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Three major steps toward the conservation of freshwater and riparian biodiversity

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Abstract
Freshwater ecosystems and their bordering wetlands and riparian zones are vital for human society and biological diversity. Yet, they are among the most degraded ecosystems, where sharp declines in biodiversity are driven by human activities, such as hydropower development, agriculture, forestry, and fisheries. Because freshwater ecosystems are characterized by strongly reciprocal linkages with surrounding landscapes, human activities that encroach on or degrade riparian zones ultimately lead to declines in freshwater–riparian ecosystem functioning. We synthesized results of a symposium on freshwater, riparian, and wetland processes and interactions and analyzed some of the major problems associated with improving freshwater and riparian research and management. Three distinct barriers are the lack of involvement of local people in conservation research and management, absence of adequate measurement of biodiversity in freshwater and riparian ecosystems, and separate legislation and policy on riparian and freshwater management. Based on our findings, we argue that freshwater and riparian research and conservation efforts should be integrated more explicitly. Best practices for overcoming the 3 major barriers to improved conservation include more and sustainable use of traditional and other forms of local ecological knowledge, choosing appropriate metrics for ecological research and monitoring of restoration efforts, and mirroring the close links between riparian and freshwater ecosystems in legislation and policy. Integrating these 3 angles in conservation science and practice will provide substantial benefits in addressing the freshwater biodiversity crisis.

KEYWORDS
biodiversity, conservation, freshwater, policy, riparian, traditional ecological knowledge, wetlands

INTRODUCTION

Fresh water is a vital resource for life, yet freshwater ecosystems are among the most highly threatened on Earth (Albert et al., 2021; Tickner et al., 2020). Historically, ecological research focused on freshwater and terrestrial areas separately, and research on riparian zones only started to develop in the 1980s (Odum, 1979). Riparian zones are generally defined as the land along a freshwater waterbody that is affected by its hydrological regime and can be as narrow as mere decimeters or so wide that they encompass entire floodplains and wetlands (Naiman et al., 2005). Although fresh water and riparian zones make up only a small fraction of Earth's surface, many people's social and economic well-being depends on them (Dudgeon et al., 2006).

The development of riparian research has improved understanding of the reciprocal links between freshwater biodiversity, adjacent riparian zones, and surrounding wetlands (Baxter et al., 2005; Nakano & Murakami, 2001). Despite considerable progress in understanding of these ecosystems, anthropogenic pressures on freshwater, riparian, and wetland ecosystems have increased (Hoppenreijs et al., 2022; Reid et al., 2019; Stendera et al., 2012). Land-use change, fragmentation, pollution, and biological invasions are among the main threats to freshwater, riparian, and wetland biodiversity (Reid et al., 2019; Tolkkinen et al., 2020). Because biodiversity and ecosystem functioning are closely linked (Cardinale et al., 2006; Yachi & Loreau, 1999), these pressures also can lead to declines in ecological functioning and potentially to the collapse of important ecosystem services (Moi et al., 2022). These problems are particularly urgent because freshwater and riparian systems, despite their close ecological linkage, are rarely considered together in research, management, and policy (Maasri et al., 2022; Rodríguez-González et al., 2022). The most effective way forward in dealing with the threats humanity poses to these vital systems is stewardship in which freshwater and riparian research and management are integrated (Muehlbauer et al., 2019; Singh et al., 2021; Vicente-Serrano et al., 2020).

Research and conservation thus need to reflect the close linkages of the freshwater, riparian, and wetland components of the landscape. The flow regime and water quality determine the extent to which riparian life is facilitated, for example, through material deposition and by creating habitat for riparian species (Bejarano et al., 2020; Naiman et al., 2005). Simultaneously, the riparian zone is a determinant of in-stream conditions because it buffers lateral inflow, regulates water temperature, and supports in-stream life through nutrient addition, habitat provision, and protection from pollution (Luke et al., 2007; Riis et al., 2020). Wetlands also play key roles in water storage by creating a diversity of aquatic and semiaquatic conditions and connections (Lane et al., 2018). Many species use or contribute to more than one of these ecosystems, which further solidifies their linkages (Juhász et al., 2020; Larsen et al., 2021; Naiman et al., 2002). Anthropogenic transformation and disturbances lead to a weakening of these crucial connections or a disruption of flows. Thus, efforts to counter freshwater biodiversity loss and biodiversity change (Arthington, 2021; Xu et al., 2023) must explicitly acknowledge and address freshwater–riparian linkages.

This essay results from a symposium held at the 2022 European Congress on Conservation Biology (ECCB), at which conservation scientists and practitioners from around Europe and the world gathered to address the theme of the meeting Biodiversity Crisis in a Changing World. The symposium Biodiversity across the Aquatic-Terrestrial Boundary: Rivers and their Riparian Zones addressed freshwater and riparian issues. We assembled scientists, conservationists, and policymakers from freshwater, wetland, and riparian disciplines and explored how these fields may be better integrated and how this integration can improve biodiversity. The symposium presentations and consequential discussions between presenters and organizers led to a consensus on 3 key conservation issues and potential solutions: application of traditional and local ecological knowledge and citizen science in research and conservation; measurement of freshwater and riparian biodiversity to support ecosystem-scale research questions and justify research actions, while acknowledging the uncertainty and limitations of biodiversity measurements; and embedding of freshwater–riparian linkages in policy and management. Advances in these areas will help researchers, policymakers, managers, and local stakeholders work together more effectively, and advance freshwater conservation.

KNOWLEDGE AND PERCEPTIONS OF INDIGENOUS PEOPLES, LOCAL STAKEHOLDERS, AND CITIZEN SCIENTISTS

Ecosystem conservation needs to involve the people who depend on the focal ecosystems and who are affected by their degradation. Traditional ecological knowledge (TEK) is one form of knowledge that should be recognized more widely (Huntington, 2000). It is especially relevant in riparian and freshwater ecosystems that play a part in people's daily lives, for example as hunting and fishing grounds and recreational areas (Arthington et al., 2010; Riis et al., 2020). Scientists and conservationists should respect TEK, strive for the constructive engagement with TEK holders beyond using their local expertise during data collection (Shackeroff & Campbell, 2007), and help build transformative social–ecological systems based on common visions (Lam et al., 2020; Molnár & Babai, 2021).

Traditional and other forms of local ecological knowledge shared among fishers, hunters, foresters, farmers, and water managers, as well as local conservationists, can have significant conservation relevance. All these knowledge holders can provide expert knowledge and may have valuable and diverse perceptions about riparian–freshwater conservation and restoration targets (Berkes et al., 2000; Remm et al., 2019; Wheeler & Root-Bernstein, 2020). To ensure that conservation impacts are equitable, it is also crucial to integrate gender dimensions. Men and women may have different knowledge sets because they experience the environment and its changes differently (McElwee et al., 2021). For example, gender-specific labor specialization can lead to differences in perceptions of the environment (Maliao & Polohan, 2008). Regardless of the source, researchers need to ensure that the inclusion of TEK or local knowledge represents more than "buy-in" (Hall et al., 2016). Researchers should also avoid reducing these forms of knowledge to a single idea or action (Shackeroff & Campbell, 2007) and make sure that knowledge holders are collaborating based on free prior and informed consent well before measures are decided on and implemented (Hanna & Vanclay, 2013).

Citizen science programs have a key role to play in conservation science (Adler et al., 2020). Because rivers and riparian zones often have cultural significance and are popular places to visit (Riis et al., 2020), there is considerable scope for data collection even by people who do not use them on a day-to-day basis. Citizen science programs have been responsible for the accumulation of millions of data points worldwide (Kobori et al., 2016), and freshwater ecosystems make up a relatively large share of those, compared with terrestrial and marine ecosystems (Theobald et al., 2015). Engaging TEK holders and other knowledge holders in conservation can help improve scientific and community support especially for freshwater and riparian projects (Cash et al., 2003), potentially beyond the lifetime of the project itself (Arnold et al., 2012).

Declines in freshwater biodiversity and weakening of freshwater and riparian systems can be countered by involving TEK and local perceptions because both can provide important ecological information outside of other research methods. The impacts of involving TEK and other local knowledge more can extend far beyond ecological conservation. By aligning conservation actions with traditional practices, other cultural aspects of TEK are maintained and can develop further.

TEK and biodiversity conservation in the Philippines

TEK in the Philippines contributes to freshwater ecosystem conservation, particularly in species-deprived and data-deficient freshwater ecosystems (Magbanua et al., 2017). In the province of Aklan, artisanal riverine fishers exhibit an extensive understanding of local environmental changes and resource fluctuations, reflecting the intimate relationship of subsistence communities with their local environment (Maliao et al., 2023). Riverine biodiversity is perceived as declining, with overall catch and their respective sizes shrinking (Altamirano & Kurokura, 2010). River prawn (*Macrobrachium* spp.) harvest in 2021 was approximately 0.4 kg per individual per fishing trip, a 76% decrease in the catch since the 1960s (Maliao et al., 2023). The overall decline of freshwater biodiversity is locally associated with the diminished state of river systems. Water quality is poorer due to pollution and siltation, riverbanks have weakened and have become prone to erosion, and flow and discharge have been altered. The local communities attribute these changes to continuing deforestation, alteration of riparian vegetation, pollution, and overexploitation. Some people connect the diminishing state of rivers to "ageing earth" and thus show an understanding of the planet as a living entity. The diminished state of rivers is heralded by the decline of frog and dragonfly populations, locally used as indicators of river condition (Maliao et al., 2023).

In Aklan, fishing is prohibited on Tuesdays and Fridays, when malevolent *engkantos* (nature spirits) are thought to be most active, and around big boulders and old trees, where benevolent *engkantos* are perceived to reside (Maliao et al., 2023). Such local resource and habitat taboos can simplify local conservation efforts because of the voluntary compliance features implicit in the taboo system (Colding & Folke, 2001). They are analogous to Western temporal and spatial management measures against overfishing (Watson et al., 2021). Through the shared culture, local communities of TEK holders can have relevant informal institutions that can provide insights for building resilient governance systems to address local freshwater conservation issues and concerns. Traditional and local knowledge can thus lead to better understanding of past and ongoing transformations, and inform future transformative changes (Lam et al., 2020).

BIODIVERSITY MEASUREMENT AND UNCERTAINTY IN FRESHWATER AND RIPARIAN ECOSYSTEMS

Reflecting the high human impact on freshwater ecosystems (Albert et al., 2021), one of the goals of the International Union for Conservation of Nature (IUCN, 2023) is that, "[b]y 2030, freshwater systems support and sustain biodiversity and human needs." However, biodiversity is a multidimensional concept that can be quantified in multiple ways, each of which provides different insights into the status of the focal system. A key decision point, then, in research on freshwater and riparian biodiversity and conservation, is how to measure biodiversity.

Classical measures of biodiversity quantify diversity at local levels (α diversity), between communities (β diversity), and at regional levels (γ diversity) (Magurran, 2004). When used in the traditional way, measures of alpha or beta diversity in isolation (i.e., that do not consider species' identities) may be of limited value for conservation decision-making. However, recent work (Gotelli et al., 2022) on beta diversity shows how species of conservation interest are mediating biodiversity change at the assemblage level. Analyses of these facets can also employ the different dimensions of biodiversity, namely taxonomic, functional, and phylogenetic diversity (Chao et al., 2021; Gallardo et al., 2011); patterns of biodiversity change that were not apparent when only taxonomic diversity is measured can be uncovered in the process. However, the scaling patterns of different α and β metrics over space and time are complex (McGill et al., 2015), particularly in linear or fragmented systems, or where connectivity patterns are complex, as is often the case in freshwater and riparian ecosystems or connected watersheds embedded within heterogeneous landscapes. Tools that uncover cross-ecosystem linkages and trophic diversity provide further insight into biodiversity patterns and are thus also relevant in the freshwater and riparian context (Horká et al., 2023; Kraus et al., 2021). In addition, there are suites of metrics that set out to quantify ecosystem functioning in a broader sense. Indices of biotic integrity, which quantify change in species composition in fresh waters, were introduced in the 1980s (Karr, 1981) and continue to be refined today (Hill et al., 2023). Ecosystem intactness and resilience, as measured by species composition, are also applied to riparian and freshwater ecosystems (Baho et al., 2017), as are other metrics, such as mean species abundances (Rowe et al., 2002), potentially extirpated fractions (Hanafiah et al., 2011), and extinction rates (Burkhead, 2012).

We present a short overview of biodiversity measurement with particular relevance to freshwater and riparian ecosystems. Our overarching message is that there is no single best descriptor of an aquatic system's biodiversity. It is therefore essential that users justify their metrics as appropriate to the research question being asked or the management task at hand and be explicit when reporting progress in relation to the IUCN and other targets. These points are well established in the ecological literature. However, they bear reemphasis because many studies discuss concepts, such as biodiversity loss, in general terms only or quote metrics, such as species richness, without providing information on sampling duration or coverage. They are also relevant to emerging technologies, such as eDNA (Carraro et al., 2020). Furthermore, because basing conservation plans on inadequate information can lead to ineffective action (Catalano et al., 2019), choosing appropriate time frames and spatial scales rather than being restricted by funding-based periods and political boundaries is crucial for understanding ecological changes over time (Lowe et al., 2006; Mace, 2014).

Tailoring freshwater and riparian biodiversity measurement for conservation

Considerations on which aspects and scales to measure apply to assessment of biodiversity in any system but have additional implications for freshwater and riparian ecosystems. First, because sampling methods are often ecosystem specific as well as taxon specific (Radinger et al., 2019), sampling across ecosystem types brings particular challenges. For example, freshwater and terrestrial phases of a wetland may be important determinants of the diversity of its insects; sampling methodologies, and data analyses, need to accommodate this heterogeneity. Second, the highly dynamic nature of freshwater, riparian, and wetland ecosystems can cause high seasonal and interannual variation (Biggs et al., 2005). Timing and amplitude of flooding are among the main drivers of the composition of communities in and along watercourses (Davidson et al., 2012; Greet et al., 2013). This type of variation needs to be accounted for when designing studies and when interpreting their outcomes. It is also crucial to take into account sampling effort and to report uncertainty (Wiens, 2008). Third, most of the reports of biodiversity change are framed in terms of loss of taxonomic α diversity (Albert et al., 2021), whereas growing evidence indicates that losses in taxonomic β diversity in freshwater systems may be even more severe (Blowes et al., 2019; Magurran et al., 2018). Using a range of complementary metrics will improve understanding of biodiversity change in aquatic ecosystems. Fourth, because biodiversity assessment is at its core a comparative quest, decisions about the choice of baseline or control assemblages against which to compare new data points are crucial (Soga & Gaston, 2018). Because all ecological assemblages undergo compositional turnover and population fluctuations across space and time, a baseline is not a single species list or diversity level but rather a range of values or qualities within which functional or restored systems would be expected to be placed. Researchers also need to be aware of the possibility of ecological inertia in their study system (Essl et al., 2015).

EMBEDDING OF COMBINED RIPARIAN–FRESHWATER RESEARCH IN POLICYMAKING

The strong reciprocal linkage between freshwater and riparian ecosystems and the urgency of the conservation of these systems require that policymakers apply an integrated approach in management. Many scientists and policymakers in the field call for a more fundamental, transformative change to achieve more effective conservation (DellaSala, 2021). This requires that the scientific community develops inter- and transdisciplinary collaboration, fostering connections not only among scientific domains, but also actively participating in policymaking. This facilitates information flow to and from decision-makers, increasing their access to the most accurate and up-to-date scientific evidence (Ekberzade et al., 2024). These connections are especially relevant in the freshwater–riparian context, where different research fields and different groups of funding agencies, managers, and stakeholders meet. Because of the many ecological functions that freshwater and riparian ecosystems fulfill, the societal stakeholders make for a very diverse group with different, and sometimes opposing, interests (Arnold et al., 2012). Effective communication (Cash et al., 2003) among all parties about these interests, the parties' knowledge, and action plans and uncertainty is key to successful freshwater and riparian research and management.

Freshwater–riparian conservation cannot rely on good communication and effective collaboration between scientists and policymakers alone. A good understanding of the ecological reality should not depend on which groups or individuals are involved and thus risk being different from case to case. Rather, it needs to be anchored in legislation so that it can serve as a baseline for practical implementation. Anchoring the functioning and conservation of riparian and freshwater ecosystems combined and following the precautionary principle, such as suggested in the section "Watercourses and their riparian zones in Norwegian national laws and policies", can stimulate timely communication and help policymakers and practitioners balance society's many and sometimes divergent interests better. Realistically, such legislation does not prevent every potential damage to riparian–freshwater ecosystems. In cases where such damage seems unavoidable, legislation should oblige the initiator to consider possibilities to mitigate and compensate for ecological losses and to implement the strategies that account for the reciprocal linkages between riparian and freshwater ecosystems and limit or counteract the damage on both the most.

Watercourses and their riparian zones in Norwegian national laws and policies

Norwegian laws, regulations, and national guidelines acknowledge the link between watercourses and their riparian zones and recognize the importance of functional riparian zones by including both parts in many of their laws and regulations. This way, Norway makes their mutual protection the default.

The Norwegian Water Resources Act states that "some natural vegetation zone must be maintained to reduce runoff and provide habitat along the banks of watercourses" (Vannresursloven, 2000). The European Union's Water Framework Directive has been applied in Norwegian law in the form of the Norwegian Water Regulation. It states that whether a water body reaches "good ecological status" partially depends on the structure and condition of its riparian zones (Vannforskriften, 2006). Finally, the Norwegian Planning and Building Act states that "special consideration must be given to the natural environment in the 100-metre zone alongside watercourses" (Plan- og bygningsloven, 2008). Any plans for projects that could affect the riparian zone or its watercourse must abide by these 3 laws and regulations. As such, any project that is likely to violate or interfere with these laws, because it will negatively affect a watercourse or its riparian zones, cannot take place. This is unless the initiative taker can prove that an exception is warranted given the alternatives or other issues, or if there is no significant expected damage, before the project is permitted. The integrated effects of projects on waterbodies and their riparian zones are thus taken into account while simultaneously placing the burden of riparian protection on the project initiator.

Norway implicitly sees the riparian zone as a nature-based solution for climate change adaptation, for example, through bank stabilization by functional riparian vegetation and through natural water retention by the riparian flood plain. The Norwegian National Planning Guidelines for Climate Action and Adaptation state that "wetlands, riparian zones etc. which can mitigate the effects of climate change, are important to safeguard in spatial planning" (Statlige planretningslinjer for klima- og energiplanlegging og klimatilpasning, 2018). These guidelines specifically put the burden of protection on actors who are considering constructing so-called gray infrastructure, such as retaining walls along watercourses. They state "if other solutions are chosen, explanations must be given as to why nature-based solutions have not been chosen." We are unaware of any other laws or guidelines that so distinctly favor the choice of nature-based solutions, strengthening the argument for combined conservation of riparian and freshwater ecosystems.

Norwegian regional and local authorities are "expected to contribute to good environmental status and manage land use in the riparian zone along the watercourses in a comprehensive and long-term perspective" (Ministry of Local Government and Regional Development, 2019). This means that well-integrated management of Norwegian freshwater and riparian ecosystems is guaranteed even further, offering a third aspect in which Norwegian legislation and policy are likely to enhance freshwater and riparian functioning in the future.

The 3 issues detailed above provide distinct, but complementary, angles from which one can approach the freshwater biodiversity crisis and mitigate or even reverse ecosystem degradation. Fundamentally, they require an integrated approach where freshwater and the connected riparian and wetland ecosystems are considered. This integration needs to involve

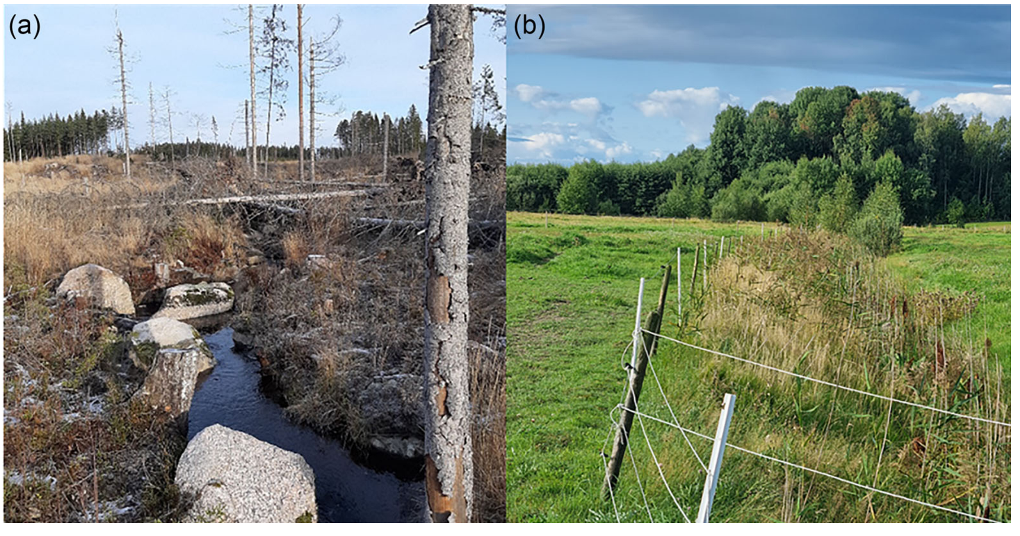

FIGURE 1 Small streams with (a) a forest clearcut reaching to the stream bank and windfallen trees and (b) between pastures with a narrow grazing exclosure.

the people affected by ecosystem degradation, which sustains the cultures of knowledge production and practical conservation stewardship; lead to adequate biodiversity measurement and clear communication about what can and cannot be inferred from the outcomes; and be implemented through institutional policies and practices.

We illustrate the above through examples of small-stream riparian zones in forest and pasture landscapes (Figure 1). Riparian zones are often subject to intensive land use through agriculture, urbanization, or forestry (Hoppenreijs et al., 2022), which have cascading effects on in-stream conditions. In the forest case (Figure 1a), clearcutting extended up to the streambank, disrupting ecological functions, such as subsidy input, recruitment of woody debris, and nutrient and sediment filtration (Lind et al., 2019). In the pasture case (Figure 1b), a livestock exclosure allowed recovery of riparian vegetation, improving in-stream flow, reducing sedimentation, and modulating water temperature (Krall & Roni, 2023). For both forest and pasture riparian systems, scientific knowledge and TEK exist that support the positive effects of riparian zone protection for biodiversity and ecosystem function. Such ecological knowledge is the basis for the policies described in "Watercourses and Their Riparian Zones in Norwegian National Laws and Policies." In our forest case example (Figure 1a), ecological recommendations were not followed, whereas in the pasture example ecological function was restored by following best practices. Better integration of local stakeholder needs and knowledge with scientific research has the potential to improve knowledge transfer to ensure that best practices are implemented more consistently.

CONCLUSION

Our society is currently at a crossroads; it has the chance to better integrate riparian, freshwater, and wetland research and management for sustaining these socioecological systems for the future. Researchers can contribute by involving the people who hold forms of relevant knowledge in research and management, asking the right research questions, and helping the public and policymakers prioritize integrated freshwater and ecosystem protection. Mirroring the ecological links in our research and policy practices can help identify and mend broken linkages in the current conservation of freshwater–riparian systems and provides an opportunity to preserve and restore their biodiversity.

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