Title: A Global Agenda for Advancing Freshwater Biodiversity Research

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Abstract: Global freshwater biodiversity is declining dramatically, and meeting the challenges of this crisis requires bold goals and the mobilization of substantial resources. While the reasons are varied, investments in both research and conservation of freshwater biodiversity lag far behind those in the terrestrial and marine realms. Inspired by a global consultation, we identify 15 pressing priority needs, grouped into five research areas, in an effort to support informed global freshwater biodiversity stewardship. The proposed agenda aims to advance freshwater biodiversity research globally as a critical step in improving coordinated action towards its sustainable management and conservation.

Keywords: Fresh waters, Freshwater biodiversity crisis, Research priorities, Data infrastructure, Monitoring, Ecology, Management, Social ecology

Freshwater biodiversity encompasses the genes, populations, species, communities, and ecosystems of all inland waters, and provides essential ecosystem services that are fundamental for human livelihoods and well-being (Dudgeon *et al.* 2006). Currently, this biodiversity is declining at unprecedented rates (IPBES 2019). The most recent Living Planet Report (WWF 2020) documents an average 84% decline in abundances – within less than 50 years – for 3,741 monitored populations representing 944 freshwater vertebrate species. This is the steepest decline in the three major realms of land, oceans, and freshwaters , and underlines the disproportionate threat to freshwater biodiversity. Despite the ongoing, unprecedented decline, research on and conservation of freshwater biodiversity have been insufficiently prioritized. International and intergovernmental science-policy platforms, funding agencies, and major philanthropy initiatives continue to fall short of giving freshwater biodiversity its rightful place in global biodiversity, climate, and socioeconomic forums (Darwall *et al.* 2018; Tickner *et al.* 2020; Heino *et al.* 2021). For instance, a recent report on environmental funding by 127 European foundations (Moralis 2021) shows that freshwaters received a mere 1.75% of a total of € 745 million (US$ 873 million) granted in 2018 for environmental work and ranked next-to-last among the 13 thematic-issue categories used to assess grant distribution. In another example, major global philanthropy initiatives that contribute substantially to environmental conservation, e.g., the US$ 1-billion commitment of the Wyss Campaign for Nature (www.wysscampaign.org), focus solely on marine and terrestrial realms. The latter includes but does not sufficiently address fresh waters in the funding schemes. Indeed, the majority of funding schemes do not recognize fresh waters as a distinct biome.

Here, we propose an agenda for advancing freshwater biodiversity research globally. We view this as a critical step in supporting and improving global coordinated actions toward the sustainable management and conservation of fresh waters. Our agenda aims to inform funding provision and provide guidance to civil society, philanthropic organizations, and governmental agencies. We also encourage scientists, conservation practitioners, environmental managers, and policymakers to engage with one another to support informed global freshwater biodiversity stewardship. Indeed, research priorities for sustainable management and conservation should be guided by management and conservation needs. We identify 15 priority needs grouped into five major integrated research areas designed to support conservation and management actions (Fig. 1). We also acknowledge that our 15 priority needs reflect different types of challenges, and as such we grouped the challenges into three categories (Fig. 2) summarizing: i) knowledge gaps that result from limited research, disparities in access to information, or both; ii) insufficient communication and exchange among scientists, practitioners, managers, and policy makers; and iii) inadequate policy, lack of political will, or the decoupling of current policy from demonstrated best practices for preserving and recovering freshwater biodiversity and the services it provides. We therefore provide a direct link between priority needs and main challenges to overcome. However, our agenda is not exhaustive of all priority needs and does not seek to rank them. We are aware that additional global challenges exist, including numerous local and regional disparities.

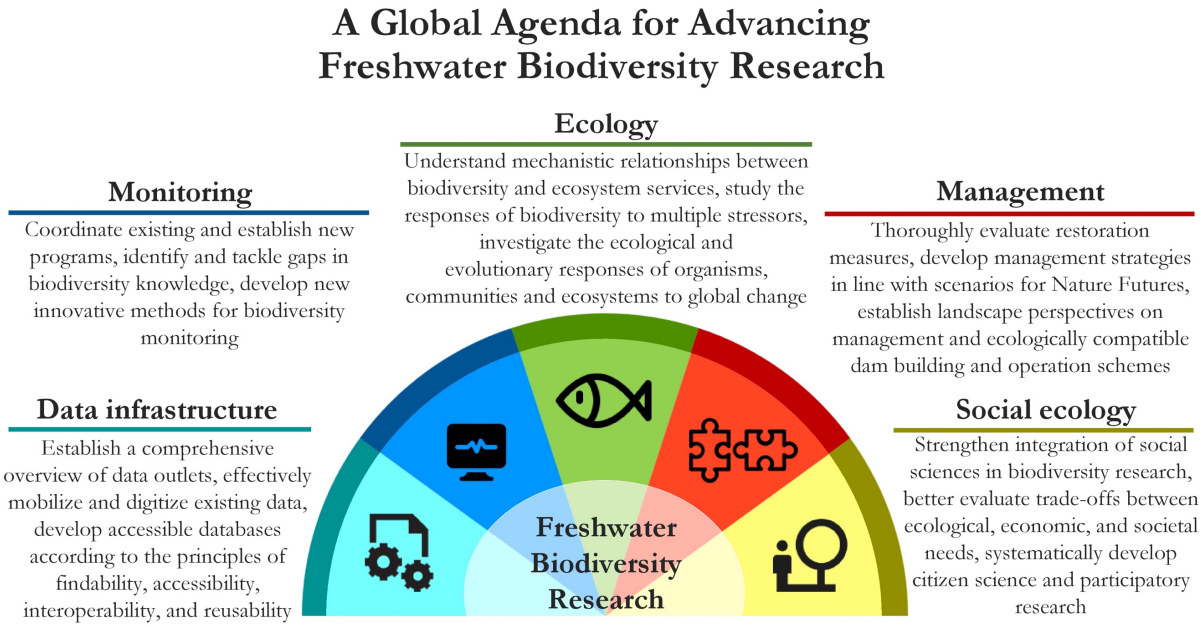

Figure 1: A global agenda for advancing freshwater biodiversity research, consisting of 15 priority needs grouped into five major research areas, all aiming to support research for conservation and management actions.

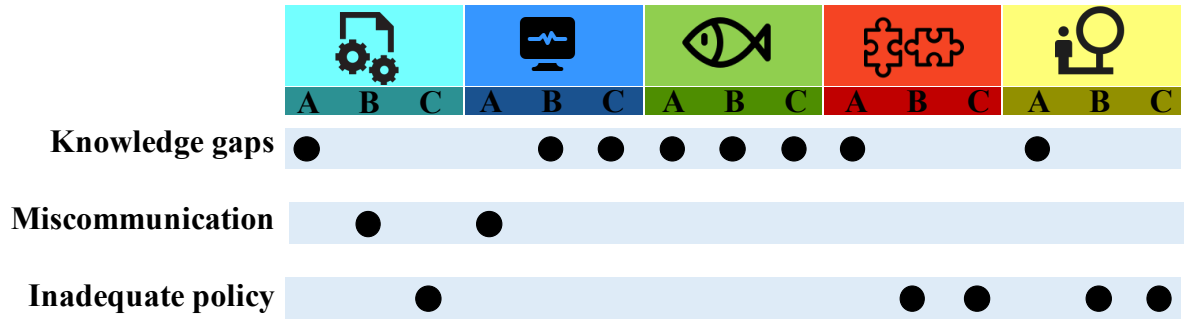

Figure 2: Three main challenges (listed on the left) associated with the global priority needs identified to advance freshwater biodiversity research. A, B, and C are priority needs identified in each of the five research areas as described in the text below.

Our agenda reflects the collective opinion of the authors and grew from a consultation conducted in 2020 (Supplementary Material). The consultation provided a platform for discussing and facilitating the exchange of ideas. The priority needs presented here are an extension of the consultation results. Authors of this agenda represent researchers and policy advocates from 38 countries, 18 (47%) of them considered Global South countries. Out of the 96 authors, 28 (29%) are affiliated to Universities and research institutes in Global South countries, and 16 (17%) self-identify as currently co-creating freshwater biodiversity management and conservation in association with indigenous peoples. Consequently, we

believe that the proposed agenda, with its 15 priority needs, reflects a representative diversity of opinions and constitutes a global synthesis of major priorities for advancing freshwater biodiversity research.

Data infrastructure – Establish and empower information hubs for the acquisition, mobilization, integration, and provision of data across all areas of freshwater biodiversity research. Identified priority needs include:

A. Establish a comprehensive compilation of data sources on freshwater biodiversity and work toward integrating them. This is an essential step for selecting a tractable number of efficient data outlets. Prioritize the use of existing platforms where metadata are available, so that robust and verifiable protocols for data processing, handling, and validation can be implemented (Nesshöver *et al.* 2016; Stephenson & Stengel 2020).
B. Mobilize and make available existing data to facilitate the co-production of biodiversity and conservation research with the wider stakeholder and rights-holder communities. This should be accompanied with the digitization of data from regional and national monitoring agencies, museum collections, and research institutions (Ball-Damerow *et al.* 2019). Special attention should be given to non-English-language sources, which tend to be neglected in global meta-analyses (Konno *et al.* 2020).
C. Develop accessible databases according to the FAIR principles of Findability, Accessibility, Interoperability, and Reusability (Wilkinson *et al.* 2016), in addition to the Nagoya Protocol on access to genetic resources (Buck & Hamilton 2011) and any future agreements concerning genetic and digital resources. As the global community increasingly relies on computational support to process large data, this step is fundamental to increasing data availability and usage by scientists, environmental managers, conservation practitioners, and other associated stakeholders and rights-holders.

Monitoring – Implement strategic programs that efficiently and comprehensively document the status and trends of freshwater biodiversity. Identified priority needs include:

A. Coordinate existing freshwater biodiversity monitoring programs to increase the efficiency of ongoing monitoring activities, with the aim of achieving a globally consistent approach to collecting and assessing biodiversity data (Turak *et al.* 2017). This should be accompanied by the development of probabilistic survey designs to infer the global status of freshwater biodiversity (Hawkins & Yuan 2016) and enhance integration across locations (e.g., Long Term Ecological Research Network (LTER) and Global Lake Ecological Observatory Network (GLEON) sites).
B. Enhance the taxonomic, ecological, and genomic knowledge of freshwater organisms to increase coverage of efficient monitoring across organismal groups and geographical areas. This endeavor will directly benefit biodiversity monitoring specifically and also biodiversity research in ecology at large. Special attention should

be given to fungi, protists, parasites, and other neglected taxa often described as "hidden biodiversity" (Mlot 2004).

C. Develop and improve methodologies to overcome the taxonomic limitations and inefficiencies of monitoring programs (Baird & Hajibabaei 2012; Rimet *et al.* 2021). Such methodologies include (i) omics approaches, which use DNA, RNA, proteins, and the full suite of metabolites; (ii) optic and acoustic recording methods ranging from automated image and video analyses supported by artificial intelligence to remote-sensing technologies involving drone, airplane, and satellite imagery; and (iii) biodiversity informatics, citizen science, and other emerging approaches to gather and process information. Additionally, new developments need to capture dimensions of freshwater biodiversity beyond the traditional concepts of species diversity, notably inter and intraspecific genomic diversity, species interactions that modulate distribution patterns of species in freshwater communities, ecosystem functioning and ecosystem services, and habitat diversity at local to global scales.

Ecology – Strengthen research on freshwater biodiversity and its ecological context, which is fundamental to conservation and management, as are the interactions among organisms and the environment that determine responses to global change. Identified priority needs include:

A. Further identify relationships among biodiversity, ecosystem functioning, and nature's contributions to people (Dudgeon 2010; Díaz *et al.* 2018; Vári *et al.* 2021). This requires developing a mechanistic understanding of these relationships, integrating the multidimensionality of the role of biodiversity in ecosystem processes, and improving process-based models (Tonkin *et al.* 2019) for freshwater biodiversity and their contribution to human well-being.

B. Establish cause-and-effect relationships to understand and predict the responses of biodiversity to multiple stressors (Birk *et al.* 2020) and the release from such stressors. Field and system-wide experimentation that draw on short- (1-3 years) and long-term (>20 years) studies, with associated funding streams, will be necessary to understand the dynamics of change, coupled with modeling to develop future scenarios.

C. Explore the acclimation, evolutionary, and evasion potentials of organisms (Merilä & Hendry 2014), and the associated ecosystem responses to global change (Heino *et al.* 2009; Urban *et al.* 2016; Kelly 2019; Orr *et al.* 2021). Targeted field surveys will be most effective when combined with coordinated multi-site experiments through global research networks and spatially explicit modeling (Alberti *et al.* 2020). Experiments must go beyond small scale mesocosm and microcosm studies, to include large-scale enclosures and exclosures, whole lakes, streams, wetlands, and entire catchments. The coordination will crucially require creative funding mechanisms to establish, maintain, and facilitate effective exchange among long-term and large-scale experimental platforms (e.g., AQUACOSM, a European network of mesocosm facilities for research on marine and freshwater ecosystems open for global collaboration).

Management – Enhance science-based strategies and methods for sustainable freshwater biodiversity management, and ensure that research data, information, and knowledge can be easily accessed by managers and conservation practitioners. Identified priority needs include:

A. Improve outcome assessment of restoration measures using large-scale replication of before-after-control-impact (BACI) designs, a practice still far from being common in current management practices (Geist & Hawkins 2016). Additionally, meta-analyses of results from long-term post-monitoring phases will be essential to assess restoration success and failures, enabling improved design of future restoration programs to recover freshwater biodiversity (Lu *et al.* 2019).
B. Develop models and projections in line with the scenarios for Nature Futures (IPBES 2016; Rosa *et al.* 2017) to shift traditional ways of forecasting human impacts on nature to nature-centered visions that integrate social-ecological interlinkages across biodiversity, ecosystem functions and services, and human well-being (Pereira *et al.* 2020; Kim *et al.* 2021).
C. Develop and test landscape- and catchment-based management and restoration programs that explicitly consider lakes, rivers, ponds, and wetlands. This includes environmentally and ecologically compatible dam schemes to minimize negative impacts. Given the current global surge in hydropower dam construction and planning, and acknowledging the wealth of literature available on the impacts of dams on freshwaters (Reid *et al.* 2019; Zarfl *et al.* 2019; Thieme *et al.* 2021), it is fundamental to implement evidence-based guidelines for improving dam building and operation to preserve ecological connectivity. As a broad-guiding principle, evidence-based strategies need to be implemented to enhance blue infrastructure and preserve the associated ecosystem services provided by freshwater biodiversity.

Social ecology – Design conservation strategies that account for the societal responses to biodiversity change, and consider the social, cultural, and economic context of protecting and recovering freshwater biodiversity. Identified priority needs include:

A. Develop solutions for conflicts between biodiversity conservation and the human use of freshwaters and their catchments, and foster social-ecological approaches that integrate cultural and societal practices in knowledge co-production (Norström *et al.* 2020; Chambers *et al.* 2021). In doing so, it is important to acknowledge the shifting baseline syndrome (Humphries & Winemiller 2009; Soga & Gaston 2018), which refers to the temporal shifts in people's perception of reference states of biodiversity over time when examining how humans value freshwater biodiversity, while ensuring its preservation and restoration in the future.
B. Address trade-offs among ecological, economic, and societal targets by concurrently engaging local communities, scientists, and policymakers to develop adaptive management strategies and measures to protect freshwater biodiversity. This includes embracing traditional and indigenous ecological knowledge (Heino *et al.* 2020).

C. Systematically develop citizen science (McKinley *et al.* 2017; Fritz *et al.* 2019) and participatory research to harness the societal competencies and workforce extending beyond academia and government authorities. This should include developing and sharing new experimental approaches that can be upscaled at low cost. Furthermore, due attention should be given to involving dedicated citizen experts (Eitzel *et al.* 2017), a tremendously valuable and yet often overlooked resource, to advance freshwater biodiversity research.

The ambitious agenda we propose is intended to initiate and advance the strategic development of freshwater biodiversity research and to further support efforts that are underway. The global freshwater biodiversity crisis clearly requires the definition of bold goals and the mobilization of substantial resources to meet the challenges. By identifying the most pressing needs to counter the freshwater biodiversity loss, our agenda is intended to maintain the global momentum recently exemplified by calls for action (Darwall *et al.* 2018), the Emergency Recovery Plan for freshwater biodiversity (Tickner *et al.* 2020) including calls to mobilize practitioners (Twardek *et al.* 2021) and promote strategic activities (Arthington 2021), and the 25 essential questions to inform the protection and restoration of freshwater biodiversity (Harper *et al.* 2021). Our succinct and clear agenda comes at a pivotal time when governments around the world are revising major international agreements relevant to biodiversity conservation (e.g., the Sustainable Development Goals (SDG)), or are at the brink of major conventions including the Convention on Biological Diversity (CBD) and the UN Framework Convention on Climate Change (UN-FCCC). We believe these 15 priority needs are critical for the successful protection and recovery of freshwater biodiversity globally. We call upon scientists, conservation practitioners, environmental managers, and policymakers to support this agenda.

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