and the loss of Neotropical freshwater fish diversity) of Neotropical Ichthyology, depicting topics addressed by each study. Review articles are highlighted in a darker blue line.

Type	Driver	Impact	Ecological effects	Ecosystem	Region or Basin	Country	Paper
Review Article	Dams	Anoxia and gas supersaturation	Fish die-off	River and reservoir	Neotropical	Neotropical	Agostinho *et al.* (2021)
Original Article	Dams	Hydrology, habitat and connectivity	Population decline, loss of species and ecosystem services	River and reservoir	Lower São Francisco River	Brazil	D'avilla *et al.* (2021)
Original Article	Dams	Hydrology, habitat and connectivity	Changes in assemblage structure and functional diversity	River and reservoir	Upper Uruguay River	Brazil	De Bem *et al.* (2021)
Original Article	Dams	Hydrology, habitat and connectivity	Changes in assemblage structure, loss of species and functional diversity	Reservoir	Upper Paraná River	Brazil	Ferraz *et al.* (2021)
Original Article	Dams	Hydrology, habitat and connectivity	Population decline	River	Magdalena River	Colombia	Moreno-Arias *et al.* (2021)
Original Article	Dams	Hydrology, habitat and connectivity	Changes in feeding ecology	River	Madeira River	Brazil	Lonardoni *et al.* (2021)
Original Article	Mining	Pollution	Contamination	River	Essequibo River	Guyana	Montaña *et al.* (2021)
Review Article	Mining	Pollution and habitat	Contamination, population decline and changes in assemblage structure	River	Neotropical	Neotropical	Azevedo-Santos *et al.* (2021)
Original Article	Land use	Land cover, hydrology and habitat	Changes in assemblage structure	Stream	Upper Paraná River	Brazil	Miiller *et al.* (2021)
Original Article	Land use	Land cover, hydrology and habitat	Changes in population structure and functional diversity	Stream	Atlantic	Brazil	Pott *et al.* (2021)
Original Article	Land Use	Land cover, hydrology and habitat	Changes in assemblage structure and functional diversity	Stream	Madeira River	Brazil	Brejão *et al.* (2021)
Original Article	Land use	Land cover, hydrology and habitat	Changes in assemblage structure and functional diversity	Stream	Upper Paraná River	Brazil	Alvarenga *et al.* (2021)
Original Article	Land use	Land cover, hydrology and habitat	Changes in assemblage structure and functional diversity	Stream	Xingú River	Brazil	Freitas *et al.* (2021)
Original Article	Land use	Land cover, hydrology and habitat	Changes in assemblage structure	Stream	Paraguay River	Brazil	Ortega *et al.* (2021)
Original Article	Aquaculture	Biological invasion	Biotic differentiation	Stream	Paraíba do Sul River	Brazil	Magalhães *et al.* (2021)
Original Article	Aquaculture and fisheries	Biological invasion	Population decline, loss of species and functional diversity	Lake	Doce River	Brazil	Souza *et al.* (2021)
Original Article	Fisheries	Biological invasion	Population decline, loss of species and ecosystem functions	Reservoir	Upper Paraná River	Brazil	Leal *et al.* (2021)
Original Article	Fisheries	Overfishing	Population decline	River	La Plata Basin	Argentina	Scarabotti *et al.* (2021)
Original Article	Fisheries	Overfishing	Changes in population structure	River	Purus River	Brazil	Tregidgo *et al.* (2021)
Original Article	Multiple	Multiple	Multiple	Multiple	La Plata Basin	Neotropical	Oliveira *et al.* (2021)
Original Article	Multiple	Multiple	Multiple	Subterranean stream	Neotropical	Brazil	Bichuette, Gallão (2021)
Original Article	Multiple	Multiple	Species extinction	Multiple	Neotropical	Neotropical	Tagliacollo *et al.* (2021)

concurrent deforestation, silting and road construction; this review also addresses large-scale degradation caused by the failure of tailings dams in southeastern Brazil.

Several research articles of the SI complement these reviews, investigating impacts caused by hydroelectric dams and mining activities. Some studies show how hydrological alterations, losing connectivity, and habitat degradation impact fish diversity and ecological relationships in the Uruguay (de Bem *et al*., 2021), Paraná (Ferraz *et al*., 2021), São Francisco (D'avilla *et al*., 2021), Madeira (Lonardoni *et al*., 2021), and Magdalena River basins (Moreno-Arias *et al*., 2021). The erosion of fish diversity included the loss of migratory and commercial species, especially in areas affected by cascades of dams — confirming previous investigations (*e.g*., Petesse, Petrere Jr., 2012; Agostinho *et al*., 2016; Loures, Pompeu, 2018; Pelicice *et al*., 2018; Santos *et al*., 2018; Ganassin *et al*., 2021). Concerning mining activities, Montaña *et al.* (2021) provide evidence of mercury contamination in fish captured near gold mining zones in the Essequibo River basin, Guyana. Predatory fish, regularly consumed by local communities, had the highest pollution burden, pointing to a public health risk. Studies on mining impacts are scarce and rarely assess ecosystem effects and losing fish diversity (*e.g*., Azevedo-Santos *et al*., 2016); the two studies published in the SI (Azevedo-Santos *et al*., 2021; Montaña *et al*., 2021) are clear about negative effects and emphasize the need for more research on the subject.

A series of articles provide evidence that changes in land cover impact NFF in streams, complementing many other studies published in the last decade (*e.g*., Casatti *et al*., 2015; Benejam *et al*., 2016; Dala-Corte *et al*., 2016; Teresa, Casatti, 2017; Leal *et al*., 2018; Brejão *et al*., 2018; Ilha *et al*., 2019). Overall, studies included in the SI reported changes in assemblage structure and loss of taxonomic and functional diversity associated with deforestation, urbanization, changes in hydrology, and the degradation of instream habitats. In the upper Paraná River basin, Miiller *et al.* (2021) report changes in functional diversity along rural and urban gradients, while Alvarenga *et al.* (2021) investigate mechanisms and indicate multiple pathways of impacts emerging from changes in the landscape. Concerning urbanization, Ortega *et al.* (2021) show that non-native species dominate urban streams in the Cuiabá River basin, where the proportion of impervious surfaces significantly affected species richness and beta diversity. Two studies were conducted in the Amazon Basin. In the Madeira River basin, Brejão *et al.* (2021) show that different deforestation regimes affect beta diversity patterns across streams, showing that the assemblage composition is affected by changes in land use; in the Xingu River basin, Freitas *et al.* (2021) report significant alteration in natural stream conditions and functional diversity in streams affected by deforestation. Finally, Pott *et al.* (2021) investigate the effects of land use on the distribution of body sizes in fish assemblages in coastal streams of the Brazilian Pampa, indicating that effects depend on the spatial scale and functional group considered. Results emerging from these studies are clear about the effects of land use on diversity patterns, but they also reinforce the difficulty of making broad generalizations, since the response of NFF apparently depends on many factors, such as the local biota, biome, intensity and history of disturbances, spatial and temporal scales, among other drivers.

Three studies investigate the impacts of invasive species on NFF, confirming the role of aquaculture and sport fishing as main vectors of non-native fishes. Magalhães *et al.*

(2021) investigate streams crossing the largest ornamental aquaculture center in Brazil (Muriaé, in Paraíba do Sul River basin), and show how multiple fish escapes, involving dozens of non-native species, affect the composition of local assemblages and induce biotic differentiation patterns. The case of Muriaé is one of the most emblematic examples of biological invasions involving the mass introduction of fish originated from multiple ecoregions of the planet (Magalhães, Jacobi, 2013; Magalhães *et al*., 2019). Other studies investigate the effects of non-native predators, complementing previous studies (*e.g*., Latini, Petrere Jr., 2004; Pelicice, Agostinho, 2009). In the Doce River basin, Souza *et al.* (2021) demonstrate that the invasion of several predatory fish eroded the taxonomic and functional diversity of NFF in natural lakes, including the extirpation of seven species. In Rosana reservoir, upper Paraná River basin, Leal *et al.* (2021) use an innovative approach to investigate how the invasion of *Cichla kelberi* Kullander & Ferreira, 2006 relates to the loss of ecosystem functions generated by fish populations. This topic remains poorly understood, and this study adds to previous works showing the great complexity associated with species invasion and losing ecosystem multi-functionality (*e.g*., Moi *et al*., 2021).

Two studies investigate the effects of fishing activities on fish populations, an issue poorly investigated in the Neotropical region. Scarabotti *et al*. (2021) analyze historical catches and population trends in the La Plata basin, covering different sectors of the basin. Results reveal different temporal trends among species and locations, with declining trends in the lower reaches of the basin, particularly for large migratory fish. Overfishing, and environmental degradation were identified as main drivers inducing demographic changes. In the Amazon basin, Tregidgo *et al.* (2021) examine the catch composition along the Purus River, pointing to strong selectivity induced by urban markets. The study shows that commercial fishing supplying large urban centers (*e.g*., Manaus) targets a few species, when compared to subsistence fishing carried out in remote localities. This fishery dynamics induces strong pressure on a few stocks, especially large species with greater commercial value [*e.g*., *Arapaima gigas* (Schinz, 1822), *Colossoma macropomum* (Cuvier, 1816), and *Pseudoplatystoma punctifer* (Castelnau, 1855)]. The effects of overfishing are difficult to quantify, requiring long time-series data and the measurement of associated and synergistic drivers. Therefore, the two studies published in the SI are highly valuable as they provide robust evidence of overfishing in large Neotropical rivers, especially upon large migratory fish historically exploited and subjected to multiple impacts.

Finally, three studies evaluate multiple threats and the conservation status of NFF. Bichuette, Gallão (2021) show major threats affecting fish diversity in caves and other subterranean ecosystems in Brazil, a fauna characterized by high endemism and vulnerability. Multiple stressors have affected these fishes, especially physical changes in the habitat, resource restrictions, and geo-hydrological changes. Oliveira *et al.* (2021) demonstrate that protected areas in the Paraná-Paraguay basin are not efficient in protecting fish diversity (taxonomic, functional, and phylogenetic), as the overlap between protected areas and more diverse sites is lower than 1.5%; protection will be even lower in projected climate change scenarios. Finally, Tagliacollo *et al.* (2021) assessed the extinction risk for over 5,300 species of NFF, based on criteria established by the IUCN. The authors listed 1,093 threatened or potentially threatened species (*ca*. 18% of all NFF), expanding the official IUCN list that currently lists 422 fish species.

The risk is greater for species with restricted geographic distribution that inhabit upland areas and have been described recently. These results agree with other studies published in the SI and epitomize the growing threats and the critical conservation status of many NFF.

NEOTROPICAL FISHES IN THE ANTHROPOCENE

The SI gathered studies on human impacts and the loss of freshwater fish diversity in the Neotropical region, complementing previous studies published by Neotropical Ichthyology (*e.g.*, Pelicice *et al*., 2018; Ilha *et al*., 2019; Van Damme *et al*., 2019; Tonella *et al*., 2019; Brejão *et al*., 2020) and other scientific journals (*e.g.*, Daga *et al*., 2015; Correa *et al*., 2015; Anderson *et al*., 2018; Brejão *et al*., 2018; Loures, Pompeu, 2018; Bezerra *et al*., 2019; Herrera *et al*., 2020; Dias *et al*., 2021). The topic has attracted growing attention from the scientific community, as aquatic ecosystems have been progressively degraded, impaired, and lost (Strayer, Dudgeon, 2010). The articles published in the SI show that ichthyologists in the Neotropical region have been conscious of this troubling scenario.

There is a general pattern of environmental degradation in the Neotropical region and elsewhere, as human stressors tend to be the same: river damming, changes in land use (agriculture and urbanization), aquaculture, mining, and overfishing (Fig. 3). There are other drivers (Pelicice *et al*., 2017; Santana *et al*., 2021), but the articles published in the SI reinforce the idea that human development has subjected NFF to similar stressors, which involve changes in natural flow regimes, habitat fragmentation and loss, environmental degradation, and biological invasion. Some drivers have received more research effort (*e.g.*, large hydroelectric dams), which allowed the development of robust knowledge and a predictive basis (Agostinho *et al*., 2016). Other activities, however, remain poorly investigated (*e.g.*, mining), or need further examination and detailing (*e.g.*, changes in land use, biological invasion) – pointing in the direction for future research. Ichthyologists must continue to focus on the topic, to quantify the magnitude of each impact, identify main stressors, test, and propose causal links, build a framework that allows wide generalization and predictions, and propose management and restoration actions.

Environmental degradation and the decline of fish diversity is a global process, affecting unique ecosystems and drainages on the planet (Toussaint *et al*., 2018; Grill *et al*., 2019; Deinet *et al*., 2020). This phenomenon has been reported consistently since the second half of the 20th century, but it has sped up with the expansion of human activities in the last *ca*. 50 years. In the Neotropical region, losing fish diversity has been widely reported (*e.g.*, Pelicice *et al*., 2017 and references). Losing diversity entails changes in different levels of biological organization, from genes to ecosystems, implying changes in the genetic structure, biochemistry, physiology, demography, assemblage structure and biogeography, besides the extinction of lineages. Concerning NFF, diversity losses are a matter of great concern, as the Neotropical region holds the greatest fish biodiversity on the planet (Toussaint *et al*., 2016; Vitule *et al*., 2017; Albert *et al*., 2020). Losing NFF has effects on patterns and processes (*i.e.*, evolutionary, ecological, ecosystem, economic) operating at multiple

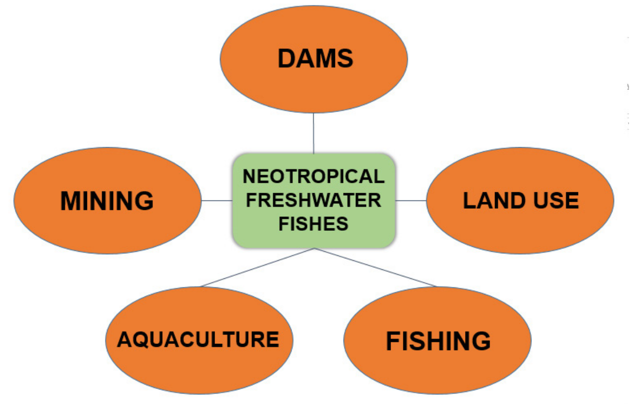

FIGURE 3 | Main human stressors associated with the loss of Neotropical freshwater fishes, investigated by studies published in this Special Issue of Neotropical Ichthyology.

spatial scales. In fact, it has negatively affected fishery resources (*e.g.*, Agostinho *et al*., 2007; Hoeinghaus *et al*., 2009; Hallwass *et al*., 2013; Van Damme *et al*., 2019) and the generation of important ecosystem functions (*e.g.*, Taylor *et al*., 2006; Winemiller *et al*., 2006; Correa *et al*., 2015; Costa-Pereira, Galetti, 2015). Fish are key components of aquatic ecosystems, where they play essential functions and services (Holmlund, Hammer, 1999; Flecker *et al*., 2010), including fishing goods, assimilation and transfer of matter/energy, population control, or the dispersion of propagules. Therefore, losing NFF represents an important component of the current biodiversity crisis, which has triggered growing environmental, economic, social, and cultural implications, many of which are irreversible.

The conservation of NFF in the Anthropocene faces increasing challenges. Current human activities have induced large-scale environmental degradation, and new stressors are emerging (*e.g.*, climate change, pandemics). Currently, the Brazilian Red List of Endangered Species includes 311 NFFs (ICMBio, 2018), but the number of imperiled species and populations is certainly underestimated (Pelicice *et al*., 2017; Santana *et al*., 2021; Tagliacollo *et al*., 2021). The current scenario is pessimistic, fueled by unsustainable policies, economic and social crisis, and pressure for short-term development based on high-impact activities (*e.g.*, Dobrovolski *et al*., 2018; Pelicice, Castello, 2021). Nations in Latin America have a great responsibility to preserve NFF, which will require the revision of current economic and environmental policies. Priority actions, based on scientific information, should promote the preservation and restoration of freshwater ecosystems, to preserve natural flow regimes, connectivity, fluvial and riparian environments, and critical habitats. The establishment of protected rivers should be seriously considered (Azevedo-Santos *et al*., 2019), as well as the strict preservation of riparian areas (Dala-Corte *et al*., 2020). Such measures conflict with current development approaches, but the lack of effective conservation policies will deepen the biodiversity crisis and jeopardize future ecosystem services and human welfare. The studies published in this SI represent a relevant sample of the current situation of freshwater fishes in the Neotropical region and call for an urgent revision in environmental policies, management and conservation initiatives, and socioeconomic priorities.

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