Title: A Global Agenda for Advancing Freshwater Biodiversity Research

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Abstract: Freshwater biodiversity is declining dramatically, and the current biodiversity crisis requires defining bold goals and mobilizing substantial resources to meet the challenges. While the reasons are varied, both research and conservation of freshwater biodiversity lag far behind efforts in the terrestrial and marine realms. We identify fifteen pressing global needs 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: Freshwater biodiversity, Global biodiversity crisis, Research priority, Data infrastructure, Monitoring, Ecology, Management, Socio-ecology

Freshwater biodiversity encompasses genes, populations, species, communities, and ecosystems, and provides essential ecosystem services that are fundamental for human livelihoods and well-being. Freshwater biodiversity, however, is disproportionately threatened at unprecedented rates. The most recent Living Planet Report documents on average 84% decline of abundances of 3,741 monitored populations – representing 944 vertebrate species –in freshwater habitats since 1970, the steepest decline of any of the major realms: land, oceans, and fresh waters[1]. Yet, research on and conservation of freshwater biodiversity have been insufficiently prioritized. Freshwater biodiversity remains underappreciated relative to marine and terrestrial biodiversity[2-4]. International and intergovernmental science-policy platforms and funding agencies continue to fall short of giving freshwater biodiversity its rightful place in global biodiversity, climate, and socio-economic forums[5-7], often including freshwater biodiversity in the terrestrial realm or simply overlooking it.

We propose an agenda to advance freshwater biodiversity research as a critical step in supporting and improving coordinated action towards its sustainable management and conservation. Our agenda informs funding provision, provides guidance to civil society and governmental agencies, and spurs scientists and policymakers to engage with each other to support informed global freshwater biodiversity stewardship. Our agenda does not constitute an exhaustive assessment of all priority needs, nor does it aim to rank them. Instead we identify fifteen pressing global needs, grouped into five major research areas to support conservation and management actions (Fig. 1). The global needs reflect the collective opinion of the coauthors based on responses to a consultation conducted in 2020 and described in the supplementary document.

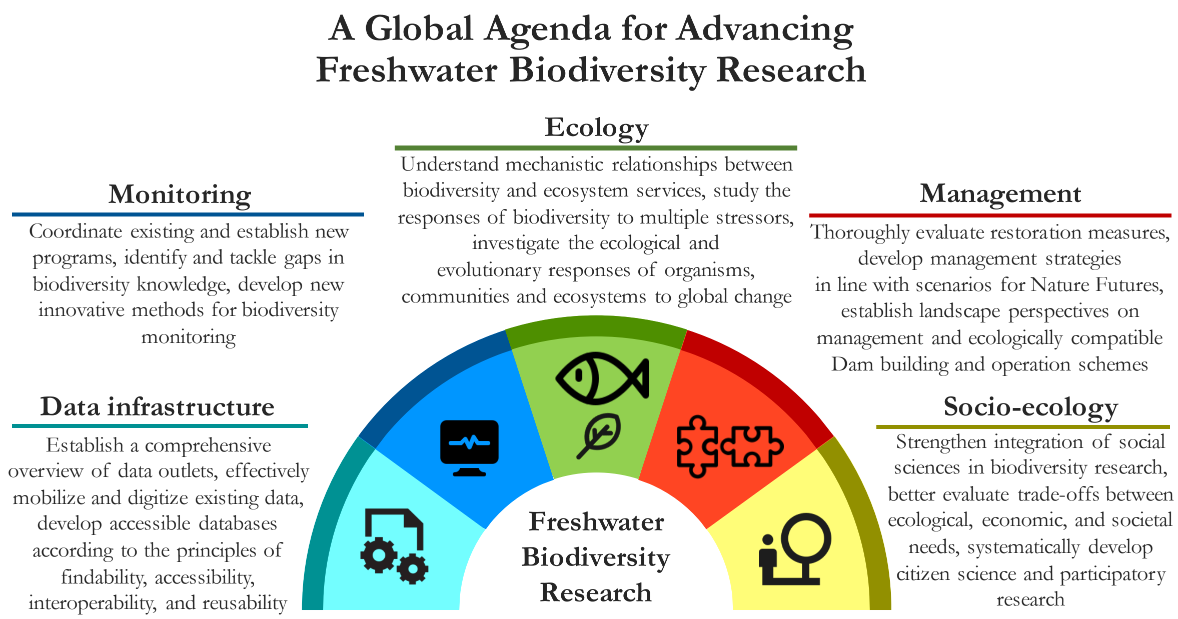

Figure 1: A global agenda for advancing freshwater biodiversity research, with a summary of fifteen priority global needs in five major areas to support research for conservation and management actions.

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

- Establish a comprehensive compilation of data sources on freshwater biodiversity that documents their interrelationships. This step is essential to select a tractable number of efficient outlets and prioritize the use of existing platforms where metadata are available, such that robust and verifiable protocols for data processing, handling, and validation can be implemented.
- Mobilize and make available existing data for the wider research community by digitizing data from regional and national monitoring agencies, museum collections, nature conservation associations, and research institutions, among others. Special attention must be given to non-English-language sources, which tend to be neglected in global meta-analyses.
- Develop accessible databases according to the FAIR principles of Findability, Accessibility, Interoperability, and Reusability[8], in addition to the Nagoya Protocol on access to genetic resources[9].

Monitoring – Strategic programs that efficiently and comprehensively document the status and trends of development of freshwater biodiversity are key to research, management, and conservation. Necessary steps include:

- Coordinate existing freshwater biodiversity monitoring programs to increase the efficiency of ongoing monitoring activities, develop probabilistic survey designs to infer the global status of freshwater biodiversity[10], and enhance integration across locations (e.g., LTER, GLEON sites).
- Enhance the taxonomy and ecological knowledge of freshwater organisms to increase coverage of organismal groups and geographical areas. Special attention to fungi, protists, and other neglected taxa often described as "hidden biodiversity"[11] is required.
- Develop and improve methodologies to overcome the taxonomic limitations and inefficiencies of monitoring programs. Such methodologies include (i) omics, which use DNA, RNA, proteins, and the full suite of metabolites; (ii) optics, ranging from automated image analysis or artificial intelligence supported video, to remote-sensing technologies such as drones and satellites; and (iii) biodiversity informatics, citizen science, and other emerging approaches to gather and processing information. Additionally, new developments need to capture dimensions of freshwater biodiversity beyond taxa diversity, notably interspecific genetic diversity, species interactions that modulate biogeographic patterns of species in freshwater communities, ecosystem functioning and ecosystem services, and habitat diversity.

Ecology – Ecological context is key to conservation and management, as are the interactions among organisms and the environment that determine the responses to global change. We advocated developing research to identify major local, regional, and global drivers affecting patterns of change in freshwater biodiversity. Required steps includes:

- Further identify relationships among biodiversity, ecosystem functioning, and nature's contributions to people. 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 for freshwater biodiversity and their contribution to human well-being.
- Establish cause-and-effect relationships to understand and predict the responses of biodiversity to multiple stressors and the release from such stressors. Field and system-wide experimentation will be necessary to achieve this step, coupled with modeling to develop current and future scenarios and identifying general principals.
- Explore the acclimation, evolutionary, and evasion potentials of organisms, and the associated ecosystem responses to global change. Targeted field surveys, combined with coordinated multi-site experiments through global research networks, will be required. Such and effort should include large-scale enclosures, exclosures, and experimental lakes, streams, wetlands, and entire catchments. However, new and creative funding mechanisms will be crucial to establish and maintain long-term and large-scale experimental platforms to advance this research (e.g., AQUACOSM).

Management – Enhance science-based strategies and methods for sustainable freshwater biodiversity management. Necessary steps include:

- Improve outcome assessment of restoration measures using large-scale replication of before-after-control-impact (BACI) designs, including long-term post-monitoring phases. Meta-analyses of results from post-monitoring phases will be essential to explain restoration success and failures and to provide the foundations for a fundamental rethinking of restoration programs to recover freshwater biodiversity.
- Develop models and projections in line with the scenarios for Nature Futures[12,13] and promote research that expands and evaluates nature-based solutions (e.g., constructed wetlands and riparian buffer strips) for management strategies.
- Develop and test landscape- and catchment-based restoration programs including lakes, ponds and wetlands, and develop and test environmentally and ecologically compatible dam schemes to minimize ecological impacts. Given the current global surge in hydropower dam construction and planning[14], biodiversity research on the impacts of such dams must improve to support regulatory instruments, preserve the longitudinal connectivity and migratory corridors, and accompany the sustainable management of freshwater biodiversity. More broadly, strategies are needed to enhance blue infrastructures and the associated ecosystem services provided by both large and small, lentic and lotic freshwater ecosystems.

Socio-ecology – Considering freshwater biodiversity in its socio-economic context and societal responses to biodiversity change and conservation are essential to design conservation implementation strategies. Proposed steps include:

- Develop solutions for conflicts between biodiversity conservation and the human use of freshwater ecosystems and their catchments. Socio-ecological approaches that integrate cultural and societal practices in knowledge co-production are needed[15]. The shifting baseline syndrome[16,17] needs to be acknowledged when examining how humans value freshwater biodiversity at present while ensuring its preservation and restoration for the future.
- 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[18].
- Systematically develop citizen science[19,20] and participatory research to harness the societal competencies and workforce that extend beyond academia and government. Developing and sharing methods and designing new experimental approaches that can be scaled at low cost are critical aspects for consideration. Additionally, we should place greater emphasis on engaging dedicated citizen experts[21], a tremendously valuable yet often overlooked resource to advance freshwater biodiversity research.

In conclusion, we propose an ambitious agenda to initiate and further support the strategic development of freshwater biodiversity research to document patterns, processes and changes, and to improve management and conservation. Our agenda provides a framework for the pressing needs to counter the unprecedented global challenges faced by freshwater biodiversity. The proposed steps underscore major research priorities to cultivate informed global action to protect and sustainably manage freshwater biodiversity. Research needs and priorities vary regionally, and the development of regional agendas and priorities are an essential next step. Clearly, the current freshwater biodiversity crisis requires defining bold goals and mobilizing substantial resources to meet the challenges. We call upon scientists, policymakers, and stakeholders to provide the necessary support for a powerful agenda to protect our fresh waters, which provide the key resources for the sustainable development and functioning of our societies.

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