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VIEWPOINT

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 mobilisation 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 stewardship of freshwater biodiversity. The proposed agenda aims to advance freshwater biodiversity research globally as a critical step in improving coordinated actions towards its sustainable management and conservation.

K E Y W O R D S
data infrastructure, ecology, freshwater biodiversity crisis, freshwaters, management, monitoring, research priorities, social ecology

Freshwater biodiversity encompasses the genes, populations, species, communities and ecosystems of all freshwaters, and provides essential ecosystem services that are fundamental for human livelihoods and well-being (Dudgeon et al., 2006). This biodiversity is currently 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 3741 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 this unprecedented and ongoing decline, research on and conservation of freshwater biodiversity have been insufficiently prioritised. 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; Heino et al., 2021; Tickner et al., 2020). For instance a recent report on environmental funding by 127 European foundations (Moralis, 2021) shows that freshwaters received a mere 1.75% of € 745 million (US$ 873 million) in environmental grants awarded in 2018 and ranked next-to-last among the 13 thematic-issue categories used to assess grant distribution.

Here, we propose an agenda for advancing freshwater biodiversity research globally. We view this as a critical step in supporting and improving globally coordinated actions towards the sustainable management and conservation of freshwaters. Our agenda aims to inform funding provision and provide guidance to civil society, philanthropic organisations 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 (Figure 1). Acknowledging that the 15 priority needs reflect different types of challenges, we grouped the challenges into three categories (Figure 2) summarising: (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 identify the main challenges as a first step towards overcoming the current barriers. The 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.

Our agenda reflects the collective opinion of the authors and grew from a consultation conducted in 2020 among a diverse panel of freshwater biodiversity researchers (Supporting Information). 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. The 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 with universities and research institutes in the Global South, and 16 (17%) self-identify as currently co-creating freshwater biodiversity management and conservation in association with indigenous peoples.

A Global Agenda for Advancing Freshwater Biodiversity Research

Ecology
Understand mechanistic relationships between biodiversity and ecosystem services **(A)**, study the responses of biodiversity to multiple stressors **(B)**, investigate the ecological and evolutionary responses of organisms, communities and ecosystems to global change **(C)**

Monitoring
Coordinate existing and establish new programs **(A)**, identify and tackle gaps in biodiversity knowledge **(B)**, develop new innovative methods for biodiversity monitoring **(C)**

Management
Thoroughly evaluate restoration measures **(A)**, develop management strategies in line with "Nature Futures" scenarios **(B)**, establish perspectives on management and ecologically compatible dam building and operation schemes **(C)**

Data infrastructure
Establish a comprehensive overview of data outlets **(A)**, effectively mobilize and digitize existing data **(B)**, develop accessible databases according to principles of Findability, Accessibility, Interoperability and Reusability **(C)**

Social ecology
Strengthen integration of social sciences in biodiversity research **(A)**, better evaluate trade-offs between ecological, economic, and societal needs **(B)**, systematically develop citizen science and participatory research **(C)**
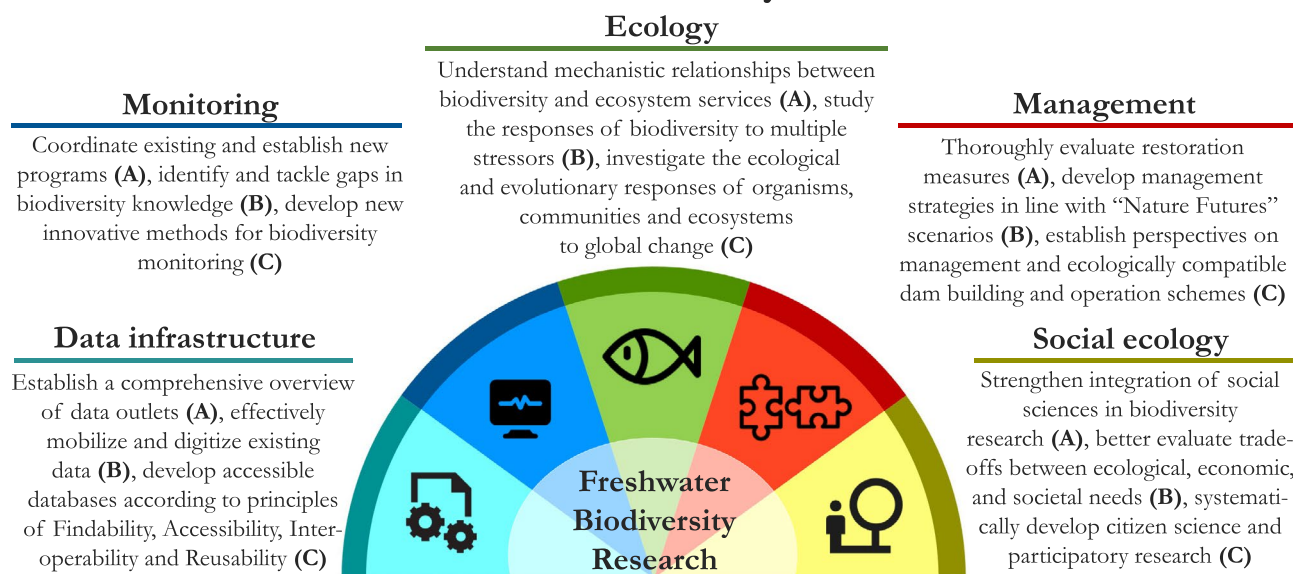
Freshwater Biodiversity Research

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. A, B and C correspond to the priority needs as described in the text below
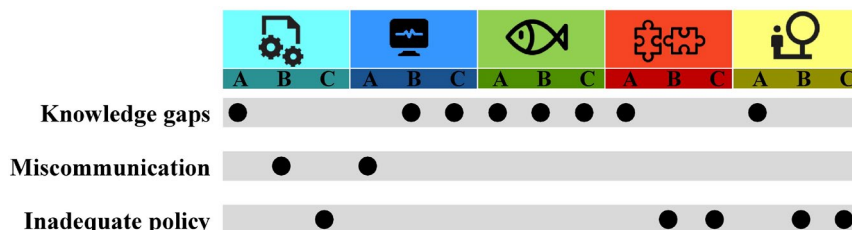
FIGURE 2 Three main challenges (listed on the left) associated with the global priority needs identified to advance freshwater biodiversity research. Knowledge gaps correspond to limited research, disparities in access to information or both; miscommunication corresponds to insufficient communication and exchange among scientists, practitioners, managers and policy makers; and inadequate policy corresponds to deficient 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. A, B and C correspond to the priority needs identified in each of the five research areas as described in the text below

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, mobilisation, 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 towards integrating them. This is an essential step for selecting a tractable number of efficient data outlets. Prioritise the use of existing platforms where metadata are available (e.g. the Global Biodiversity Information Facility or the Freshwater Information Platform), so that robust and verifiable protocols for data processing, handling and validation can be implemented (Nesshöver et al., 2016; Stephenson & Stengel, 2020).

B Mobilise and share existing data to facilitate the co-production of biodiversity and conservation research with the wider stakeholder and rights-holder communities. This effort should be accompanied by the digitisation 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 programmes that efficiently and comprehensively document the status and trends of freshwater biodiversity. Identified priority needs include:

A Coordinate existing freshwater biodiversity monitoring programmes 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 endeavour will directly benefit biodiversity monitoring specifically and biodiversity research in ecology at large. Special attention should be given to parasites, fungi, protists 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 programmes (Baird & Hajibabaei, 2012; Rimet et al., 2021). Such methodologies include (i) omics approaches based on DNA, RNA, proteins and the full suite of metabolites; (ii) optic and acoustic recordings 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 that can gather and process large amounts of 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 (Díaz et al., 2018; Dudgeon, 2010; 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 draws 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 modelling 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; Kelly, 2019; Orr et al., 2021; Urban et al., 2016). Targeted field surveys will be most effective when combined with coordinated multi-site experiments through global research networks and spatially explicit modelling (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 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 programmes 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-centred visions that integrate social-ecological interlinkages across biodiversity, ecosystem functions and services and human well-being (Kim et al., 2021; Pereira et al., 2020).
C Develop and test landscape- and catchment-based management and restoration programmes that explicitly consider lakes, rivers, ponds and wetlands. This includes environmentally and ecologically compatible dam schemes to minimise 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; Thieme et al., 2021; Zarfl et al., 2019), 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 (Chambers et al., 2021; Norström et al., 2020). In doing so, it is important to acknowledge the shifting baseline

syndrome (Humphries & Winemiller, 2009; Soga & Gaston, 2018), which refers to the shifts in people's perception of reference states 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 (Fritz et al., 2019; McKinley et al., 2017) 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. Addressing the 15 priority needs entails increased collaboration and cooperation among stakeholders if we expect to satisfy the growing demands humans place upon freshwater ecosystems while ensuring that enough water of sufficient quality remains to sustain them. A stronger political commitment will be necessary to accompany freshwater biodiversity conservation as the critical global biodiversity crisis requires the definition of bold goals and the mobilisation 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), such as the Emergency Recovery Plan for freshwater biodiversity (Tickner et al., 2020). This includes mobilising practitioners (Twardek et al., 2021), promoting strategic activities (Arthington, 2021) and embracing 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, such as the Sustainable Development Goals, or are at the brink of major conventions including the Convention on Biological Diversity and the UN Framework Convention on Climate Change. We are convinced these 15 priority needs are critical for the successful protection and recovery of freshwater biodiversity globally. Therefore, we call upon scientists, conservation practitioners, environmental managers and policymakers to support this agenda and implement it by developing local, regional and global actions that offer concrete responses to halt the loss and improve the recovery of freshwater biodiversity.

AUTHOR CONTRIBUTIONS
AM led the writing and development of the manuscript with significant contributions from HPG, JMJ, MTM, MOG, SD and SCJ. SCJ led the consultation that resulted in this agenda with significant contributions from JMJ, MTM, SD, RBS, FL and DH. All authors contributed to writing and revising the manuscript.

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