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Protecting and restoring habitats to benefit freshwater biodiversity

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Abstract

Freshwater biodiversity is under great threat across the globe as evidenced by more severe declines relative to other types of ecosystems. Some of the main stressors responsible for these concerning trends is habitat fragmentation, degradation, and loss stemming from anthropogenic activities, including energy production, urbanization, agriculture, and resource extraction. Habitat protection and restoration both play an integral role in efforts to save freshwater biodiversity and associated ecosystem services from further decline. In this paper, we summarize the sources of threats associated with habitat fragmentation, degradation, and loss and then outline response options to protect and restore freshwater habitats. Specific response options are to legislate the protection of healthy and productive freshwater ecosystems, prioritize habitats for protection and restoration, enact durable protections, conserve habitat in a coordinated and integrated manner, engage in evidence-based restoration using an adaptive management approach, ensure that potential freshwater habitat alterations are mitigated or off-set, and future-proof protection and restoration actions. Such work should be done through a lens that engages and involves local community members. We identify three broad categories of obstacles that could arise during the implementation of the response options outlined: (a) scientific (e.g., inaccessible data or uncertainties), (b) institutional and management (e.g., capacity issues or differing goals across agencies), and (c) social and political (e.g., prioritizing economic development over conservation initiatives). The protection and restoration of habitats is key to Bend the Curve for freshwater biodiversity, with a comprehensive, connected, and coordinated effort of response options needed to protect intact habitats and restore fragmented, degraded, and lost habitats and the biodiversity and ecosystem services that they support.

Key words: environmental management, aquatic ecosystems, fisheries, Anthropocene, conservation

Introduction

Despite covering a very small proportion of the Earth's surface, freshwater ecosystems support a high amount of biodiversity (WWF 2022), providing important ecosystem functions and services (Postel and Carpenter 1997; Creed et al. 2017) and forming the foundation of livelihoods for billions of people (Lynch et al. 2016). Unfortunately, freshwater ecosystems and their biota are facing many threats and are in a crisis state (Harrison et al. 2018; Tickner et al. 2020). Specifically, freshwater species are experiencing rapid population declines of 83% (WWF 2022), and habitat fragmentation, degradation, and loss have been identified as the leading threat to freshwater biodiversity (Dudgeon et al. 2006; Reid et al. 2019). Given the remarkable declines of freshwater species, it is imperative that we protect remaining intact systems, avoid further habitat deterioration, and promote recovery (Tickner et al. 2020).

Global events and initiatives have been launched to mitigate the ongoing loss of freshwater biodiversity, including the UN Convention on Biodiversity (CBD), the UN

Decade on Biodiversity (2011–2020), and the UN Decade on Ecosystem Restoration (UN DER; 2021–2030). A major constraint on the efficacy of these global initiatives to "Bend the Curve" and reverse worldwide declines in freshwater biodiversity loss is that until December 2022, freshwater ecosystems were not explicitly mentioned in the UN CBD (https://www.worldwildlife.org/blogs/sustainability-works/posts/inland-waters-finally-get-the-mention-they-deserve). Further, the global agenda to protect 30% of lands and waters by 2030 (i.e., 30 × 30) and the UN DER signify the challenges faced in curbing freshwater biodiversity losses and restoring species populations (Moravek et al. 2023). As we aim to elevate the profile of freshwater biodiversity, we are starting to see positive trends in protection and restoration efforts at local, regional, and global scales. For example, there have been increasing numbers of bright spots of freshwater habitat restoration, including the provision of fishways (e.g., Baumgartner et al. 2014), the removal of dams in the US and Europe to restore habitat connectivity (e.g., Bellmore et al. 2017), and campaigns to protect a million miles of rivers by 2030 in the US (https://www.americanrivers.org/protect-1-million-miles-of-rivers/). The UN Water Conference, held in March 2023, included the launch of the Freshwater Challenge, a nation-driven initiative that aims to leverage the support needed to bring 300,000 km of rivers and 350 million hectares of inland waters under restoration by 2030 (https://www.unep.org/news-and-stories/press-release/largest-river-and-wetland-restoration-initiative-history-launched-un).

Freshwater habitat is being identified explicitly as a priority for protection and restoration. Habitat protection has been a dominant strategy for conservation of biodiversity, where human disturbance is minimized or eliminated from specific areas of the environment (Crivelli 2002). Relative to marine protected areas, freshwater protected areas remain an underused strategy despite evidence suggesting that they may be effective at reducing the impacts associated with anthropogenic stressors (Saunders et al. 2002; Suski and Cooke 2007; Azevedo-Santos et al. 2019). Habitat protection, in the sense of protected areas, is usually focused on preserving areas that are more intact with limiting extraction of biological resources. More recent developments of protection strategies are more broad ranging, for example, including other effective area-based conservation measures (OECMs) and strategies such as "Rights of Rivers" that may include protection of less intact ecosystems (https://www.nature.org/content/dam/tnc/nature/en/documents/Pathway_for_Inland_Waters_Nov_2022.pdf). On the other hand, habitat restoration is usually focused on assisting the recovery of ecosystems back to a more undisturbed state through management actions (Hobbs and Harris 2001). Habitat restoration and protection can be combined into multidimensional strategies that can extend beyond habitat to specific species (e.g., headstarting imperiled freshwater turtles in captive breeding facilities; Mullin et al. 2023) and entire ecosystems (e.g., restoration of the lower Danube River across multiple countries; Schiemer et al. 1999). Taken together, these two strategies can mitigate past and present anthropogenic stressors and reduce the risk of future threats.

In this paper, we offer a new vision for freshwater habitat protection and restoration that is ambitious yet practical in efforts to Bend the Curve. Although in Tickner et al. (2020), the priority Action refers to critical habitat, we have opted to examine habitat more broadly, due to variations in definition and legality across species, populations, and political boundaries (Hagen and Hodges 2006; Rosenfeld and Hatfield 2006). We first provide an overview on the impact of habitat fragmentation, degradation, and loss on increasingly imperiled freshwater species. From there, we identify response options that aim to prevent further biodiversity loss by protecting intact habitats and restoring those habitats that are degraded or destroyed. We share case studies of successful implementation of these response options, describing the conditions and contexts that have enabled that success. We underscore the need to go back to basics during the implementation of these response options—starting with the identification of ecological attributes and identification of key species that can drive the design of effective interventions. This paper, in combination with the other five Emergency Recovery Plan Actions, offers guidelines required to Bend the Curve to save freshwater biodiversity. Given that habitat protection and restoration are inherently connected to other Actions (e.g., restoring connectivity—see Thieme et al. 2023; use of protected areas to prevent overexploitation of biological and aggregate resources—see Cooke et al. in press), we acknowledge that there is perhaps more overlap between this Action and others emphasizing the need to implement the Actions in a coordinated manner.

The issue

Freshwater ecosystems include many different types of habitats, including rivers, wetlands, ponds, streams, and lakes, which collectively support at least 126 000 species, representing 10% of all known species on Earth (Balian et al. 2008) from glacial fed streams in high mountains to carbon-storing peatlands to brackish estuaries where freshwater rivers meet saline waters. Collectively, there are three categories of freshwater ecosystems: lentic (i.e., ponds or lakes), lotic (i.e., rivers or streams), and palustrine habitats (e.g., soils that are at least partially inundated, wetlands). Societies and economies across the globe rely on the estimated 20–32 different ecosystem services provided by freshwater ecosystems (Postel and Carpenter 1997; Vári et al. 2022). These ecosystem services include provisioning (i.e., food, fiber, and drinking water), regulating (i.e., flood and drought mitigation, erosion control, and water quality), and cultural (i.e., recreational, symbolic, and well-being) services. There will always be inherent conflict between humans and organisms due to the mutual and perpetual need for freshwaters (Vári et al. 2022). Yet, for sustainable ecosystem management and water security, we should strive to strike a balance between all competing interests (Zeitoun 2014). Further, freshwater ecosystems have suffered more extensive declines relative to other ecosystem types. Although there are many different causes for biodiversity declines (see Dudgeon et al. 2006; Reid et al. 2019), habitat damage and destruction are among the most devastating.

Population viability is highly dependent on the availability of habitat. Habitat is defined as the resources and environmental conditions (i.e., physical, chemical, and biological) required for individuals to persist (Hall et al. 1997). Habitats can be broken down into patches, where animals may move among them to achieve at least one ecological function linked to demographic success (e.g., reproduction, survival, growth, or refuging) (Lapointe et al. 2014). Freshwater habitats can be negatively impacted by anthropogenic activities through direct (e.g., substrate extraction; see Cooke et al. in press) or indirect (e.g., forestry or agriculture within the watershed) manipulations (Dudgeon et al. 2006). Anthropogenic effects on habitats can be categorized into the fragmentation (i.e., configuration), degradation (i.e., quality), or loss (e.g., infill) of habitats, as well as the cumulative effects of anthropogenic stressors that have deleterious impacts on species and the ecosystems they inhabit.

Habitat fragmentation (which is related to habitat loss) can occur when patches of contiguous habitat become altered, resulting in smaller, more disparate areas, therefore negatively impacting connectivity. A highly recognizable example of habitat fragmentation within freshwater ecosystems are dams used for hydropower, irrigation, water control, weirs, and the like on rivers, but other types of barriers include crossings (e.g., roads or railway), water withdrawals, or water quality (e.g., thermal or chemical barriers). Decreased connectivity via habitat fragmentation impacts the distribution and movement of aquatic organisms, as well as energy/nutrient exchange. For freshwater fishes, decreased connectivity has been shown to reduce growth rates, decrease feeding, and force individuals into sub-optimal environments, which negatively impact performance and ultimately populations, putting species in jeopardy (Jeffrey et al. 2015).

Habitat degradation can occur when anthropogenic activities decrease the quality of the habitat (while the quantity may remain intact), which may still be able to support some of the original biodiversity (Dudgeon et al. 2006). Specifically, the physical, chemical, or biological attributes within that habitat become altered (Minns 1997). The degradation of freshwater habitats can occur from source (e.g., wastewater treatment plant on a river) or non-point source (e.g., the application of fertilizer to agricultural fields within the watershed) pollutants (Albert et al. 2021). For example, the occurrence of Eurasian otters (*Lutra lutra*) in Spain was directly linked to several habitat quality measures: water pollution, conductivity, temperature, and flow (Prenda et al. 2001).

Habitat loss occurs when destroyed areas no longer provide many of the resources or conditions of the pre-existing ecosystem, ultimately leading to a decrease in the quantity of habitat (Pardini et al. 2017). Examples of anthropogenic activities that contribute to the reduction of freshwater habitat quantity include land infilling or dredging, as well as water withdrawal, draining, or diversions. Habitat loss is not limited to the freshwaters alone; destruction of riparian habitat (e.g., through deforestation) or floodplains can also have a significant negative impact on freshwater ecosystems (Dala-Corte et al. 2020). Habitat loss can have devastating impacts on populations, lead to species endangerment, and have cascading adverse effects throughout freshwater ecosystems. Indeed, both fish abundance and biomass have been positively linked to the quantity of available suitable habitat (Lapointe et al. 2014).

It is rare that freshwater habitat alterations occur independently of each other. Multiple sub-lethal alterations can accumulate, affecting freshwater biodiversity and their ecosystems (Langer 2000). Unfortunately, due to the interacting nature of these multiple alterations that are now being exacerbated by climate change, it can be difficult to assess and manage, although their importance has received increased recognition as of late (e.g., the inclusion of inland waters in the UN CBD or Fisheries and Ocean Canada's Consideration of Cumulative Effects; see https://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2022/2022_055-eng.html).

Response options

Tickner et al. (2020) identified the Action of protecting and restoring habitats to Bend the Curve for global freshwater biodiversity. To expand upon this Action, we identify seven response options (Fig. 1) and explore the application of each response option through case studies, providing examples of protection (Table 1) and restoration (Table 2). All response options must be founded on the best available scientific evidence. Readers are encouraged to consult Conservation Evidence (summaries of evidence on conservation actions; see https://www.conservationevidence.com/) or evidence syntheses conducted to the standards of the Collaboration for Environmental Evidence (an independent source of reliable evidence informing decision-making in environmental management; see https://environmentalevidence.org/). Those sources of evidence should be supplemented with knowledge of community members (including rights holders) and practitioners given that much of the knowledge about protection and restoration efforts (especially failed attempts) do not appear in traditional peer-reviewed outlets.

1. Legislate the protection of healthy and productive freshwater ecosystems

The most straightforward measure for protecting freshwater ecosystems is to have legislation, other policies, and agreements that acknowledge habitat as the foundation for healthy and productive freshwater ecosystems (Lapointe et al. 2014). Yet, in practice, this is not always simple, given complicating factors such as competing interests, weak governance structures, prioritizing development over environmental protections, corruption, and so on. We recognize that development of infrastructure (e.g., housing, hydroelectric capacity, irrigation systems, and roads) is essential to human progress, and questioning such activities is beyond the scope of this paper (see Forman 1993; Parisi 2022). However, when such development activities are being considered, it is crucial to ensure that all efforts are taken to consider the potential consequences of such activities, evaluate alternative sites (especially in the context of hydropower) and forms of development, and embrace mitigation strategies (e.g., Robec

Fig. 1. Response options to Bend the Curve for freshwater biodiversity through freshwater habitat protection and restoration.

and Hanson 2009; Person et al. 2014) or compensation efforts (off-setting; Moilanen and Kotiaho 2018; see Guillet and Semal 2018 for critique of off-setting; Accatino et al. 2018; Creed et al. 2022) that collectively achieve no net loss of freshwater habitats.

Around the globe, protection efforts for freshwater habitat range from reasonably robust to entirely absent (Higgins et al. 2021; Perry et al. 2021*a*). Creating a minimum level of protection (Yagerman 1990) and embedding that within all government bodies (Moynihan and Magsig 2020) would be a significant advance over the status quo. In more recent years, there have been increasing actions to legally grant rivers personhood status (e.g., in New Zealand, India, Australia, and Ecuador), which transforms these ecosystems from being subjects of rights to a legal entity that owns their rights (see Table 1; Hutchison 2014; Clark et al. 2019; Cyrus R. Vance Center for International Justice 2020). Nonetheless, it is one thing to have such protective legislation in place, but it is another to provide developers (proponents) and regulators with functional tools to operationalize policies in ways that yield desired goals (e.g., Toews and Brownlee 1981; Braden et al. 1989; Clare and Creed 2022). For example, if legislation and regulations are in place, there needs to be mechanisms to ensure compliance (Quigley and Harper 2006). This means that institutions need compliance staff as well as the necessary legal mechanisms to bring charges or levy penalties. When charges are laid, it then requires the judiciary to take those cases seriously rather than dismiss them to focus on other societal criminal issues (e.g., violence and theft). Judicial tone is often dictated by societal values (Mishler and Sheehan 1996), emphasizing the role of public and politicians in recognizing the value of protecting freshwater habitat (Cooke et al. 2013). In summary, protecting individual freshwater species has value but given that all aquatic life is dependent upon freshwater habitat, efforts that protect habitat have manifold benefits that transcend species while also benefiting humanity. Making freshwater habitat protections explicit and supported by all branches of government (executive, legislative, and judicial) and spanning levels (international to regional) is essential.

Case study: legislating minimal flows for ecological protection in Mexico

The San Pedro Mezquital river (SPM) crosses the western Sierra Madre connecting the Chihuahuan Desert in the Mexican highlands with the wetland of international importance, Marismas Nacionales Nayarit Biosphere Reserve (200,000 ha Ramsar Site 732; see Fig. 2A). Given the role that instream wa-

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Table 1. Examples of habitat protection focused on various freshwater taxa.

Location of protected habitat	Taxa	Details	Reference
Protected areas throughout China	Amphibian	Predicted declines of amphibian species richness were lower in protected versus unprotected habitats	Chen et al. (2017)
Protected areas across Myanmar	Bird	Woolly necked storks (*Ciconia episcopus*) used wetlands more inside protected areas compared to outside	Non and Sundar (2020)
Phu Luang Wildlife Sanctuary, Thailand	Crustacean	Six species of freshwater crabs will lose the amount of suitable habitat within protected areas under climate change, while two species will experience gains	Yousefi et al. (2022)
Freshwater protected areas in Ontario, Canada	Fish	Freshwater protected areas resulted in higher abundances for largemouth bass (*Micropterus salmoides*) and shiner species, with evidence of spillover to adjacent areas	Zolderdo et al. (2019)
Periyar Tiger Reserve, Western Ghats, India	Fish	Within this key biodiversity area (as designated by the IUCN), eight endangered fish species have triggered additional protection under the Alliance for Zero Extinction	Molur and Raghavan (2014)
Mae Ngao Community Fish Reserve, Thailand	Fish	This OECM is a fisheries reserve that is managed by Indigenous P'ganyaw (Karen) communities where they enforce boundaries, develop penalties for noncompliance, and sell licenses for angling	Koning et al. (2020)
Keibul Lamjao National Park (Ramsar site), India	Insect	While the protected site did support aquatic insect diversity, they were impacted by anthropogenic activities outside the protected areas in the watershed	Takhelmayum and Gupta (2015)
Manu National Park, Peru	Mammal	Giant otter (*Ptreronura brasiliensis*) are particularly sensitive to human disturbance, emphasizing the importance of protected areas	Groenendijk et al. (2014)
Kejimkujik National Park, Nova Scotia, Canada	Reptile	Protection of at-risk Blanding's turtles (*Emydoidea blandingii*) within a national park was required to mitigate against depredation of eggs	Standing et al. (2000)
5-Country Biosphere Reserve Mura–Drava–Danube, Europe	Multi-species	Protection of freshwater lotic and floodplain habitats for various endangered species at a UNESCO OECM that connects Austria, Croatia, Hungary, Serbia, and Slovenia	Köck et al. (2022)
Riparian Zones, Mongolia	Multi-species	The Mongolian government has designated millions of hectares of riparian habitats through OECM to protect aquatic habitat, water quality, and connectivity from mining activities and development	The Nature Conservancy, Conservation International, IUCN World Commission on Protected Areas and WWF (2022)
Whanganui River, New Zealand	Multi-species	The river was granted legal personhood status, changing it from a property subject to rights to a person who is an owner of rights.	Hutchison (2014)

Note: Although the application of protected areas within freshwaters remains underutilized, this is a promising strategy that has been used more extensively throughout terrestrial and oceanic ecosystems. More research is required to improve the implementation and efficacy of protected areas. OECMs = other effective area-based conservation measures.

ter, sediments, and nutrients play in Marismas Nacionales, flow variability of discharging rivers is a protected area management plan milestone for sustaining the crucial habitat of aquatic species, the ecosystem's ecological integrity, wetland dynamics, and related environmental services (SEMARNAT-CONANP 2013). In 2014, the SPM river became the first watershed out of nearly 300 in Mexico with a water reserve enacted for environmental protection for about 84% of the mean annual runoff based on current flow regime attributes and components (Presidencia de la República 2014; Moir et al. 2016; Harwood et al. 2017; Salinas-Rodríguez et al. 2018, 2020). Such an amount of water for the environment protects the riverine ecosystem against unsustainable use rates. According to Mexican legislation, an environmental water reserve (EWR) is the volume of water to "guarantee minimal flows for ecological protection, including the conservation or restoration of vital ecosystems" (National Water Law, Article 41; Presidencia de la República 1992), and is determined based on the technical norm or standard for conducting environmental flow assessments (Barrios Ordóñez et al. 2015;

Table 2. Examples of targeted restoration or enhancement activities focus on a specific site or taxa.

Restoration activity	Taxa	Details	Reference
Pond and wetland creation and enhancement	Amphibian	Crested newt (*Triturus cristatus*) and the common spadefoot toad (*Pelobates fuscus*) in southern and southeastern Estonia; breeding activity and population size increased with restoration	Rannap et al. 2009
Wetland and floodplain restoration	Bird	Various freshwater waterbirds benefit from restoration of wetlands and floodplains	Hagy et al. 2017
Stream restoration benefits crayfish populations when added to streams	Crustacean	Crayfish (*Paranephrops planifrons*) benefitted from addition of natural wood products to streams in New Zealand	Parkyn et al. 2009
Wood addition to create complex habitat for fish	Fish	Wood led to increases in juvenile salmonid biomass and abundance in an Oregan, USA coastal stream	Johnson et al. 2005
Pond restoration (planting of submergent vegetation)	Insect	Odonata biodiversity in ponds in southern Germany increased with restoration of shoreline vegetation	Janssen et al. 2018
Using beavers to aid in habitat restoration	Mammal	The re-introduction of Eurasian beavers (*Castor fiber*) to an agriculturally degraded fen-assisted expedited restoration	Law et al. 2017
Captive breeding of imperiled freshwater mussels	Bivalve	Freshwater pearl mussel (*Margaritifera margaritifera*) can be successfully reared and raised in captivity for eventual release for targeted restoration projects where they have been extirpated	Gum et al. 2011
Wetland creation benefits at-risk turtles	Reptile	Wetlands created were colonized and used by three species of freshwater turtles in Ontario, Canada	Dupuis-Desormeaux et al. 2018

Note: Alone, these actions are insufficient to restore freshwater biodiversity, but when aggregated and combined with other broader scale restoration and protection initiatives, they can have substantial benefit. It is important to note that context matters such that not all restoration and enhancement activities will be successful or achieve meaningful conservation gains. Indeed, some activities intended to benefit biodiversity may in fact do harm (Cooke et al. 2018). Building a robust evidence base to enable evidence-based decision-making is necessary to ensure limited resources directed toward restoration or enhancement activities are effective.

Salinas-Rodríguez et al. 2018, 2020). To date, this EWR in this river successfully coexists with two other reserves, one for domestic-urban use and the other for public hydropower use. Although the latter was also legitimately enacted, the EWR supporting environmental flows prescription has proven to be an effective legislative tool to guarantee healthy aquatic habitat against unsustainable water infrastructure as it is grounded on flow–ecology relationships. Despite the Mexican government having reserved water for electricity generation in the SPM, "Las Cruces" hydropower project was rejected by the environmental authority because its design would have compromised such critical relationships to sustain habitat functioning in the wetland of international importance, Marismas Nacionales (National Marshlands) (Opperman et al. 2018, 2019; Salinas-Rodríguez et al. 2020, 2021). As a result, the "Las Cruces" hydropower project in the SPM was rejected by the environmental authority due to the fact it would have compromised critical processes that sustain habitat functioning in the wetland of international importance Marismas Nacionales (National Marshlands) (Opperman et al. 2018, 2019; Salinas-Rodríguez et al. 2020, 2021). Among the many biodiversity and ecosystem service benefits, San Pedro's EWR secures the water flow connectivity along its main course and its floodplain. Sediment transport in the river and nutrient deposition in its delta provide suitable aquatic habitat conditions in 65–175 km^2 of the river's floodplain ruled by the set of peak flood events and instream flows that sustain the salinity gradient of nearly 63 ,600 ha of 2–8 m height mangrove forest with three species-differentiated freshwater requirements. Such conditions support up to 50 species of plants, macroinvertebrates, and fishes surveyed in riparian and wetland freshwater and brackish environments. This includes 37 species protected by international listings and 6 species of fishes that are strictly freshwater-dependent (Salinas-Rodríguez et al. 2018, 2021).

2. Prioritize habitats for protection and restoration

Freshwater ecosystems across the world are poorly protected (Abell 2002; Finlayson et al. 2018), having experienced disproportionately larger habitat loss compared to other ecosystems (Dudgeon et al. 2006). It is crucial to increase mitigative actions that protect and restore freshwater habitat. With limited funding and capacity (Lapointe et al. 2014), it is important to allocate resources for freshwater habitat protection and restoration in an efficient and effective manner (Golden et al. 2017; Proctor et al. 2022). Due to the uneven allocation of resources across freshwater ecosystems, taxa, and populations (Noss et al. 2009), both scientists and decision-makers have determined that prioritization is required to minimize biodiversity loss (Bottrill et al. 2008). Conservation projects can be prioritized using methods such as biodiversity indices (e.g., richness; Jenkins et al. 2015; Zaffaroni et al. 2019), optimizing algorithms (Hanson et al. 2019), or ranking projects based on efficiency and effectiveness (Cawardine et al. 2019). Further, decisions regarding protection and restoration of freshwater habitat often occur rapidly and in the face of uncertainty (e.g., species lacking sufficient data). It is therefore important that factors such as costs, benefits, goals, and values (i.e., of the community and (or) stakeholders) are taken into consideration in addition to more traditional aspects during prioritization (Bottrill et al. 2008). While the prioritization process may be time consuming, frameworks such

Fig. 2. (A) Wetland of international importance, Marismas Nacionales, dependent on instream flows from the environmental water reserve of the San Pedro Mezquital River to sustain habitat functioning (Photo: A. Martínez/WWF). (B) Members a community fishery committee (CFi), Cambodian Department of Fisheries Inland Fisheries Research and Development Institute, Conservation International, and USAID-funded Wonders of the Mekong Project inspect and map a corner marker for community-establish no-take fishing reserve in Tonle Sap Lake near Peam Bang, Cambodia. (C) Implementation of the successful Sea to Lake Hume fish passage program that constructed 15 fishways to open 2225 km of the Murray River in south-eastern Australia required extensive collaboration across four jurisdictions, many agencies and between fish ecologists, managers, and engineers (Photo: J. O'Connor, ARI). (D) Salmonid-bearing streams have been the focus of extensive restoration efforts, and in the process, a large evidence base has been generated through research to guide future initiatives (Photo: S. Landsman). (E) Construction of offsetting spawning habitat for Lake Sturgeon (*Acipenser fulvescens*) in the tailrace downstream of a powerhouse during its development in 2019 at Keeyask Generating Station, Nelson River, Manitoba, Canada (Photo: Keeyask Hydropower Limited Partnership).

as Structured-Decision-Making can expedite decisions while maintaining a deliberate process (Gregory et al. 2012). It is impossible to protect every intact freshwater habitat or restore every degraded freshwater habitat, so we argue that prioritization will play an important role in the protection and restoration of freshwater ecosystems (Visconti et al. 2019; Guetz et al. 2022).

Case study: prioritizing protected areas based on cross-taxa interactions

Prioritization can be used to inform conservation decisions, including the identification of areas that could be protected or restored. Prioritization can be based on various criteria, including the belief that a species is becoming endangered, that an area has significant biodiversity, or that an area's biodiversity offers significant ecosystem services (McGowan et al. 2017). For example, Nogueira et al. (2023) examined biotic interactions across multiple freshwater species in the Duoro River basin within Spain and Portugal to guide the establishment or enlargement of protected areas. Imperiled bivalves, including the freshwater pearl mussel (*Margaritifera margaritifera*), have a parasitic stage that includes its attachment to specific fish species, including brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*), among others. In addition to considering these three species independently, their biotic interactions were incorporated into spatial prioritization analysis as the mussels are fully dependent on the fishes to complete their life cycle. Species distributions were modeled based on field surveys for the mussels and their obligate hosts, as well as habitat characteristics. From there, a spatial prioritization tool (Marxan) was used to identify priority areas based on three scenarios: mussels alone, mussels and fishes together, and species and interactions (i.e., that mussels rely on fish to complete their life cycle). An important finding was that the species and interaction scenario captured more areas within the Duoro River watershed, which were missed by the other two scenarios. If the species interaction had not been considered, these important areas would not have been able to be considered for protected areas, which could further jeopardize the mussels. Specifically, based on the results, the authors recommended that the western portion of the Duoro River watershed be the focus of protected areas, as there is lower anthropogenic disturbance (i.e., agriculture and habitat fragmentation).

3. Enact durable protections

Although 30% of freshwater ecosystems have disappeared since 1970 (Dixon et al. 2016), we still have a chance to "get it right" by increasing protection for remaining intact habitat to conserve biodiversity. Habitat protection has been a popular strategy for both terrestrial and marine ecosystems, where the goal is to minimize anthropogenic disturbances within specific areas of the environment such as angling/harvesting or boating (Suski and Cooke 2007; Higgins et al. 2021). An important consideration is that freshwater ecosystems are directly connected to their watersheds (Craig et al. 2017; Lane et al. 2023) and riparian zones (Richardson et al. 2010), as water and materials (e.g., sediment or nutrients) flow over land until reaching receiving waters (e.g., lakes or rivers). In addition to the freshwater itself, protection should also be applied to the watershed, mitigating the anthropogenic impacts of urbanization, agriculture, forestry, or mining (Lapointe et al. 2014). Additionally, most of the habitat protections that do exist currently focus on above-ground areas, leaving important groundwater ecosystems vulnerable to exploitation (Huggins et al. 2023). Habitat protection can be implemented in many ways, ranging from top-down measures such as those initiated by international governing bodies (e.g., the International Union for Conservation of Nature's Key Biodiversity Areas, https://www.iucn.org/resources/conservation-tool/key-biodiversity-areas; Key Biodiversity Alliance partnership of several global conservation organisations, https://www.keybiodiversityareas.org/working-with-kbas/programme/partnership#:∼:text=The%20KBA%20Partnership%20will%20enhance,most%20important%20places%20for%20nature) and policy initiatives (e.g., the 30 × 30 goal of the Kunming–Montreal Global Biodiversity Framework to protect 30% of land and water) to bottom-up initiatives such as community-based management (e.g., Campos-Silva and Peres 2016; Jumani et al. 2022) and non-governmental organizations (e.g., the purchasing of property for protection; Prahalad and Kriwoken 2010). Some of these protection initiatives can be classified as OECMs, which are governed in ways to achieve positive outcomes for biodiversity (e.g., fisheries reserves or UNESCO World Heritage sites; The Nature Conservancy, Conservation International, IUCN World Commission on Protected Areas and WWF 2022). Land-use planning could play a substantial role in habitat protection, whereby developments must take into consideration specially designated areas (e.g., Provincially Significant Peatlands Designation under the *Peatlands Stewardship Act* of Manitoba, Canada; https://web2.gov.mb.ca/bills/40-3/b061e.php). It will be important to ensure that protections are durable over time (e.g., maintained across political regime shifts), where durability refers to having a high probability of providing dedicated and enforceable protection into the future (Higgins et al. 2021). An unfortunate example of weak durability is the changes to Provincially Significant Wetlands protections in Ontario, Canada, whereby economic development is now permitted despite the potential presence of endangered freshwater species (https://www.ola.org/en/legislative-business/bills/parliament-43/session-1/bill-23). Although there may be many challenges associated with the implementation of freshwater habitat protection (e.g., prioritization), this response option could decrease anthropogenic disturbances, therefore benefiting biodiversity.

Case study: community fisheries management in Mekong

Cambodia's inland fisheries are among the most productive in the world, producing an estimated 505,000 tons of fish each year, primarily for local and regional consumption (Baran and Gallego 2015). Most of this annual harvest comes from Tonle Sap, a seasonally inundated floodplain lake of the Mekong River. For nearly a century, access to the most productive fishing locations in the Lake and the Tonle Sap River, which connects the lake with the Mekong mainstem, were auctioned off to private, commercial fishing operations. While private "dai" fishing leases on the Tonle Sap River continue to be auctioned, all formerly leased fishing lots in the lake were abolished by 2012 (Cooperman et al. 2012). In 2012, Cambodian Fisheries law was amended to establish a community-based fisheries (CFi) model of government-community fisheries co-management, wherein communities delineate harvest zones and establish and enforce their own regulations in cooperation with Cambodia's Department of Fisheries (Fig. 2B). These arrangements are legally documented and must be renewed by communities and approved by the Department of Fisheries every

5 years. Many communities also implement small, no-take fish refugia during the six-month dry season. During this time, fish that spend the dry season in the lake and recently hatched young-of-year fish are protected during the low-water conditions that increase vulnerability to harvest. Communities recognize the protection of refugia in helping to sustain local catches, and many have dedicated larger areas for seasonal protection based on perceived benefits. Like other community-based no-take reserves in the region (e.g., Loury et al. 2018; Koning et al. 2020), there is growing evidence to suggest these small refugia also harbor substantially higher fish richness, abundance, and biomass than adjacent unprotected areas (Koning, unpublished data). As well as determining the size of refuge areas, community members often enforce these no-take areas via volunteer committees or paid guards, typically in collaboration with international conservation organizations. The size of the refuge areas is typically scaled to the community's capacity to enforce protection. The high densities of fish in these protected areas, often located in deeper tributary channels, also attract a variety of water birds, snakes, and endangered hairy-nosed otters (*Lutra sumatrana*; Heng et al. 2016), indicating the biodiversity benefits of these reserves extend beyond fish. Although the community no-take areas show small-scale success, the limited capacity of communities to enforce their exclusive access to extensive CFi areas and the widespread illegal fishing practices around the lake have challenged the success of the broader co-management plan. A controversial national crackdown on illegal fishing operations in Tonle Sap that began in April 2022 and continues today appears to be effective in reducing large-scale illegal fishing efforts, and early reports from fishers suggest improved catches six months later. Not enough time has passed to assess the impact of the increased enforcement on larger, long-lived species, but the Tonle Sap catch is mostly composed of small-bodied fishes (<15 cm) that have rapid population turnover. The crackdown on illegal trawling, seining, and electrofishing operations that routinely catch larval and juvenile fish may be responsible for increased recruitment of these species and for fishers' reports of improved catches. The success of small community-managed fish refugia as part of broader collaboratively managed CFi, with continuing support of high-level legal actions to enforce standing fishery laws, could provide the foundation for more sustainable and durable protections for community fisheries as well as the Lake's important biodiversity.

4. Protect and restore habitat in a coordinated and integrated manner

For decades, conservation scholars have advocated for engaging in conservation actions that transcend scales (Paloniemi et al. 2012) and that are conducted in a coordinated and integrated fashion (Soulé 1985; Salafsky et al. 2002; Knight et al. 2006). This is particularly salient for freshwater ecosystems given their inherent connection to the surrounding landscape (Hynes 1975; Hermoso et al. 2012; Lane et al. 2023) and that everything flows downstream (Vannote et al. 1980; Dodds and Oakes 2008). Yet, the norm for freshwater conservation efforts is to focus on a specific population or species, or specific places or spaces, rather than considering the scale at which freshwater systems function (Gomi et al. 2002; Vaughn 2010), the scale at which threats operate (Collen et al. 2014; Albert et al. 2021), and the scale at which conservation interventions need to be applied (Albert et al. 2021). Therefore, key to freshwater conservation is embracing measures that consider all relevant scales (Hermoso et al. 2012), with a particular eye to integrating different processes and doing so in a coordinated manner (Cid et al. 2022).

Coordination of conservation measures is particularly important in freshwater ecosystems given how they operate. If efforts in an upstream reach are not coordinated with those in a downstream reach, it is easy to yield conflict; for example, hydropower dam planning is rarely conducted at a watershed scale. There is a wide body of literature advocating for a watershed approach to protect (Saunders et al. 2002; Vollmer et al. 2023), restore (Wissmar and Beschta 1998; Roni et al. 2002), and manage (Nguyen et al. 2016) freshwater ecosystems. Achieving such an approach requires embracing the idea that traditional management boundaries may fail to fully encapsulate the logical planning and management unit that is a watershed (Warner et al. 2008). An additional consideration will be the provisioning of freshwater organisms that migrate across jurisdictional boundaries (e.g., migrating salmon; Worthington et al. 2022). In some instances, this may mean creating multi-national bodies to coordinate management given that neither water nor biota adhere to geographical boundaries (Davidson and de Loë 2014). Although the tools for embracing a watershed approach have existed for more than a decade (Cohen and Davidson 2011), governance issues remain with implementation (Loures and Rieu-Clarke 2013; de Loë and Patterson 2017).

Case study: restoring native fishes in the Murray–Darling Basin in Australia

The Murray–Darling Basin (MDB) covers 1.1 million km^2, involving six legislative jurisdictions and myriad agencies, providing an excellent example of the complexities of coordinated and integrated management across large spatial scales. Fish compete for water with agriculture (Koehn 2015), and MDB's highly regulated rivers are generally in poor ecological condition (Davies et al. 2010). Native fish populations are estimated to be at <10% of pre-European (~1850s) abundances (MDBC 2004). These fishes are prized for their endemic biodiversity and their social (e.g., recreational fishing), economic, and cultural values, yet there are considerable public concerns about their future. Two major long-term (10–50 years) initiatives have been developed to improve MDB's river health and fishes. The *MDB Plan* addresses overuse of water to better balance environmental, social, and economic outcomes through infrastructure improvements and water license buybacks (MDBA 2011). The *Native Fish Strategy* addresses threats and rehabilitates fish populations (MDBC 2004; Koehn and Lintermans 2012). For example, one of many successful projects was the Sea to Lake Hume fish passage program that constructed 15 fishways to open connectivity along 2225 km of the Murray River (Baumgartner et al. 2014; Fig. 2C). Both initiatives existed within existing governance structures and management programs (Koehn and Lintermans 2012). Despite extensive consultation across the MDB jurisdictions, state agencies, stakeholders, and political tiers, the *MDB Plan* has proven to be one of the most controversial natural resource management reforms in Australia's history, generating high levels of political debate and protest from irrigation interests (Koehn 2015). Progress is ongoing but implementation has not been straightforward. The *Native Fish Strategy* provided powerful changes to MDB fish management; however, its funding was largely discontinued after 10 years, not because of its lack of success or its ongoing need, but due to jurisdictional political changes and cuts to its collaborative funding structure (Koehn et al. 2014, 2019; MDBA 2020). While programs to address priority conservation issues may have great intent, their large-scale and long-term nature can put them at risk from changing jurisdictional and sectoral politics.

5. Engage in evidence-based restoration using an adaptive management approach

Ecological restoration seeks to repair habitats that have been destroyed, with the aim of conserving biodiversity and associated ecosystem services (Gann et al. 2019). Despite restoration ecology being founded in science, personal biases can often creep in throughout the process, resulting in efforts that are ineffective or even counterproductive (Cooke et al. 2018). For example, plastic "habitat" structures for freshwater fishes have been deployed in the US despite a limited evidence base, potentially leading to more harm than good (Cooke et al. 2023). We posit that ecological restoration must be based on the best available scientific evidence (e.g., systematic reviews) (Pullin et al. 2004) that includes both western and Indigenous science (Esselman and Opperman 2009) and an adaptive management approach whereby continuous learning feeds back into actions (Gann et al. 2019). To advance the evidence base, rigorous monitoring should be designed as true experiments to allow for stronger inferences (Block et al. 2001) and be conducted throughout all phases of restoration (i.e., before, during, and after). Although ecological restoration is often focused on habitat, other forms of restoration could also benefit freshwater species. For example, in cases where recruitment may be limited due to decreased availability of critical habitats, captive breeding (i.e., ex situ conservation) can be used to augment wild populations (e.g., pearl mussels; Gum et al. 2011; Blanding's turtles, *Emydoidea blandingii*; Thompson et al. 2020).

Case study: restoration lessons emerging from decades of salmonid stream restoration

More effort has been devoted to the restoration of salmonid-bearing streams than any other freshwater ecosystem (Fig. 2D). Decades of experimentation (going back to the 1800s; Van Cleef 1885) have generated a massive evidence base. Key lessons that have emerged from this evidence base are relevant to other freshwater ecosystems. The first lesson is that habitat restoration must address the underlying causes of degradation rather than the symptoms (Frissell and Nawa 1992; Boudell et al. 2015). There are many examples of failed restoration attempts arising from symptom-focused restoration efforts (Wohl et al. 2015). A second lesson is to look beyond the stream itself and include restoration of adjacent riparian areas. From shading to bank stabilization to input of allochthonous materials, protecting and restoring riparian habitats is an essential aspect of stream restoration (Goodwin et al. 1997). A third lesson is to ensure that restoration efforts emulate nature and use natural materials (Kauffman et al. 1997) that require minimal maintenance (Moore and Rutherfurd 2017). Working with nature and natural processes (e.g., fluvial geomorphology, sediment transport, and hydrology) is crucial to long-term success (Shields et al. 2003; Beechie et al. 2010). A review of spawning habitat creation or enhancement found that the addition or alteration of rock material (e.g., addition of gravel and substrate washing) was an effective means of enhancing spawning habitat (Taylor et al. 2019). Further, the placement of coarse woody material had demonstrated benefits to the physical habitat and associated benefits for fish abundance (Roni et al. 2015). Collectively, these reviews have provided support for continued restoration efforts but also emphasize the value of robust monitoring to continuously assess the efficiency and effectiveness of interventions (see Block et al. 2001), particularly across long time scales (years to decades; Rubin et al. 2017). A fourth lesson is the need to engage with multiple disciplinary domains spanning groundwater hydrologists, fluvial geomorphologists, ecologists, engineers, landscape architects, and watershed planners to ensure a holistic restoration praxis (Bennett et al. 2011; Serra-Llobet et al. 2022). A final lesson emerging from salmonid stream restoration is that it is possible to engage and mobilize volunteers (community members) in such efforts. Volunteers can fundraise, implement, and (or) monitor to ensure the broad-scale, long-term success of the salmonid stream restoration (e.g., see volunteer engagement through stewardship groups such as Trout Unlimited). Supporting these key lessons are science-based guidance documents (e.g., Hunt 1993; Jenkinson et al. 2006; Yochum and Reynolds 2018) that provide practical direction on how to do restoration that works.

6. Ensure that potential freshwater habitat alterations are compensated or off-set

The human population is projected to continually increase in coming decades, and habitat destruction caused by anthropogenic development will almost certainly follow suit. Although limiting the amount of development or making wiser decisions (i.e., not building on pristine habitat) would be advisable, policy makers have turned to habitat compensation to offset human activities (Moilanen et al. 2009). Ecological compensation includes actions that mitigate losses or result in a "net gain" by requiring habitat restoration (i.e., enhancement or creation) or habitat protection in another area but with similar structure and function (Quintero and Mathur 2011; BBOP 2012). For example, Canada has adopted the No Net Loss policy under the *Fisheries Act* (FA) (Harper and Quigley 2005) and Colombia has implemented environmental compensation under the *National Policy for the Integral Management of Biodiversity and its Ecosystem Services* (Reid et al. 2015). In one application, offsite habitat compensation for threatened golden bell frogs (*Litoria aurea*) in Australia was found to achieve a no net loss in population, although a large amount of habitat was required (Pickett et al. 2013). Habitat compensation is not intended to be an "easy way out" for developers; it should only be used as a worst-case scenario after all other forms of harm avoidance and mitigation have been exhausted (Quetier and Lavorel 2011; Maron et al. 2015). To maximize success of habitat compensation, it has been recommended that a high offset ratio be used (i.e., create more habitat than was lost; Bruggeman et al. 2005), that the offset habitat be built within close proximity to the lost habitat (i.e., to maximize connectivity; Moilanen et al. 2009), and that development is delayed to increase the chances of colonization and ecosystem structure (Morris et al. 2006).

Case study: the Canadian experience of habitat policy and management

Canada has a long history of legislation protecting its valuable fishery resources, starting with the first enactment of the FA in 1868 and then with the addition of specific habitat protection provisions in 1977. Since that time, the FA and supporting policy have evolved, culminating in the current 2019 version that provides comprehensive protection for all fish and supporting aquatic organisms (including mollusks) and for fish and riparian habitat in Canada (Fig. 2E). The focus on habitat recognizes its foundational role in supporting healthy and productive fish populations (Lapointe et al. 2014). A key aspect of current policy is the prohibition against the harmful alteration, disruption, or destruction of fish habitat (HADD) and against the "death of fish, other than by fishing" unless authorized. The federal Department of Fisheries and Oceans Canada (DFO) is responsible for implementing these provisions of the FA, which allows broad latitude to maintain regulatory oversight of works, undertakings, or activities that affect fish and fish habitat in Canada. However, the ability to grant authorizations does allow HADD and death of fish to occur but only with appropriate offsetting measures to counterbalance the residual effects (after avoidance and mitigation are implemented but unable to reduce the negative effect to zero) of the project. There are a number of guiding principles that are considered when designing an offset project (see https://www.dfo-mpo.gc.ca/pnw-ppe/reviews-revues/policies-politiques-eng.html#_688), including the need to support fisheries management objectives; giving priority to restoration of degraded fish habitat; ensuring that they balance the adverse effects resulting from the works, undertakings, or activities; ensuring that offsets provide additional benefits to the ecosystem; and ensuring that benefits are self-sustaining. Working with proponents, DFO habitat managers apply the policy to ensure that there is a "net gain" in habitat during offsetting efforts (Goodchild 2004). Previous efforts to achieve no net loss have been mixed (Quigley and Harper 2006), emphasizing the need for additional research on offset science as well as better monitoring. Monitoring for effectiveness of these offsets is required, but DFO is working toward implementing a new standardized monitoring system that would transform the utility of monitoring data, contribute to more effective decision-making, and provide a scientifically sound understanding of whether fish habitat losses are indeed being balanced effectively with habitat offsets for future generations. Similar freshwater habitat protections are lacking in many jurisdictions around the globe. Given the manifold importance of habitat for freshwater ecosystems, there is need for improved governance and habitat management policies and practices that could be modeled after experiences in Canada as well as the US (the National Fish Habitat Partnership; https://www.fishhabitat.org/; Whelan 2019), Australia (the New South Wales Policy for Fish Habitat Conservation and Management; https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/468927/Policy-and-guidelines-for-fish-habitat.pdf), and other locales with such experiences.

7. Future-proof protection and restoration actions

Protection and restoration actions for freshwater ecosystems need to happen now, yet the world is changing so that there is dire need to ensure that those decisions and investments are effective both in the short and long term (Barmuta et al. 2011). As such, there is a need to "future-proof" protection (van Kerkhoff et al. 2019) and restoration measures for freshwater biodiversity (Rowell 2010). Doing so has the potential to enhance system resiliency, a concept that has been explicitly recognized as essential when addressing threats to waters and associated social–ecological systems (Folke 2003). Unfortunately, this way of thinking has yet to fully permeate conservation practice and become a normal part of planning for protection and restoration in freshwater systems (Rowell 2010). Operationalizing future-proofing means ensuring that practitioners are equipped with the skills and tools to make good decisions about how different interventions will perform across different time periods and contexts (e.g., climate change; Grantham et al. 2019; Gupta and Schmeir 2020). It also means ensuring that politicians are thinking beyond the term of holding an elected position and instead focus on what is good for the planet and its peoples. Future proofing of freshwater conservation is in its early days (Lynch et al. in press) and requires dedicated research and opportunities for learning through adaptive management. What is most apparent is that the protections and restoration efforts of today may be moot in the future in a warming world (Pittock et al. 2008). Failure to think about the future risks freshwater ecosystems and the ecosystem services they provide, emphasizing the need for forward-looking conservation planning and action (Nel et al. 2009). This will require a recalibration of relevant temporal and spatial scales for thinking about management as well as an adaptive management approach whereby learnings are used to inform ongoing conservation efforts. Ensuring system resiliency will provide capacity for adaptation (Folke 2003); however, that also needs to be supplemented with more dynamic protection options that can themselves adapt to changing conditions. Dynamic protections have had some early success in marine systems (Game et al. 2009) and policies such as the *US Wild and Scenic Rivers Act* allow for adaptive management and inclusion of new conservation concerns in a changing climate (e.g., refugia, climate buffers; Perry 2021).

Case study: are protected areas for freshwater fishes in South America future-proof?

Species distributions are changing across the globe because of climate change, and previously established protected areas may not be appropriate for the intended species in warmer waters. To assess whether protected areas can achieve intended goals, retain climate suitability, and persist effectively into the future, Oliveira et al. (2021) examined the distribution of 496 native fishes under current and future climate scenarios. The Parana–Paraguay watershed within South America occupies Argentina, Bolivia, Brazil, and Paraguay and includes various freshwater habitats, including wetlands, lakes, and rivers that collectively support rich biodiversity. The authors used fish occurrence records to generate habitat suitability with species distribution models based on current and future (2050 and 2080) conditions. From there, they calculated species richness and phylogenetic diversity within protected areas. Their analysis determined that the protected areas within the watershed would not be effective at protecting the areas with the highest richness of freshwater fishes for both current and future climate scenarios. Further, they found that the areas that supported the most species were insufficiently protected (i.e., outside the protected areas). These types of analyses highlight the shortcomings of current conservation strategies such as habitat protection. To future-proof and preserve freshwater biodiversity, as well as the ecological roles and services these fishes provide, protected areas that reflect new climate conditions must be established (Oliveira et al. 2021). Similarly, protection policies need to be designed to be adaptive and responsive to climate and other non-stationary changes (e.g., human settlement and use patterns).

Overcoming obstacles to implement response options

Freshwater biodiversity will almost certainly continue on the path of decline without drastic intervention, owing to threats associated with habitat, which contribute to population and species loss. We have proposed response options to save freshwater biodiversity with habitat protection and restoration. However, there are several challenges that can be anticipated to the implementation of these responses, and these fall broadly into three groups: (a) knowledge gaps and uncertainties, (b) institutional and management, and (c) social and political will. In addition to identifying these barriers, we also suggest mechanisms and interventions to overcome challenges.

All response options require a strong evidence base, which should be derived from many different types of knowledge, including scientific, Indigenous, and local. Throughout the access and use of data, it is important to ensure that involved organizations use the data to serve not only biodiversity but the needs of the local people (i.e., communities). Unfortunately, throughout decision-making and environmental management processes, there will always be data gaps and uncertainties (López-Gamero et al. 2011). These data gaps and uncertainties can stem from a variety of sources such as a lack of data (e.g., in many areas, data are simply not collected) or lack of data accessibility (e.g., behind paywalls or within inaccessible databases; Piczak et al. 2022). There has been an increasing use of tools to operate in the face of data gaps and uncertainties, including adaptive management that iteratively incorporates learning into decisions (Runge 2011), and structured decision-making that is an organized framework designed to incorporate uncertainty while maintaining a deliberate process (Gregory et al. 2012). Yet, uncertainty is growing because of global climate change. For example, climate change is predicted to alter species ranges (Jarić et al. 2019) and hydrological and biogeochemical regimes (Knouft and Ficklin 2017), which will need to be considered while implementing response options. Furthermore, other global processes such as anthropogenic modification to flows or systemic pollution can have substantial impacts on various geographic scales, from local populations to entire species range (Lapointe et al. 2014; Reid et al. 2019). These challenges are daunting and the task at hand is massive, requiring large programs that are holistic (spanning habitats, biota, and entire systems) at scales that range from individuals to ecosystems and from reaches/sites to entire watersheds.

All response options require strong institutions across all jurisdictional scales: local, regional, national, or international. While the goal is to Bend the Curve of freshwater biodiversity, this is inherently a human-oriented problem, in that a lot of the challenges stem from institutions' strategic and operational plans. One obstacle that has been cited as a barrier for both habitat protection (Kingsford et al. 2011) and restoration (Geist and Hawkins 2016) is conflicting priorities or competing interests across agencies/stakeholders (e.g., human water use and conservation goals) involved. To mitigate this, it is crucial to develop relationships across stakeholders and rights holders early and outline goals together, which can increase relevancy throughout conservation actions (Cook et al. 2013; Bair et al. 2019). Another obstacle is that often there is a lack of funding or that the typical funding timelines are not conducive to habitat protection and restoration, which can occur over multiple years or even decades. Although under-funding is a problem encountered in conservation in general, a disproportionately small amount of funding was allocated to conservation of freshwaters (Cracknell et al. 2016). Further, conservation funding can also be misallocated or even mismanaged, including corruption or delays (Catalano et al. 2019). Similarly, operational challenges can also stem from limited capacity and time of stakeholders and rights holders, many of whom are the true "owners" of public aquatic resources. It will be important that funding regimes shift to an increased timeline to ensure that habitat protection and restoration are adequately supported throughout the entire process. Lack of knowledge (i.e., unknowns; as previously described) and knowledge exchange can also hinder conservation. Specifically, knowledge generators (e.g., scientists and researchers) and knowledge users (e.g., managers and decision-makers) have operated independently for decades, resulting in the knowledge–action gap whereby generated science is not applied in the real world (Cook et al. 2013; Clare and Creed 2022). Strategies to bridge this gap include boundary organizations (to facilitate communication; Cash et al. 2003), knowledge co-production and co-dissemination (to conduct research in a collaborative manner; Djenontin and Meadow 2018), and ensuring scientists operate within planning and management agencies (Cook et al. 2013). For example, knowledge co-production has been successfully used to implement habitat restoration aimed at native freshwater fishes in the Laurentian Great Lakes (Piczak et al. 2022).

All response options require strong political will. Social and political aspects of conservation have also been cited as obstacles to conservation. For example, political aspects that have been cited as impediments include lack of incentives for conservation and restoration, the prioritization of economic development, and shifting political conditions (e.g., across elections; Catalano et al. 2019). Although the public is generally aware of threats facing biodiversity (e.g., climate change), there is a lack of understanding of the importance of freshwater ecosystems and their species to society (Monroe et al. 2019). To raise the profile of freshwater ecosystems, an increase in the awareness of the importance of freshwater habitats through education across demographic scales, from politicians, businesses, elementary pupils, university students to those in assisted living, will be needed. To raise the resources to protect and restore freshwater habitat, communities, champions, volunteers, tourists, and sectors (e.g., industry) should be engaged. A more educated public that values freshwater biodiversity can help generate the political support and willingness to vote for conservation measures (Cooke et al. 2022). We should also build off the momentum of initiatives such as the UN DER or Rights of Wetlands (https://www.rightsofwetlands.org/) in terms of public awareness and political actions. Other social and cultural driven movements, including the Rights of Rivers and Rights of Wetlands, can provide mechanisms for the conservation and protection of freshwater ecosystems and their services.

Conclusion

Freshwater ecosystems are diverse and support a large number of species, providing various ecosystem services, including provisioning, regulating, and cultural services. However, human activities have caused extensive declines in freshwater ecosystems, particularly through habitat damage and destruction. Habitat refers to the resources and environmental conditions required for individuals to persist in each location, and freshwater habitats can be negatively impacted by anthropogenic activities through habitat fragmentation, degradation, or loss. Building off of Tickner et al. (2020), we identified response options to Bend the Curve to save freshwater biodiversity through habitat protection and restoration (see Fig. 1), and we identified major obstacles that will need to be overcome to successfully implement these response options. Reflecting upon our case studies and examples of protection and restoration projects (Tables 1 and 2), there are bright spots in the fight to save freshwater biodiversity that offer glimmers of hope. Past, present, and future habitat alterations continue to demonstrate the urgency and importance of habitat protection and restoration to benefit freshwater biodiversity and the ecosystem services generated by intact and healthy freshwater ecosystems.

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