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Addressing the policy and business drivers of global freshwater biodiversity loss

David Tickner[a], **Laurenne Schiller**[b,c], **Steven J. Cooke**[d], **Eugenio Barrios Ordóñez**[e], **Ute Collier**[f], **James Dalton**[g], **Ian Harrison**[h], **Li Lifeng**[i], **Sui Chang Phang**[j], and **William J. Young**[k]

[a]WWF-UK, Living Planet Centre, Woking, UK; [b]Biology Department, Dalhousie University, Halifax, NS B3H4R2, Canada; [c]School of Public Policy and Administration, Carleton University, Ottawa, ON K1S 5B6, Canada; [d]Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada; [e]Fundación Gonzalo Río Arronte, Blvd. Pdte. Adolfo López, Mateos 2009, Piso 1, Los Alpes, 01010, Álvaro Obregón, CDMX, Mexico; [f]International Renewable Energy Agency, Abu Dhabi, UAE; [g]IUCN, Gland, Switzerland; [h]IUCN Species Survival Commission and Northern Arizona University, Flagstaff, AZ, USA; [i]Land and Water Division, Food and Agriculture Division of the United Nations, Viale delle Terme di Caracalla, 00153 Rome, Italy; [j]The Nature Conservancy, London, UK; [k]Griffith University, 170 Kessels Road, Nathan, Queensland 4111, Australia

Corresponding author: **David Tickner** (email: dtickner@wwf.org.uk)

Abstract

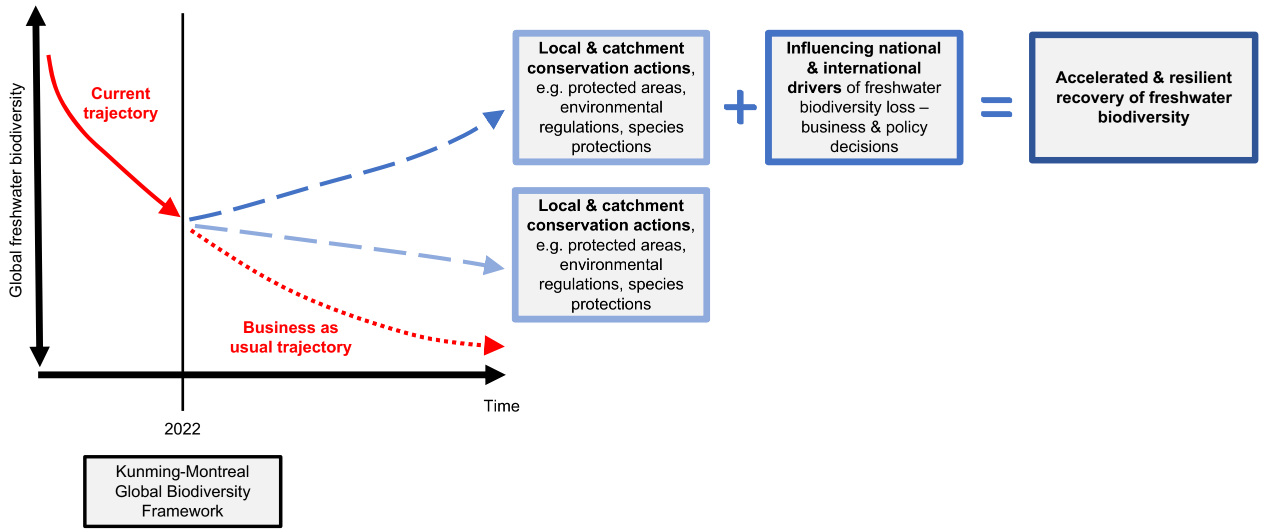
While they are important, local or catchment-level conservation efforts are by themselves unlikely to bend the curve of dramatic global-scale biodiversity loss in rivers, lakes, and freshwater wetlands. Other interventions will also be required, especially those that address the underlying socio-economic drivers of freshwater ecosystem degradation. Such drivers often manifest through decisions made at national or international scales by policymakers and business leaders in sectors including water resource management, agriculture and food production, energy generation, and inland fisheries. Few analyses have traced the impacts of such decisions on freshwater ecosystems and biodiversity, and the evidence base provides scant insight into effective approaches for addressing these underlying drivers. We begin to address this strategic knowledge gap by describing key policy and business sectors that the conservation and science communities should engage to address the systemic drivers of global freshwater biodiversity loss. Drawing on diverse experiences of international policy and business discourses and applied freshwater sciences, we provide an overview of international sector-specific risks and opportunities for freshwater conservation and propose potential priorities for engagement. We reflect on actions the freshwater sciences community can take to respond to these risks and opportunities, and we suggest priorities to shape a more systemic, driver-focused approach to freshwater conservation research that can support the integration of freshwater biodiversity considerations into policy and business decisions.

Key words: water resource management, agriculture and food, energy generation, inland fisheries, challenges and opportunities

1. Introduction

Hope remains for the flora and fauna of the world's rivers, lakes, and freshwater wetlands. In late 2022, 196 governments adopted the Kunming-Montreal Global Biodiversity Framework (GBF) (UN Convention on Biological Diversity 2022). Following the earlier publication of an Emergency Recovery Plan that set out six actions to "bend the curve" of global freshwater biodiversity loss (Tickner et al. 2020), and thanks in part to concerted advocacy from the international freshwater conservation community, the GBF explicitly incorporated "inland waters" within targets for habitat restoration (Target 2) and conservation (Target 3). This was an improvement on earlier agreements—including the GBF's predecessor framework, the Aichi Targets, and the UN Sustainable Development Goals—which omitted specific consideration of freshwater biodiversity (Dickens et al. 2020; Elliott et al. 2022; Cooke et al. 2023*a*). More tangibly, countless restoration projects are underway in rivers, lakes, and wetlands worldwide, albeit with some mixed or unclear results (Speed et al. 2016; Feio et al. 2021; Piczak et al. 2023; Thieme et al. 2023), and targeted efforts are bending the curve for species such as the Indus River Dolphin (*Platanista minor*), Eurasian Beaver (*Castor fiber*), and Arapaima (*Arapaima gigas*) (Campos-Silva and Peres 2016; Halley et al. 2021; Braulik et al. 2023). However, such hope must be tempered by a rapid decline in freshwater biodiversity writ large. The Living Planet Index shows an average fall of 85% in freshwater vertebrate populations worldwide since 1970 (WWF 2024), and the IUCN Red List shows that 25% of assessed freshwater species are threatened with extinction (IUCN 2024; Sayer et al. 2025). It seems that there has never been a better international policy opportunity, nor greater urgency,

Fig. 1. To fully implement the Emergency Recovery Plan for global freshwater biodiversity and to meet the aims of the Global Biodiversity Framework, conservationists and others can implement actions both at local and catchment scales to address acute, local biodiversity concerns and at national and international scales to address key policy and business decisions that drive freshwater biodiversity loss.



for actions to restore river, lake, and wetland habitats and species.

Local and catchment-scale conservation efforts can be successful in protecting or restoring individual habitats and species but seem unlikely to reverse the dramatic global collapse of freshwater biodiversity. Moreover, many hard-won local or catchment-scale conservation gains may be overwhelmed by impacts driven by larger scale (often national or international) socio-economic processes (Lynch et al. 2023). For instance, public or private investment in agricultural intensification aimed at enhancing food production can lead to widespread increases in consumptive water use for irrigation and pollution from farm chemicals, and thus damage or destroy multiple freshwater habitats (Moss 2008). Similarly, the global push for renewable electricity generation might lead to further proliferation of hydroelectric dams, impairing habitat connectivity and disrupting swimways for anadromous fish (Thieme et al. 2021). Therefore, there is a clear and urgent need for additional interventions that address systemic national and international drivers of ecosystem degradation and ensure that freshwater conservation and restoration efforts (as per Targets 2 and 3 of the GBF) are resilient to future socio-economic changes (Fig. 1). To date, little attention has been paid to such interventions in the scientific literature.

In this article, we address this strategic knowledge gap by (i) describing key policy and business sectors that drive changes in freshwater biodiversity internationally, and (ii) setting out opportunities for conservationists and researchers to inform and engage sectoral decision-makers. Following a brief critical synthesis of the scientific and grey literature on drivers of freshwater biodiversity loss, we outline key sectors for engagement, including water resource management, food and agriculture, energy generation, and inland fisheries. Drawing on our diverse experiences of policy and business discourses and applied freshwater sciences, we provide an overview of international sector-specific risks and opportunities for freshwater biodiversity conservation and suggest potential avenues for engagement. We provide recommendations for interdisciplinary research that could inform efforts to integrate freshwater biodiversity considerations into policy and business decisions, and aid mitigation of unavoidable trade-offs. Lastly, we suggest priorities to shape a more systemic, driver-focused approach to freshwater conservation research that can support the integration of freshwater biodiversity considerations into policy and business decisions.

2. Policy and business drivers of freshwater biodiversity loss: known knowns and known unknowns

The Driving Forces–Pressures–State–Impact–Responses (DPSIR) model (Smeets and Witterings 1999) has been widely used by organisations such as the UN Food and Agriculture Organization (Wood and van Halsema 2008), the European Environment Agency (e.g., Whytock 2021), and the US Environmental Protection Agency (e.g., Bradley and Yee 2015) to facilitate systemic analysis of the dynamic connections between human activities and the state of the environment. In this model, socio-economic interventions act as *driving forces* (hereafter, drivers) that exert *pressures* on the environment and, as a result, contribute to a change in its *state*. To address the *impacts* of that changed state on biodiversity or human wellbeing, policymakers or other actors may then design and implement *responses*. For example, in this model, concerns about food security, expressed through agriculture policies and investments by food sector companies, can drive intensification of farming methods, leading to increased

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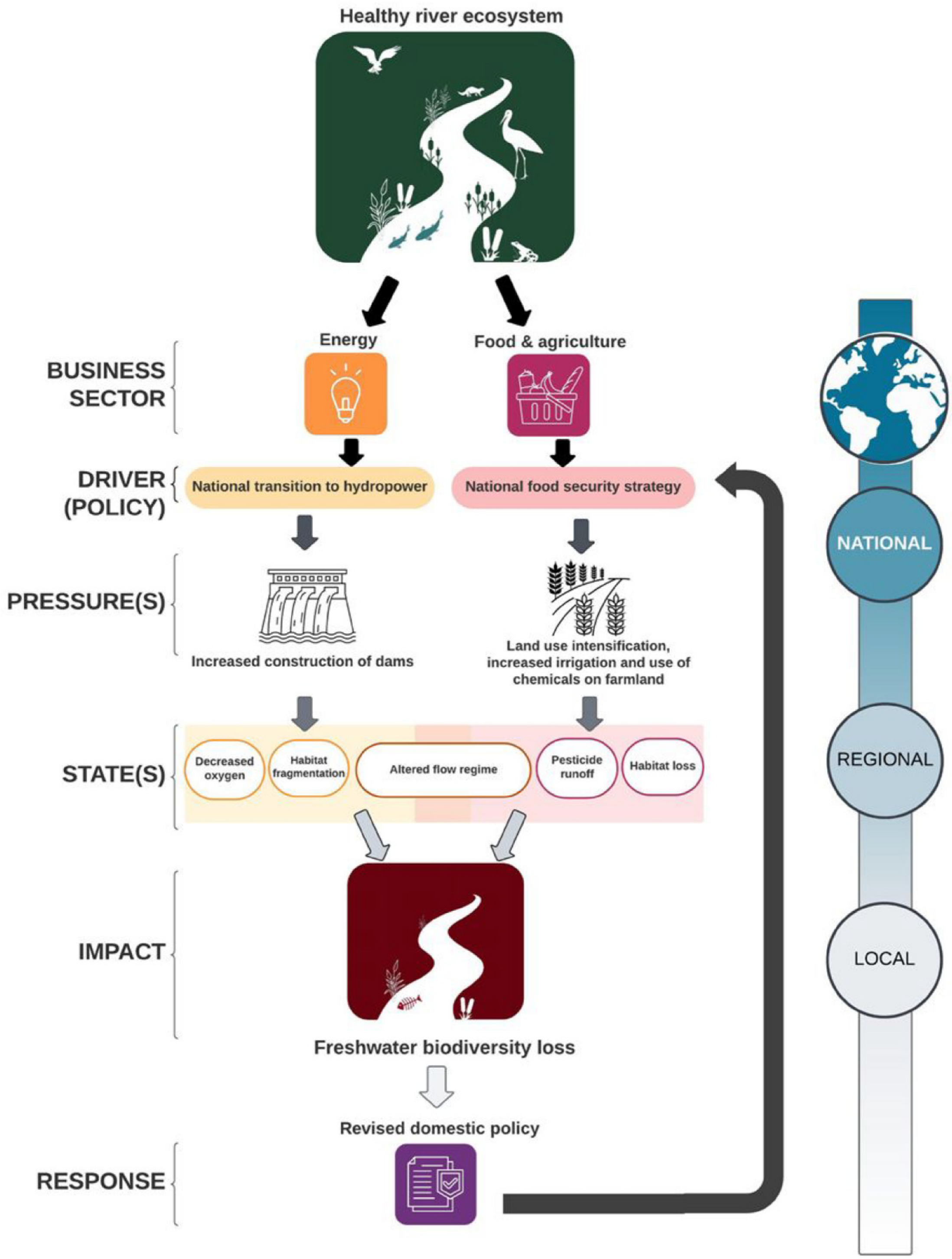
Fig. 2. The Drivers–Pressures–State–Impact–Response (DPSIR) framework as applied to two of the key drivers of freshwater biodiversity loss: (i) energy systems, including hydropower expansion, and (ii) food and agriculture.



pressures from land use change, irrigation, and farm chemical use, which in turn alter the state of hydrological regimes and water quality, eventually impacting freshwater biodiversity. Similarly, demand for increased electricity supply, reflected in energy sector policies and investments, can drive development of new hydropower capacity, thus increasing pressures from dam construction and changing the state of habitat connectivity, river and sediment flows, and oxygen saturation levels (Fig. 2), causing impacts on biodiversity upstream and downstream of dams.

In response to societal demands, governments and businesses each make decisions that reflect the nature and extent of drivers. Governments at sub-national, national, and sometimes transnational (e.g., in the European Union) scales set overall policy directions to guide the behaviours of businesses and individuals and can deploy a variety of measures to support policy implementation, including financial instruments (taxes, subsidies, incentives, grants, etc.) and environmental laws or regulations. Businesses can influence policy development and are also increasingly important actors in the delivery of national and international commitments on climate and biodiversity (Folke et al. 2019). While guided by the public policy regime of the jurisdictions within which they operate and/or sell products or services, businesses can also be agile in responding to environmental change, adjusting their operations and supply chains independently and relatively quickly in response to risks, social pressures, or market demands. Business can also potentially co-invest with governments and other stakeholders in solutions to environmental problems (Österblom et al. 2015).

The impact and interaction of different socio-economic drivers of biodiversity loss in freshwater, marine, and terrestrial realms is poorly understood (Mazor et al. 2018). However, research focused on terrestrial biodiversity has indicated that, alongside conventional local or landscape-scale conservation efforts, action to address drivers of ecosystem change will be necessary to reverse global-scale biodiversity losses (e.g., Leclère et al. 2020; Mosnier et al. 2023). The food and agriculture system is acknowledged to be the primary driver of global terrestrial biodiversity loss, including production of crops and livestock for local consumption and cultivation of internationally traded soft commodities such as soy and palm oil, which often results in deforestation, habitat conversion, and land use change (e.g., Millennium Ecosystem Assessment 2005; Green et al. 2019; Runyan and Stehm 2020). This understanding has stimulated a major focus on the food system as an area for systemic conservation interventions, e.g., through initiatives such as the Food and Land Use (FOLU) Coalition and the Food, Agriculture, Biodiversity, Land-Use and Energy (FABLE) Consortium. Similarly, the extent of corporate activity and impact across marine sectors has recently been estimated (Virdin et al. 2021), enabling a better understanding of key actors and markets related to offshore energy production, shipbuilding and port activities, and cruise tourism, among others. In the case of the world's largest transnational seafood companies, organized dialogues with scientists led to the co-development of the Seafood Business for Ocean Stewardship (SeaBOS) initiative with the stated purpose of leading a global transformation towards sustainable seafood and a healthy ocean (Österblom et al. 2022).

In contrast, and despite extensive scientific discourse on the reasons for global freshwater biodiversity losses (Table 1), few studies have thoroughly explored the causative links between policy and business decisions and changes in populations of freshwater flora and fauna. Most of the existing literature is discursive and qualitative rather than systematic and quantitative (e.g., Stendera et al. 2012; Richman et al. 2015; Albert et al. 2021). Diverse human interventions are often lumped into a single category of habitat degradation or similar, which hinders distinction of specific effects driven by separate processes such as wetland drainage for urban development, dam-building for hydropower generation or flood risk management, or changes in flow regime driven by abstraction of water for irrigation (e.g., Collen et al. 2014; Mazor et al. 2018; Jaureguiberry et al. 2022). The analytical lexicon is imprecise and terms such as "drivers", "pressures", "threats", and "stressors" are frequently used interchangeably such that direct reasons for changes in biodiversity (pressures, *sensu* DPSIR) are conflated with underlying socio-economic drivers such as the need for water, food, or energy security (e.g., Strayer and Dudgeon 2010; Vörösmarty et al. 2010; Gozlan et al. 2019; Reid et al. 2019; Williams-Subiza and Epele 2021; Oberdorff 2022). The importance of engaging relevant policy and business sectors is recognized (e.g., Cazzolla Gatti 2016; Tickner et al. 2020), but explicit discussion of the relative and/or synthetic impacts of individual sectors on freshwater biodiversity is sparse and there is a dearth of science-based insight into sectoral policy priorities, business practices, or potential regulatory responses. While there are recurring mentions in the literature of sectors such as water resource management, food and agriculture, and energy generation (most commonly relating to the impacts of hydropower dams), further research is needed to map and quantify drivers and pressures to determine the relative extent to which specific policy or business sectors are driving global and regional freshwater biodiversity losses.

Beyond the scientific community, an evolving policy discourse over the last two decades has been encapsulated within grey literature largely produced by NGOs and other nonacademic actors which has focused on the role of businesses in stewarding freshwater resources. The concept of private sector water stewardship is predicated on the assumption that chronic water scarcity and pollution pose as much risk to business operations and supply chains as to local communities or freshwater habitats (Chapagain and Tickner 2012; Hepworth and Orr 2013; Jones et al. 2015). Water stewardship principles suggest that any business that desires to mitigate physical, regulatory, or reputational impacts to their operations or value chains should be proactive in engaging other stakeholders in collective responses to these shared risks (Orr et al. 2009). Although it focuses largely on interventions to sustainably manage water as a resource for human use and seldom explicitly mentions the needs of freshwater biodiversity, the fact that the water stewardship literature links pressures to specific business sectors suggests that parts of the policy and business community are ahead of academia in thinking about the need for systemic interventions. Further analysis of real-life case studies, such as the Water Fund model developed and led by The Nature Conservancy in various locations (De Bièvre and Coronel 2022), is needed to test whether water stewardship interventions result in co-benefits for local communities and freshwater biodiversity, as well as for businesses.

A wide variety of sectors have been considered in the water stewardship literature, including food and beverages (e.g., Vatter et al. 2021), mining (e.g., Morgan and Dobson 2020), and textiles and apparel (e.g., Morgan et al. 2022). Notably, Famiglietti et al. (2022) quantified the relative impact of different sectors on five key threats to freshwater ecosystems: groundwater depletion, metals contamination, plastic pollution, diversion and transfer of water, and eutrophication. The "consumer staples" sector (i.e., food, beverages, and livestock

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Table 1. A synthesis of recent scientific literature on drivers and pressures of large-scale freshwater biodiversity loss, *sensu* the DPSIR framework (Drivers, Pressures, State, Impacts, Responses).

Article	**Article aim**	Drivers identified (*sensu* DPSIR, and expressed in terms of specific business and/or policy sectors)	**Pressures identified (*sensu* DPSIR)**
Dudgeon et al. (2006)	To "*explore why the transfer of knowledge to conservation action has, in the case of freshwater biodiversity, been largely unsuccessful*".	No systematic assessment or discussion.	Systematic assessment of "threats" including: • Over-exploitation • Water pollution • Flow modification • Destruction or degradation of habitat • Invasion by exotic species
Strayer and Dudgeon (2010)	To "*describe recent progress in freshwater conservation science, concentrating on the period since 1986*".	No systematic assessment. Brief discussion of: • Fisheries • Water supply, including for agriculture • Hydropower	No systematic assessment. Discussion of "threats" and "pressures" including: • Water withdrawals • Pollution • Large dams • Levees, river dredging & straightening • Alien species • Riparian & watershed transformation • Climate change and human responses to it
Vörösmarty et al. (2010)	To "*report the results of a global-scale analysis of threats to freshwater that, for the first time, considers human water security and biodiversity perspectives simultaneously within a spatial accounting framework*".	No systematic assessment, but some sectoral drivers–agriculture, fishing, aquaculture–incorporated into stressor analysis. Brief discussion of: • Agriculture • Inland fisheries • Water supply	Systematic assessment of "stressors" in the form of 23 geospatial "drivers" organized under four themes including: • Catchment disturbance • Pollution • Water resource development • Biotic factors
Stendera et al. (2012)	(1) To "*collate hypotheses tested in the most recent literature concerning the drivers of freshwater biodiversity; (2) to identify stressors impacting freshwater biodiversity and (3) to identify gaps in freshwater biodiversity research*".	No systematic assessment. Brief discussion of: • Water resource development	No systematic assessment. Discussion of "stressors" including: • Eutrophication • Connectivity • Invasive species • Habitat destruction • Hydrology • Others
Collen et al. (2014)	To "*identify broad-scale patterns in the distributions of species, to evaluate the processes that determine diversity and to determine how similar or different these patterns and processes are among different groups of freshwater species*".	No systematic assessment. Brief discussion of "proximate drivers" of habitat loss/degradation, focusing on: • Agriculture • Urbanization • Infrastructure development (particularly dams) • Logging.	Systematic assessment of "threats," concluding that predominant threats were: • Habitat loss/degradation • Water pollution • Over-exploitation

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Table 1. (*continued*).

Article	Article aim	Drivers identified (*sensu* DPSIR, and expressed in terms of specific business and/or policy sectors)	**Pressures identified (*sensu* DPSIR)**
Richman et al. (2015)	To "*report on patterns of crayfish extinction risk across families, analyse patterns of threat and data gaps, and make recommendations for conservation*".	No systematic assessment. Discussion of "threats" conflates pressures and drivers, including: • Energy production and mining • Climate change and severe weather events • Problematic native species • Logging • Invasive species and disease • Urban development • Agriculture • Dams/water management • Harvesting • Pollution • Human disturbance	
Cazzolla Gatti (2016)	To "*report a comprehensive review of published studies that qualitatively and quantitatively examine the current threats to biodiversity on a local and global scale*".	No systematic assessment. Brief discussion of: • Agriculture • Industry • Urban areas • Transport • Hydropower	Systematic assessment of "threats" including: • Over-exploitation • Water pollution • Flow modification • Destruction or degradation of habitat • Invasion by exotic species • Climate change • Nitrogen deposition • Runoff patterns
Mazor et al. (2018)	To "*quantify current research efforts into the different drivers of biodiversity loss and assess whether research output aligns with policy priorities using a systematic map*"	No systematic assessment or discussion.	Systematic assessment of "drivers" (pressures, *sensu* DPSIR) including: • Habitat change • Climate change • Invasive species • Over-exploitation • Pollution
Gozlan et al. (2019)	To "*provide a critical assessment of issues facing decision-makers [in Europe and Central Asia], including freshwater biodiversity and ecosystem trends as well as drivers of change*".	No systematic assessment. Discussion of: • Urbanisation, including building development and roads • Forestry • Intensive agriculture • Mineral extraction • Aquaculture and fisheries • Hydropower	Systematic assessment of "drivers" (pressures, *sensu* DPSIR) including: • Habitat loss and degradation, including from dams, weirs, irrigation and drainage canals • Pollution • Alien species and disease • Climate change • Water abstraction • Salinisation

Table 1. (*continued*).

Article	Article aim	Drivers identified (*sensu* DPSIR, and expressed in terms of specific business and/or policy sectors)	**Pressures identified (*sensu* DPSIR)**
Reid et al. (2019)	To identify "*emerging threats and* [to] *update our knowledge of continuing challenges to freshwater conservation, paying special attention to issues that may have global, undesirable effects*".	Systematic assessment of "threats." Discussion conflates pressures and drivers, including "persistent threats" (as per Dudgeon et al. (2006)—see above) and "emerging threats": • Changing climates • E-commerce and invasions • Infectious diseases (linked to, *inter alia*, aquaculture) • Harmful algal blooms • Expanding hydropower • Emerging contaminants, from mining, agriculture, aquaculture, pulp & paper production, oil & gas production, and urban runoff, and containing ingredients from, *inter alia*, pharmaceuticals, pesticides and personal care products • Engineered nanomaterials, used in sectors such as pharmaceuticals and agriculture • Microplastic pollution, including from sectors such as cosmetics and clothing • Light and noise, including from urbanisation and transport • Freshwater salinisation, exacerbated by agricultural irrigation and energy production (hydropower and fracking) • Declining calcium, linked to forestry • Cumulative stressors	
Tickner et al. (2020)	To "*present an Emergency Recovery Plan to reverse the rapid worldwide decline in freshwater biodiversity*".	No systematic assessment. Brief discussion of the need for "*a coordinated international effort to transform underlying socio-economic drivers of freshwater biodiversity declines, stemming from food, energy, industrial and infrastructure sectors*".	Systematic assessment of actions to address "pressures" including: • Accelerate implementation of environmental flows • Improve water quality to sustain aquatic life • Protect and restore critical habitats • Manage exploitation of freshwater species and riverine aggregates • Prevent and control non-native species invasions • Safeguard and restore freshwater connectivity
Albert et al. (2021)	To "*recommend a set of urgent policy actions that promote clean water, conserve watershed services, and restore freshwater ecosystems and their vital services*".	No systematic assessment. Discussion of: • Agriculture and food production • Urbanisation • Industry • Electricity supply Recommendations for regional policy actions by "freshwater" (i.e., water resource management) and energy sectors.	No systematic assessment. Discussion of "threats" including: • Habitat alteration • Water pollution • Overfishing • Exotic species introduction • Water withdrawals and river diversions • Fragmentation and flow regulation • Climate change • Rising sea levels • Altered precipitation regimes
Williams-Subiza and Epele (2021)	To "*answer four main questions: (i) what proportion of the global biodiversity literature is concerned with freshwater environments; (ii) which are the most and least researched drivers of biodiversity loss in freshwater environments; (iii) does the research effort devoted to each driver vary among freshwater ecosystems; and (iv) is there a geographical bias in freshwater biodiversity research?*"	No systematic assessment or discussion of drivers.	Systematic assessment of "drivers" (pressures, *sensu* DPSIR) including: • Climate change • Water pollution • Flow modification • Expanding hydropower • Species invasion • Habitat degradation

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Table 1. (*concluded*).

Article	**Article aim**	Drivers identified (*sensu* DPSIR, and expressed in terms of specific business and/or policy sectors)	**Pressures identified (*sensu* DPSIR)**
Jaureguiberry et al. (2022)	To "*systematically review natural science studies published since 2005 that compared the impacts that multiple direct drivers have had on any of a large set of indicators of the state of biodiversity*".	No systematic assessment or discussion of drivers.	Systematic assessment of "drivers" (pressures, *sensu* DPSIR) including: • Climate change • Land/sea use change • Direct exploitation of natural resources • Pollution • Invasive alien species
Oberdorff (2022)	To "*review the current and future effects of anthropogenic drivers on freshwater ecosystems and their biodiversity and provide some few examples of existing solutions, either technological, nature-based or policy-based, that could be applied globally to halt and/or minimize their negative consequences*".	No systematic assessment. Brief discussion of: • Agriculture • Energy, including bioenergy & hydropower • Mining • Urbanization • Inland fisheries & aquaculture	Systematic assessment of "stressors", "threats", "pressures", and "drivers" (terms used interchangeably) includes: • Climate change • Land-use and water pollution • Habitat fragmentation • Non-native species introductions • Harvesting
Sayer et al. (2025)	To "*present the results of a multi-taxon global freshwater fauna assessment for The IUCN Red List of Threatened Species covering 23 496 decapod crustaceans, fishes and odonates*".	A systematic assessment of "threats." Discussion conflates pressures and drivers, noting that 84% of threatened species are affected by more than one threat: • Pollution (54% of species) • Dams and water management (39%) • Agriculture (37%) • Invasive species and disease (28%) • Logging (25%) • Urban development (23%) • Hunting and fishing (21%) • Energy production and mining (18%) • Climate change and severe weather (18%)	

production) emerged from this analysis as the largest driver of both groundwater depletion and water pollution globally. However, there was no mention in that study of specific businesses, nor any systematic exploration of relative company impacts and influence within these sectors. Such distinctions are important, given that the impacts of individual companies on common pool resources, and their influence in policy-making processes, are heterogeneous (Jacquet et al. 2013; Österblom et al. 2015). Thus, it is important to understand the respective business cases that might persuade different sectors or companies to invest in co-developing strategies to restore aquatic ecosystem health in different contexts (Österblom et al. 2022).

While the scientific and grey literature provide clues as to which policy and business sectors are key, there is little coherent information on the relative and cumulative impacts of specific policy frameworks and business sectors on regional or global freshwater biodiversity. We have found no robust and specific analyses of the ways in which policy and business imperatives might drive further decline and/or recovery of freshwater ecosystems. Freshwater conservation practitioners endeavouring to reverse freshwater biodiversity losses regionally or globally through systemic interventions therefore require a better understanding of (a) which are likely to be the key policy and business sectors to engage, and (b) current and future priorities for governments, companies, and investors within those sectors, as indicated by prevailing policy and business narratives, supply chain geography, and corporate sustainability obligations. Such understanding can inform tactics for engagement with policymakers and business leaders to encourage a shift towards activities and investments that meet their respective priorities while mitigating harmful impacts on, or promoting recovery of, freshwater biodiversity.

3. The key policy and business sectors driving freshwater biodiversity losses

As noted above, a wide variety of sectors are discussed in the literature as driving changes in freshwater biodiversity, including mining and mineral extraction, urbanisation, transport, forestry, textiles and apparel, and pharmaceuticals (Table 1). A short perspective paper cannot provide a comprehensive analysis of every sector and across different regions and contexts. Instead, we describe indicative driver-focused strategies for engaging four policy and business sectors that emerged from our literature review and our collective experience as likely to have the most widespread and substantial effects on freshwater biodiversity worldwide: water resource management; food and agriculture; energy generation; and inland fisheries and aquaculture. For each sector, we set out a concise assessment of: (a) how each drives changes in freshwater habitats and biodiversity; (b) prevailing international policy and business imperatives that are likely to guide future operations and frameworks; and (c) priority challenges and opportunities for freshwater biodiversity recovery linked to those imperatives.

3.1. Water resource management

3.1.1. How this sector drives changes in freshwater habitats and biodiversity

Water resource management is the process of planning, developing, and implementing actions to ensure that societies and economies have access to water for multiple uses, are adequately protected from water-related risks, and are addressing water quality concerns. It incorporates institutions, incentives, and information systems as well as physical interventions to store, move, treat, and distribute water (World Bank 2022). The history of water resource management has been dominated by the need to assure water supply for political and economic priorities such as food production, energy generation, urban development, and public water supply and protection (Pegram et al. 2013). As such, water resource management is both a distinct policy and business sector in itself and an enabler for other sectors. These other sectors have strongly influenced relevant policy frameworks, with investments largely focused on tackling perceived "difficult hydrologies" (Grey and Sadoff 2007) through construction of infrastructure for storage and conveyance of water, treatment of wastewater, and mitigation of flood risks. Approaches to water resource management have followed varying implementation pathways, guided by context-specific policy frameworks, institutional arrangements, and political priorities at sub-national, national, and regional scales. Until recently there has been little explicit consideration of freshwater biodiversity in such policy frameworks and, although the health of rivers, lakes and wetlands has become a higher profile issue in some contexts, environmental considerations often remain secondary priorities. Consequently, the sector has played a major role in driving freshwater biodiversity loss through alterations to natural hydrological levels and flows caused by water abstraction for different human uses; pollution from urban, industrial, agricultural and other sources; and connectivity loss through construction of storage, diversion, and flood management infrastructure (Gorenflo and Warner 2016).

3.1.2. Prevailing international policy and business imperatives

Developed in the late 20th century, the concept of Integrated Water Resource Management (IWRM) is the prevailing paradigm guiding water resource management policy internationally. IWRM reflected a conceptual shift from a largely engineering-led approach to managing water, to a more nuanced and multi-disciplinary approach that tries to incorporate at least some social and environmental safeguards into design and development of water infrastructure and institutions. The main tenets of IWRM are embedded in water management policy and planning in many jurisdictions and in international agreements and frameworks, such as UN Sustainable Development Goal 6. However, recently it has been suggested that IWRM has been only partially successful in addressing the complex and often competing pressures on water resources and freshwater ecosystems (Griggs 2024) and there is emerging evidence in countries such as China of a further shift to strategic water management approaches that might, among other things, move beyond simply safeguarding freshwater ecosystems to actively encouraging their restoration (Pegram et al. 2013; Speed et al. 2016; Sayers et al. in press). These developments in the water resource management policy arena have occurred in parallel with the evolution of business-focused water stewardship approaches, discussed above, and with the emergence of extensive scholarship on the Water–Food–Energy (WEF) Nexus and related concepts that analyse the complex relationships and trade-offs between sectors (e.g., Simpson and Jewitt 2019; IPBES 2024). It is not yet clear whether or how water resource management and water stewardship will be brought together in practice at national or catchment scales, nor what implications such co-evolution might have for freshwater biodiversity. However, recent attempts to transpose water stewardship principles to selected national and transboundary contexts suggest that it might be possible to deploy analyses of risks and trade-offs to support more environmentally sustainable management of freshwater ecosystems at a large scale (e.g., WWF 2016, 2018).

3.1.3. Priority challenges and opportunities for freshwater biodiversity recovery

Trade-offs between the potential uses of water resources and healthy freshwater ecosystems are unlikely to reduce in the foreseeable future. Demand for water and for protection from flood and drought risks will inevitably grow in many places as populations grow, towns and cities develop, and agricultural and industrial drivers increase. Climate change exacerbates such challenges by increasing uncertainty over the amount and intensity of rainfall and run-off patterns. Pressures on freshwater biodiversity will magnify in the absence of effective water resource management policies, plans, and financing mechanisms that emphasize allocations of water for the environment (in the form of environmental flows, for instance), pro-active approaches to restoring rivers and other aquatic habitats, and expansion of nature-based solutions (NbS). However, shifts in water resource management have demonstrated that it is possible to facilitate the protection and recovery of freshwater ecosystems at a variety of scales while also addressing societal objectives (e.g., Harwood et al. 2017; Arthington et al. 2023). For example, in Mexico, a 2018 policy mandated the establishment of water reserves in 300 river basins nationwide, to provide a buffer to protect biodiversity from droughts or human water demands (Barrios 2021); across Africa, NbS initiatives have helped to address water and climate-related problems (Acreman et al. 2021); and the European Union has adopted a flagship Nature Restoration Law that requires Member States to reconnect at least 25 000 km of the continent's rivers by 2030 (European Commission 2023).

Attention to water resource management challenges seems to be rising within the global policy arena, as evidenced by successive UN Water conferences held in 2023 and planned for 2026, and by the appointments in September 2024 of the first UN Secretary-General's Special Envoy on Water and the first EU Commissioner for water resilience. Commentators have proposed that water resource management—and by extension, the freshwater ecosystems from which water is sourced—should be acknowledged as a connector of multiple Sustainable Development Goals, the UN Framework Convention for Climate Change, the Global Biodiversity Framework, and the Sendai Framework on Disaster Risk Reduction (Barrios 2021). This framing has been foundational for the Freshwater Challenge, a new country-led initiative that aims to support, integrate, and accelerate the restoration of 300 000 km of degraded rivers and 350 million hectares of lost and degraded wetlands by 2030, as well as conserve intact freshwater ecosystems. Potentially, the Freshwater Challenge provides an unprecedented platform to encourage governments and companies to work together to implement environmental water allocations, NbS, and other water resource management interventions that can aid the protection and recovery of freshwater biodiversity while also addressing the challenges of policy fragmentation across policy and business sectors. However, political leadership will be needed to mainstream healthy freshwater ecosystems and biodiversity as an essential ingredient of sustainable water resource management (UNESCO and UN Water 2020).

3.2. Agriculture and food production

3.2.1. How this sector drives changes in freshwater habitats and biodiversity

Agriculture is a major driver of alterations to hydrological flows and levels in freshwater ecosystems and of disruptions to habitat connectivity. An estimated 70% of water withdrawals worldwide and more than 90% of consumptive water use are for agricultural purposes (Gleick 2014). Within this sector, water use is often associated with development of built infrastructure for inter-basin transfers, water storage, and conveyance of water for irrigation purposes. Hydrological regimes are also affected by drainage and conversion of wetlands to agricultural land use and by the disconnection of floodplains from rivers resulting from levee construction to protect farmland and other property from flooding. Pollution by organic and mineral fertilizers, pesticides, and active pharmaceutical ingredients used in agriculture, and by sediment mobilized by conversion of land for agricultural uses, also has substantial impacts on freshwater ecosystems worldwide (Ayers and Westcot 1985; Pericherla et al. 2020). Through combined effects of the use and pollution of water, agriculture is likely to be a primary driver of freshwater species population declines and extinctions (Dudgeon 2019; Albert et al. 2021; Sayer et al. 2025). Further along the value chain, the storage, processing, transport, and consumption of food can involve the use of water, land, chemicals, and plastics and therefore exert pressure on hydrological regimes and water quality in many freshwater habitats, especially where water allocation arrangements and wastewater treatment facilities are ineffective. (Note that inland fisheries are an important element of food production in many places but are considered in a separate section below.)

3.2.2. Prevailing international policy and business imperatives

Several recent assessments and initiatives—including FOLU and FABLE (as discussed earlier), the EAT Lancet Commission (Willett et al. 2019), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessment on Land Degradation and Restoration (IPBES 2018)—have focused on how the food system, agriculture, and land use globally can transition to a more environmentally sustainable footing while ensuring just outcomes for all actors, including farmers. Drawing on these, the UN Food System Summit held in 2021 resulted in 115 countries developing national pathways for food system transformation, in support of the UN Sustainable Development Goals including those on poverty (SDG1), hunger (SDG2), and water (SDG6). Among the five Action Areas featured during the Summit, one focused on boosting NbS, including through the expansion of agro-ecology. Elsewhere, signatories to the UN Convention to Combat Desertification (UNCCD) have taken a close interest in the connections between land use, climate change, drought, and desertification. There is also growing policy interest in the links between food production, nature conservation, and climate change mitigation and adaptation, as evidenced by the agreement at COP28 to the UN Framework Convention on Climate Change (UNFCCC) of targets for the Global Goal on Adaptation, and of a decision emphasizing "the importance of conserving, protecting and restoring nature and ecosystems" within the process of delivering Nationally Determined Contributions (NDCs) towards the Paris Agreement 2050 climate goal.

Private sector actors have been engaged in many of these debates and, in parallel, have also been the focus of dedicated initiatives to encourage more environmentally sustainable agricultural supply chains. Such initiatives have included establishment of certification and standard-setting schemes for specific agricultural commodities, including the Better Cotton Initiative (https://bettercotton.org) and Bonsucro (focused on sugarcane: https://bonsucro.com/); mechanisms to discourage conversion of natural ecosystems, especially forests, including definition of principles for Deforestation and Conversion Free commodity supply chains (WWF 2021); platforms that promote broad improvements in sustainability throughout food supply chains, such as the Sustainable Agriculture Initiative Platform (https://saiplatform.org/); and forums that explicitly aim to address water risks that affect business's bottom lines as well as local communities and ecosystems, such as the Alliance for Water Stewardship (https://a4ws.org/). Emerging tools from the Science Based Targets for Nature network (SBTN, https://sciencebasedtargetsnetwork.org/) and the Task Force for Nature-related Financial Disclosure (TNFD, https://tnfd.global/) offer further opportunities to encourage businesses and financial investors to incorporate action for biodiversity into their risk and sustainability strategies.

3.2.3. Priority challenges and opportunities for freshwater biodiversity recovery

The discourse on agriculture and food is complex and often interwoven with politically sensitive debates about national security, rural livelihoods, just transitions, perceived "land grabbing", and appropriation of virtual water supplies by overseas actors. Arguably, these factors have become more prominent in recent years as agricultural commodity supply chains have become disrupted by regional conflicts and large-scale economic shifts. On a technical level, debates on the future of the food system often pay more attention to land use than to water. For instance, the Global Commission on the Economics of Water (https://watercommission.org/) has warned that despite mounting scientific evidence pointing to increased water stress in the regions hardest hit by the global food crisis, water continues to be left out of the discourse and decision making around sustainable agrifood systems. Similarly, the Land and Water Division of the Food and Agriculture Organisation of the UN (FAO) conducted a review of the 116 national pathways for food system transformation submitted after the UN Food Systems Summit and concluded that only one third of the pathways included meaningful consideration of water issues (Li Lifeng, FAO, personal communication).

There has been a growing debate about the potential role of agroecology and regenerative agriculture in the global food system, although this discourse has been criticized for paying insufficient attention to water issues (Lankford and Orr 2022). Conversely, a considerable body of "Water–Food–Energy Nexus" scholarship has discussed policy synergies and trade-offs in water use for food and other priorities, but it is largely disconnected from the mainstream food systems debate. IPBES and other prominent conservation organisations have repeatedly referred to land use change as a key pressure on biodiversity (IPBES 2018) but have failed to acknowledge that changes in water use, such as increasing irrigation of land that is already intensively cultivated, are likely to have distinct and profound impacts on freshwater biodiversity.

Opportunities to influence the food and agriculture debate exist. The second edition of the Global Land Outlook published by the UN Convention to Combat Desertification (UNCCD) highlights that the loss and degradation of freshwater ecosystems significantly contributes to food and nutrition insecurity (UNCCD 2022). FAO, which is co-leading the UN Decade on Ecosystem Restoration, has also begun to make water a more prominent issue, including through the organization of the annual Rome Water Dialogue since 2022, choosing water as the theme of the 43rd Session of FAO Conference in July 2023 (the highest level of the governing body of the FAO) and for the FAO biennium 2024–25, and supporting countries to develop National Water Roadmaps to support SDG implementation. The fact that approximately one third of all food produced is lost or wasted has attracted the attention of climate change campaigners concerned about greenhouse gas emissions from food production, terrestrial conservationists tackling land use change, and water resource management experts addressing unsustainable water use in agriculture. Freshwater conservationists could find common ground with such groups. Multinational companies from food, beverage, and textile sectors–all of whom rely on agricultural supply chains for core ingredients in their products–have been prominent in forums and initiatives focused on water stewardship. Some of these companies are now beginning to make similar efforts to understand and address the impacts of their business on nature, even if they have yet to explicitly focus on freshwater biodiversity.

3.3. Energy generation

3.3.1. How this sector drives changes in freshwater habitats and biodiversity

Energy production impacts freshwater biodiversity directly and indirectly through infrastructure development and operation, cultivation of biofuel crops, and climate change. Such impacts affect individual freshwater species and the structure and functioning of biotic communities from sub-reach to basin scales. Infrastructure impacts include the construction and operation of hydropower facilities that alter river connectivity, flow regimes, water temperature, and dissolved oxygen levels. Coal, gas, and nuclear power plants all require water for steam-cycle cooling, with withdrawal (often from rivers or lakes) and consumption volumes dependent on the plant's thermal efficiency. Return flows from some of these power plants can also contribute to local thermal and toxic (e.g., through waste waters from flue gas desulphurisation) pollution of fresh waters. Coal mining and extraction of coal-seam gas ("fracking") consumes water and can pollute groundwater systems and their dependent freshwater habitats (Soeder 2021). Construction of infrastructure associated with many power plants, including transmission grids and access roads, causes landscape disturbance that can in turn increase sediment and pollution loads in freshwater habitats. Biofuel crops are often irrigated and therefore contribute to consumptive water use that reduces river flows (Yeh et al. 2011) and increases demand for water storage infrastructure. Application of agricultural chemicals to commercial biofuel crops can also contribute to pollution pressures on freshwater biodiversity (Delucchi 2010). Indirectly, fossil fuel dominance in energy systems has been the key cause of anthropogenic climate change, which impacts freshwater habitats and biodiversity through shifting spatial and temporal patterns of precipitation, snowmelt, and run-off, and through altering water temperatures and dissolved oxygen levels. Where biomass (e.g., wood or charcoal) remains a dominant fuel for domestic cooking (e.g., in most of rural Africa), clearance of vegetation for fuel use impacts riparian and floodplain habitats and can alter sediment fluxes into freshwater ecosystems.

3.3.2. Prevailing international policy and business imperatives

The most significant policy challenge facing the energy sector is to increase production to meet growing demands while also rapidly transitioning energy systems to a pathway consistent with the Paris climate agreement of the UNFCCC. This requires signatories to set out Nationally Determined Contributions for achieving the goal of limiting the rise in global mean temperature to 1.5 °C. The transition necessitates major shifts in energy production and consumption away from fossil fuels and towards a primarily renewables-based system (sustainable bioenergy, hydropower, solar, wind, or ocean energy), with high levels of energy efficiency and clean hydrogen as an energy carrier for decarbonising hard-to-abate sectors (IRENA 2023). While the pathway is conceptually clear, the rate of change is currently too slow to meet the Paris Agreement climate goals so scaling up is a major challenge. Furthermore, ensuring a just transition requires, among other things, that energy access and affordability are considered within transition pathways, as set out within UN SDG target 7.1. Currently, many low-income countries find it hard to attract investment in renewable energy generation. Geopolitical factors also influence pathways through, for instance, disruptions to infrastructure and fuel supply chains caused by regional tensions and conflicts, or changing availability of financing for energy infrastructure, such as through China's Belt and Road Initiative.

3.3.3. Priority challenges and opportunities for freshwater biodiversity recovery

The energy transition is likely to alter the temporal and spatial characteristics of energy-related drivers of freshwater biodiversity loss, often in complex and uncertain ways. A declining reliance on fossil fuels could reduce pressures on flow regimes and water quality from coal, oil and gas extraction, and thermal power plants. Conversely, pressures driven by hydropower and biofuels and, indirectly, from renewable technologies such as wind and solar power are likely to increase.

Hydropower contributes around one sixth of global electricity generation and is the largest renewable electricity source. However, hydropower expansion has recently slowed (IEA 2024) while wind and solar are expanding fast and are expected to eventually dominate the sector. Hydropower will likely provide an important dispatchable back-up in many countries and new hydropower development will continue to threaten freshwater biodiversity in some regions, such as the Congo, Mekong, and Amazon basins (Winemiller et al. 2016; Thieme et al. 2021). An expected shift in the hydropower mix towards pumped storage hydropower facilities (and some run of river hydropower) should improve system reliability and efficiency. While pumped storage hydropower systems do have freshwater biodiversity impacts due to disruption to flow regime and connectivity, such impacts are generally less than conventional dams because reservoirs are typically smaller and off-river, and the water volumes involved are usually smaller than large multi-purpose reservoirs (Gilfillan and Pittock 2022). In response to concerns about environmental and social impacts of dams, the International Hydropower Association, a trade body, has worked with stakeholders to develop a Hydropower Sustainability Standard (https://www.hydropower.org/sustainability-standard), although uptake by the industry remains limited. Private companies are beginning to integrate hydropower with other forms of renewable energy, such as wind and solar, to create hybrid energy systems that enhance capacity and improve grid stability and also potentially reduce pressures from new hydropower development (Chen et al. 2024).

It is important to move from project-level considerations to integrated planning of future water and energy systems, in particular to manage river basin scale biodiversity impacts. Managing the shifting energy-related risks to freshwater biodiversity requires clarity of supply chains that are then subject to environmental management standards and enforcement, coupled with environmental stewardship efforts. While there are considerable geopolitical and financial vested interests supporting the status quo approach to hydropower, recent analyses highlight the benefits of joint planning of the water and carbon/energy implications of the energy transition and suggest this could significantly reduce the water footprint of the energy sector (Opperman et al. 2023). The challenge is to ensure that such analyses are disseminated effectively to policy- and business decision-makers.

Little global analysis has been undertaken of the water footprint and related impacts on freshwater biodiversity associated with increased reliance on nonhydropower renewable energy sources, or of impacts associated with extracting materials and manufacturing batteries for electric vehicles and domestic- and commercial-scale energy storage. Energy transition technologies will greatly increase the demand for metals such as copper and zinc, extraction of which typically involves the use and pollution of freshwater resources (although large-scale uptake of recycling might reduce these impacts). The previously discussed impacts associated with fossil fuel systems will be vastly reduced but the net impact is unclear at this stage.

3.4. Inland fisheries and aquaculture

3.4.1. How this sector drives changes in freshwater habitats and biodiversity

The inland fisheries sector is diverse, incorporating economically important industrial-scale commercial fisheries (e.g., in the Laurentian Great Lakes), small-scale commercial fisheries and subsistence fisheries (which dominate in terms of numbers of participation and total catch), and recreational fisheries (of which a remarkable component is consumed) (Lynch et al. 2016). It also includes a substantial and rapidly growing aquaculture component (Mohan Dey et al. 2005; Tezzo et al. 2021). Inland fisheries and aquaculture (hereafter, "inland fisheries") yields tend to be highest in areas with the highest levels of freshwater biodiversity (Brooks et al. 2016). One consequence of this is that fishing pressure is often focused in systems where the threats to freshwater biodiversity are greatest (McIntyre et al. 2016). Where short term overexploitation takes precedence over long-term sustainability, the impacts on freshwater biodiversity can be substantial. For example, over-harvest of species can result in food-web shifts; some fish stocking programs introduce non-native species with associated ecological consequences (Arlinghaus et al. 2015); and incidental capture (i.e., bycatch) can contribute to population declines of nontarget species (e.g., river dolphin in artisanal fisheries of Brazil; Iriarte and Marmontel 2013).

3.4.2. Prevailing international policy and business imperatives

It has been estimated that 40% of total finfish catch globally is from inland sources (Lynch et al. 2016) providing a critical source of nutrition, especially in Asia and Africa from which more than 90% of inland fisheries catch is taken (FAO 2024). Inland fisheries also underpin many Indigenous Peoples' and local community livelihoods, and they provide employment opportunities for an estimated 30 million women especially in fish processing and sales (Lynch et al. 2016). However, the inland sector is overshadowed in international policy discourse by the marine commercial sector (Welcomme et al. 2010; Cooke et al. 2016*a*) and is poorly represented in the international discourse on food systems, fisheries, and environment. Within the UN Sustainable Development Goals, for instance, SDG 14 (Life Under Water) is framed almost exclusively in terms of marine fisheries (Elliott et al. 2022); and the Aquaculture Stewardship Council, which aims to make the industry more sustainable through setting sustainability standards and overseeing third party certification and labelling schemes, focuses on marine-based aquaculture even though inland aquaculture produces a far greater volume of food fish (FAO 2024). The notion that inland fisheries are often forgotten is perhaps best illustrated by the hydropower sector where inland fisheries (and the people that depend on them) are often "invisible" (e.g., Doria et al. 2018; Campbell and Barlow 2020). A global framework for management of inland fisheries was set out in the 2016 Rome Declaration (Cooke et al. 2016*b*). This described ten steps to sustainable management, including an emphasis on biological assessment, science-based management, and improving governance. Currently, there is no mechanism to facilitate implementation of the Declaration at the national or ecosystem scale, and its incorporation into wider sustainability frameworks is lacking.

For business imperatives, application of the Blue Economy agenda in freshwater systems has been explored. While the blue economy has been mostly discussed under a marine context, the United Nations Economic Commission for Africa (UNECA) identifies freshwater as part of the "Blue Economy" and fisheries in rivers and lakes as a key sector (UNECA 2016). For example, nearly 75% of Tanzania's estimated US$104 billion income from blue economy ecosystem services is from large freshwater lakes (Maskaeva et al. 2024), which host major inland fisheries. Companies have invested in Recirculating Aquaculture Systems and/or technologies that have the potential to make aquaculture more resource-efficient and environmentally friendly by controlling water quality, minimizing waste discharge, and enabling optimized management of resource inputs and ambient conditions in inland aquaculture. However, such systems and technologies can be expensive to set up and maintain and may not be suitable for all contexts.

3.4.3. Priority challenges and opportunities for freshwater biodiversity recovery

Inland fisheries are arguably the economic and policy sector that best aligns with the recovery of freshwater ecosystems and biodiversity (Cooke et al. 2023*b*). Indeed, it is a core aim of sustainable fisheries to ensure the volume of fish removed is not detrimental to the long-term health of the ecosystem (Shelton and Sinclair 2008). There is also mutual interest in ensuring that other pressures on freshwater ecosystem health, such as pollution or flow alteration, are minimized (Phang et al. 2019). Recent FAO data indicate that 47% of major basins important to inland fisheries are under "low pressure", 40% are under "moderate pressure", and 13% are under "high pressure" (FAO 2024). These results can help inform the prioritization of interventions. The dual delivery of conservation and sustainable use of biodiversity is at the core of the Convention on Biological Diversity (Glowka et al. 1994) and a complementary indicator on inland fisheries (the Sustainable Watershed and Inland Fisheries index) has recently been included under Target 5 of the Global Biodiversity Framework. While there are opportunities for working collaboratively towards mutually beneficial solutions (Phang et al. 2019), good governance systems, science-based management, and monitoring are often lacking in the inland fisheries sector. Implementation of the Rome Declaration would support more responsible and sustainable inland fisheries and in doing so support freshwater biodiversity conservation (Cooke et al. 2021). A first step to downscaling and implementing the Declaration in local contexts could be to incorporate the ten steps in national planning processes, such as National Biodiversity Strategic Action Plans (NBSAPs–the mechanism by which the Global Biodiversity Framework is meant to be transposed to national actions). Reporting of sustainably managed inland fisheries as Other Effective area-based Conservation Measures (OECMs) in NBSAPs (Flitcroft et al. 2023) might generate wider political and financial investment. A potential opportunity for policymakers to focus on inland fisheries and aquaculture are their contribution to multiple GBF targets, ranging from area-based targets 2 and 3, targets 5, 9, and 10 addressing sustainable use of biodiversity, as well as targets 22 and 23 around equity of biodiversity for Indigenous Peoples and local communities, gender, and youth.

Challenges of monitoring and effectively managing inland fisheries (Beard et al. 2011; Lorenzen et al. 2016; Cooke et al. 2016*a*) can be addressed by working directly with local fishing communities. Many of the most successful inland fisheries have been governed through local co-management arrangements with fishers and fishing communities (Allison and Badjeck 2004; Freitas et al. 2020). In places, Indigenous people hold tenure to inland fisheries so ensuring conservation efforts do not infringe on their inherent sovereign right to self-govern will be fundamental to management efforts.

The increasing desire for sustainable freshwater aquaculture presents another opportunity but only if done right. Efforts to improve waste management, reduce climate emissions, and create more sustainable feed are critical paths and should continue. However, global freshwater aquaculture production is dominated by a handful of species (Naylor et al. 2021), where the desired characteristics for a fast-growing, disease-resilient, and highly fertile species for food cultivation are also prime traits for these species to become invasive (e.g., Xiong et al. 2023). Aquaculture of native species is a potential opportunity for locally appropriate industries but will require substantial research and development. The siting of aquaculture facilities away from areas of high freshwater biodiversity may be key in reducing their impact.

4. A fresh remit for freshwater conservationists

There has been admirable effort to protect and restore freshwater species and habitats at local and basin scales in many contexts worldwide (Speed et al. 2016). However, this review suggests that the freshwater research and conservation community needs to take strides in identifying and influencing the major underlying policy and business drivers of global freshwater biodiversity loss. The drive for water, food, and energy security, intensified by climate change, will continue to exert intense pressures on river, lake, and wetland habitats. But there are also unprecedented opportunities to integrate conservation and restoration of freshwater biodiversity within policy frameworks and business practices. Water resource managers, multinational food and beverage companies, and energy strategists are ever more interested in solutions that deliver on multiple agendas, including nature restoration. Although there is debate about their efficacy (Biermann et al. 2022), international agreements such as the Sustainable Development Goals and Global Biodiversity Framework could enable a step change in political, financial, and technical support for conservation and restoration efforts, including through the Freshwater Challenge. Although it is beyond the scope of this paper, it will also be important to influence public and private sector financial institutions that bankroll businesses and policy implementation and, in so doing, have a large indirect influence on biodiversity trends.

If the research and conservation community is to help counter the intensifying pressures on freshwater biodiversity globally, engaging policy and business drivers of biodiversity loss will be critical. To this end, we suggest three priorities to shape a more systemic, driver-focused approach to freshwater conservation research and practice:

i. First, it will be important to *raise the profile of freshwater biodiversity* within the wider discourse on conservation and sustainable development such that it is seen by policymakers and business leaders as a major issue to which they must respond. This includes greater awareness of the value of aquatic biodiversity within the conservation sector itself (Birnie-Gauvin et al. 2023). Our experience is that freshwater researchers and conservation practitioners are often isolated from or lack influence within wider global policy debates about how to bend the curve of biodiversity loss. Symptoms of this include the references to biodiversity on "land and sea" that are characteristic in recommendations from august bodies such as

IPBES (IPBES 2018); the relative lack of coverage of freshwater biodiversity by major conservation journals (He et al. 2021); and the dearth of freshwater specialists engaging in the assessment reports generated by IPBES (Kuiper 2023). Closer working between freshwater specialists and, say, forest conservationists could also help to improve understanding within the wider conservation community of the distinct challenges facing freshwater biodiversity, e.g., in relation to altered flow regimes or riverine connectivity (Tickner et al. 2020; Elliott et al. 2022), and the importance of such biodiversity for people, including inland fisheries as a source of nutrition for hundreds of millions of people across Asia, Africa, and South America. Perhaps more important, finding synergies with marine and terrestrial research and conservation communities can pay off in terms of overall conservation impact and efficiency (Leal et al. 2020). Because the challenges for governments and companies to contribute to GBF, UNFCCC, and SDG targets are intense, coherent guidance from conservation researchers and practitioners on strategies for redirecting drivers of biodiversity loss while meeting multiple goals is likely to be welcomed in many arenas.

ii. Second, there is an urgent need for *applied policy research and evidence* that identifies viable policy pathways to support recovery of freshwater biodiversity. This could be at the global scale but will often need to be spatially and temporally specific, focusing on places (regions, countries, or basins) or sectors. Research and evidence might be needed on, among other things: (a) gaining a better empirical understanding of the ways in which specific policy decisions and business strategies drive pressures on and changes in freshwater (and other) biodiversity; (b) potential synergies between current policy and business priorities and the health of freshwater (and other) habitats; (c) the extent of potential trade-offs between socio-economic development options and biodiversity recovery, incorporating impacts on groups of people that might be particularly affected by different options, such as farmers, inland fisherfolk, or flood-affected communities (Baldwin-Cantello et al. 2023; Vörösmarty et al. 2023); (d) the interaction of different sectoral drivers in terms of the additive, synergistic, or competing pressures they exert on freshwater habitats and biodiversity, building on the concepts that have underpinned emerging science on multiple stressor regimes (Jackson et al. 2016; Mazor et al. 2018); (e) the financial and nonfinancial costs and benefits of different policy and business options, including assessment of which groups of people would bear costs or reap benefits and the social justice implications of this cost-benefit distribution; (f) the extent to which governance frameworks, formal and informal institutional arrangements and stakeholder power dynamics can enable broadly acceptable and socially just policy and business solutions; and (g) the potential role of green finance—including carbon, biodiversity and water related financing instruments—in supporting freshwater biodiversity restoration. To ensure that outputs meet the needs of decision-makers and are not confined to academic journals, it will be important that research and evidence projects are co-developed with policy and business stakeholders and that data on freshwater biodiversity are gathered not only for scientific purposes but also to inform critical policy and business decisions. In many contexts, research and evidence gathering should incorporate equal elements of scientific and Indigenous knowledge, based on frameworks such as Two-Eyed Seeing (Reid et al. 2021). To successfully drive restoration of freshwater biodiversity, a systemic approach to solution design will be needed, incorporating research and evidence that supports development of better public policy and regulation, business strategies, and mobilization of finance.

iii. Third, these research and evidence priorities strongly point to the need for far greater *integration of social and natural science disciplines* under a broad banner of freshwater conservation research. Disciplines such as economics, political science, anthropology, and psychology can shed light on how to effectively engage and understand underlying values, worldviews, and priorities of communities, rights holders, practitioners, and decision-makers. Many commentators have previously called for greater inter-disciplinarity within freshwater and related research communities (e.g., Berbés-Blázquez et al. 2016; Tickner et al. 2017; Martin-Ortega 2023; Vollmer et al. 2023). However, the field of "freshwater sciences" continues to be dominated by natural science disciplines such as hydrology, geomorphology, and ecology, often to the exclusion of people- and policy-focused areas of scholarship. As one recent example, during the 2024 International Society of Limnology conference in Foz do Iguazu, Brazil, 257 out of 305 presented papers focused exclusively on natural science even though the conference theme was "Building Bridges with Society". Genuine co-development of research and outreach by natural and social scientists might require upfront investment to bridge disciplinary boundaries but, providing that the collaboration addresses urgent and important research questions, it is far more likely to attract the attention of policy and business decision-makers who are primarily concerned with socio-economic outcomes. Understanding how best to communicate with such decision-makers and with other stakeholders is also critical. This is an area in which social science can provide guidance to frustrated natural scientists who have found that simply stating evidence seldom changes minds (e.g., Toomey 2023).

5. Conclusion

In 2010, Strayer and Dudgeon wrote that "*a failure to act boldly now will lead to impoverishment or extinction of the freshwater biota and the very subjects of our research. Such an occurrence would be a tragic demonstration of the redundancy of our science*" (Strayer and Dudgeon 2010). Fourteen years on, the world is at an even more critical moment for freshwater habitats. Against a backdrop of a shifting climate and dramatic declines in biodiversity, governments and businesses urgently need coherent, evidence-based, and pithy insights on how to respond to increasingly complex challenges and how to meet multiple goals set out in international agreements. There is a clear window of opportunity for researchers and practitioners concerned about freshwater biodiversity to respond. The nature of that response in the coming years will substantially influence the prospects of bending the curve of freshwater biodiversity loss. While research and action at the local and basin scale will remain fundamental, a failure to evolve new approaches to research and engagement with systemic drivers at national and international scales risks reducing freshwater conservation to the status of a redundant discipline. Conversely, if researchers and practitioners can generate and effectively communicate new insights that respond to the challenges and opportunities that we have set out here, and thus help to redirect the underlying policy and business drivers of ecosystem degradation, there might yet be a realistic prospect of bending the curve of global freshwater biodiversity loss.

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Author information

Author ORCIDs

David Tickner https://orcid.org/0000-0001-5928-0869
Laurenne Schiller https://orcid.org/0000-0003-0329-9792
Steven J. Cooke https://orcid.org/0000-0002-5407-0659
James Dalton https://orcid.org/0000-0002-8848-3208
Ian Harrison https://orcid.org/0000-0001-8686-8502
Sui Chang Phang https://orcid.org/0000-0002-2735-0241

Author contributions

Conceptualization: DT, SJC
Methodology: DT, SJC
Resources: DT, SJC
Visualization: LS
Writing – original draft: DT, LS, SJC, EB, UC, JD, IH, LL, SP, WY
Writing – review & editing: DT, LS, SJC, EB, UC, JD, IH, LL, SP, WY

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