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Time for decisive actions to protect freshwater ecosystems from global changes

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Abstract – Freshwater ecosystems and their biodiversity provide fundamental services to humans such as nutritional resources production, water provisioning, water purification, recreation, and more globally climate regulation. Anthropogenic impacts on freshwater ecosystems and their biodiversity are already strong and will most probably increase in the near future. Anthropogenic drivers are widely known and include in particular, climate change, habitat shrinking and/or modification due to land-use (*e.g.* water abstraction for human and agricultural consumption, urbanization), habitat fragmentation and homogenization in stream flow dynamics due to the damming of rivers, introduction of non-native species, dumping of nutrient or organic loadings increasing eutrophication processes, and biodiversity over-exploitation. Here, I review the current and future effects of these 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. However, success will require systemic changes across public policy and a sufficient political will to do so.

Keywords: Inland waters / biodiversity / global change / conservation

1 General context

Throughout their existence as a species, humans have manipulated and/or transformed nature and natural resources (living and non-living nature) to produce various materials they needed to adapt to variable environmental conditions on Earth. Through progressive technological advances obtained by increasing energy production and consumption, this has allowed to achieve better living standards on average and to sustain the growing human population worldwide, but at the expense of strong social and economic inequalities (Messerli *et al.*, 2019). However, by exploiting natural resources, humans have produced unprecedented impacts on the physical, chemical and biological makeup of our planet compared to pre-human dynamics. These negative tendencies mostly happened during the late Holocene due to large-scale human changes in technologies and increasing dispersal and demography (Louys *et al.*, 2021; Nogué *et al.*, 2021). Currently, human adaptive strategies and the current pace of its population growth both indirectly over-contribute to global changes and the consequent loss of biological diversity (Crist *et al.*, 2017; Sage, 2020) and this non-sustainable exploitation of natural resources, mainly coming until recently from highly industrialized countries, may ultimately threaten the existence of humankind itself (Crist *et al.*, 2017; Human Development Report, 2020). These impacts are clearly demonstrated for many critical elements of our physicochemical environment that act as direct drivers of biodiversity changes (Fig. 1).This factual situation will continue to threaten the Earth's climate system and biodiversity by altering species ranges and abundances, reshuffling biological communities, restructuring food webs and ecosystem functions and generating negative feedbacks to human well-being at the end, especially in developing countries hosting the highest biodiversity on Earth and the most vulnerable people (Shin *et al.*, 2019; Human Development Report, 2020; Thomas, 2020). Thus, without further efforts to counteract current overexploitation, habitat loss and degradation in parallel with climate change, global biodiversity will continue to decline (Arneth *et al.*, 2020) with strong impacts on societal systems (Shin *et al.*, 2019).

2 Overview of current threats to freshwater biodiversity and ecosystems

Freshwater ecosystems provide fundamental services to humans such as food, water, nutrient retention, recreation, and climate regulation (Albert *et al.*, 2021).

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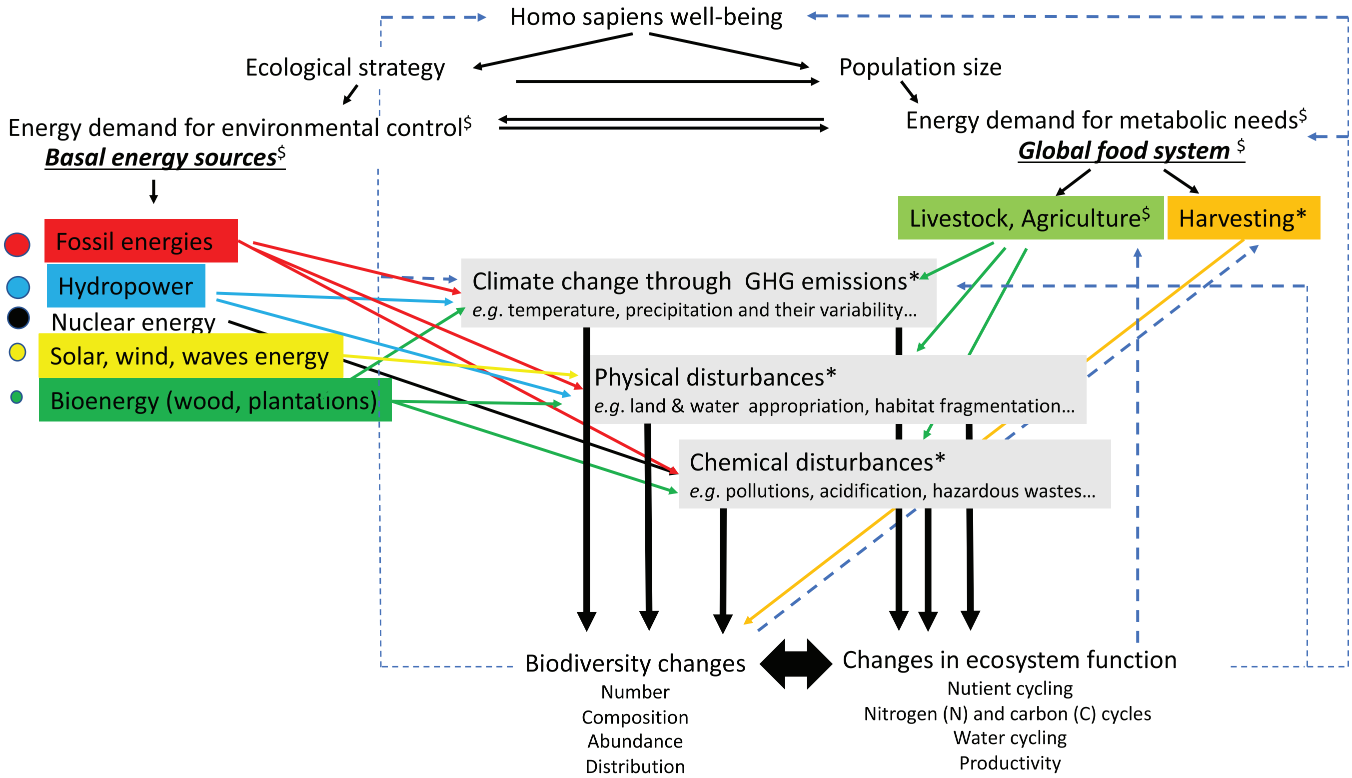

Fig. 1. Direct and indirect drivers of biodiversity changes due to human strategy for environmental control and population expansion (*i.e.* socio-cultural processes). * Direct drivers, $ indirect drivers through human production of goods and services (*e.g.* infrastructure development, industry, transport). Circles for energy sources are proportional to their current degree of use. Line arrows indicate direct links, while dotted arrows indicate feedback effects. Under the proposed scheme two broad interlinked compartments are responsible for climate and biodiversity changes, *i.e.* the basal energy sources and the global food system. Both should be tackled jointly to avoid failures in proposing soundful solutions for climate, biodiversity and human well-being issues, all the more as even if fossil fuel emissions were stopped immediately, current emission trends in global food systems would likely preclude meeting the Paris Agreement goals (Clark *et al.*, 2020).

Globally, freshwaters cover ~1% of Earth's surface with over 60% of this being permanent water bodies and the remaining being seasonally intermittent (Pekel *et al.*, 2016). Considering flowing waters only, the percentage of intermittence is even greater when analyzing the worldwide river network length (~60%, Messager *et al.*, 2021). Despite their rather marginal representation of the Earth's surface, freshwaters are home to approximately 10% of all described species of fungi, plants, invertebrates, and vertebrates on Earth (Kopf *et al.*, 2015). The relative contribution of freshwater ecosystems to global biodiversity is thus extremely high. As a flagship and well-studied example, species of bony fishes (*Actinopterygii*) inhabiting rivers and lakes (~1% of Earth's surface) are as numerous as the ones inhabiting the seas (71% of the Earth's surface; Tedesco *et al.*, 2017a; Dudgeon, 2019) (Fig. 2a). The natural (physical) fragmentation and heterogeneity of running water habitats and geographic isolation of water bodies are most probably involved in explaining this astonishing diversity of species and associated biological traits through positive effects on species speciation rates (*e.g.* Dias *et al.*, 2013; Tedesco *et al.*, 2017b; Albert, Tagliacollo and Dagosta, 2020; but see Miller 2021 for a contrasting explanation). Indeed, as biological exchange among freshwater water bodies is restricted by terrestrial barriers, freshwater habitats are kind of remote islands having experienced specific speciation processes (*e.g.* Hugueny *et al.*, 2010; Dudgeon, 2019). As a consequence, freshwater bodies usually display high degrees of taxa endemism (*e.g.* Tisseuil *et al.*, 2013).

Current major threats to freshwater biodiversity include climate change, habitat modification and pollution from land-use, habitat fragmentation and flow regime homogenization by dams, non-native species, water abstraction for industry or irrigation, and over-exploitation of natural populations (*e.g.* reviewed in Carpenter *et al.*, 2011; Stendera *et al.*, 2012; Dudgeon, 2019). Those threats and their interactions currently affect freshwater biodiversity and functioning to varying degrees (Vörösmarty *et al.*, 2010; Dias *et al.*, 2017; Su *et al.*, 2021; Albert *et al.*, 2021) and their additive and potentially synergistic effects will continue to threaten biodiversity in the future (Knouft and Ficklin, 2017; Carmona *et al.*, 2021). Recognition of this adverse situation has stimulated applied research in developing local grain (*e.g.* site grain) studies. Results from most of these studies analyzing impact of different stressors on freshwater biodiversity show without ambiguity – but most often difficulties in separating individual effects – that human pressure has globally disturbed local assemblages in their biodiversity (*e.g.* population decline, local extinctions), structure and functions with habitat loss and alteration, hydrologic modification, water pollution and

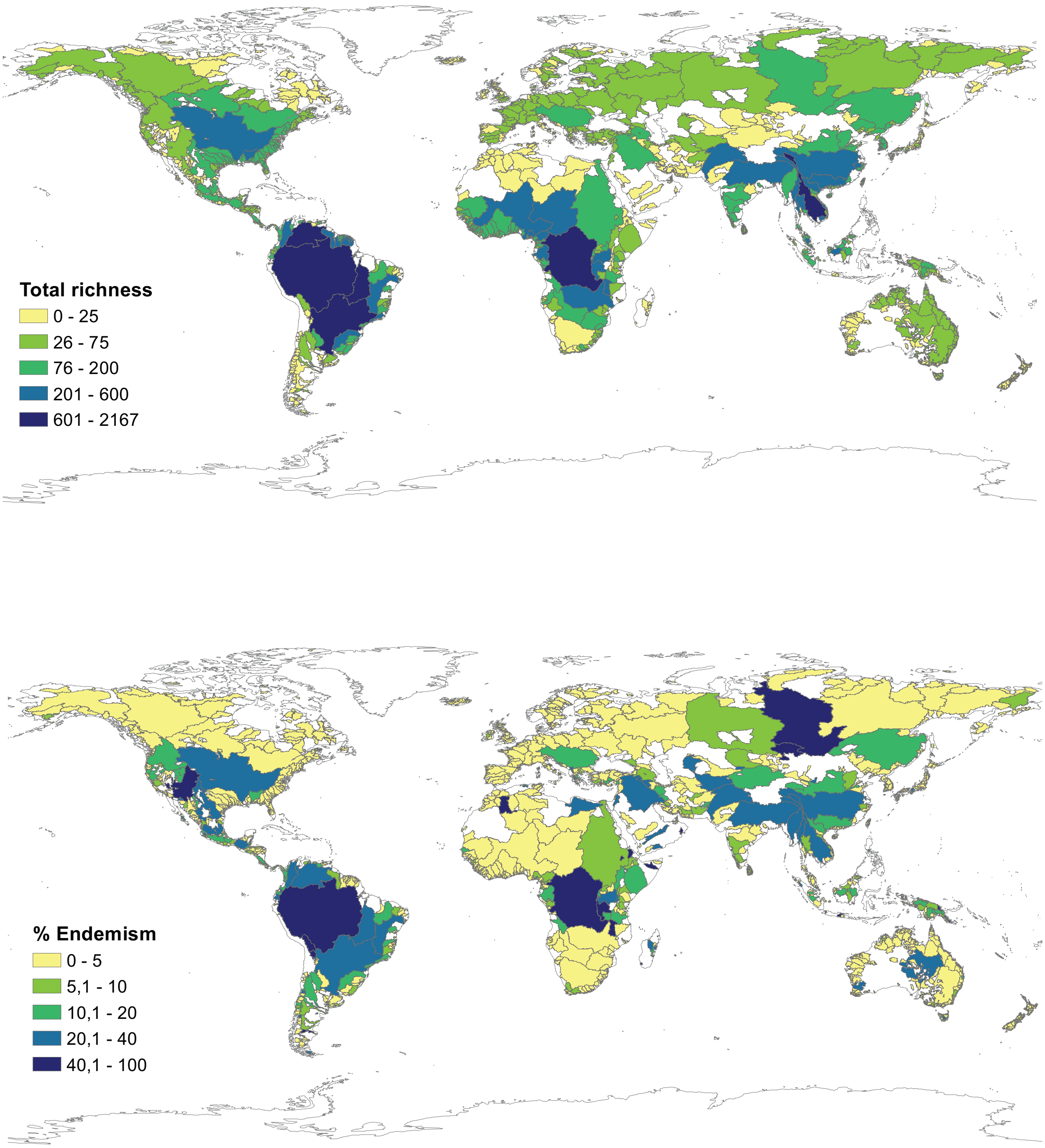

Fig. 2. Global freshwater fish species richness and % of endemic richness patterns at the drainage basin grain (after Tedesco *et al.*, 2017a).

biological invasions being the major drivers of change (reviewed in Carpenter *et al.*, 2011; Stendera *et al.*, 2012). Results are less straightforward when increasing the grain size (*e.g.* river basins, lakes, regions) in part because there has been little effort to evaluate effects of anthropogenic factors at these grains and at large extents due to limitations in data availability (Joppa *et al.*, 2016). The few studies performed at these larger grains at global or continental extents most often conclude that natural geographical factors still dominate over anthropogenic pressures in explaining species richness and community structure, and this for most water bodies and biological models analyzed (*e.g.* Brucet *et al.*, 2013; Feld *et al.*, 2016). Taking as an example a well-studied biological model (*i.e.* freshwater fishes), only water pollution (*i.e.* nutrient enrichment) through eutrophication processes, habitat fragmentation by dams and presence of non-native species have been shown to significantly, although weakly, alter overall biodiversity and the structure and function of communities in lakes (Brucet *et al.*, 2013) and river basins (Blanchet *et al.*, 2010; Villéger *et al.*, 2011; Dias *et al.*, 2017) at continental and/or global extents (but see Su *et al.*, 2021 who found that fish communities have been affected both functionally and phylogenetically by anthropogenic fragmentation and introduction of non-native species in half of the world river systems). Worldwide, the major problem at this time seems, however, the loss of freshwater species and the alteration of aquatic community structure and ecosystem functioning at the local grain (Stork, 2010). Moreover, current evidence shows that anthropogenic factors such as land-use change and pollution, habitat fragmentation, invasive species and overexploitation, are currently and consistently more important in driving biodiversity threats than the contemporary effects of climate change (Tedesco *et al.*, 2013; Dobson *et al.*, 2021; Caro *et al.*, 2022).

3 Current and future climate change threats

Climate is one of the primary driver underlying patterns of biodiversity on Earth, indirectly acting on dispersal, speciation and extinction processes through "water–energy dynamics" (*e.g.* Hawkins *et al.*, 2003; Field *et al.*, 2009). Climate and biodiversity are so closely tied that it is not a real surprise that distributions of Earth's species are changing at accelerating rates with human driven climate change. Scientific evidence is accumulating that many freshwater aquatic species are responding to warming by elevational and/or northward shifts in their distribution ranges, tracking climate warming velocities (Hickling *et al.*, 2005; Comte *et al.*, 2013; Pecl *et al.*, 2017). However, there is also evidence that species range shifts are idiosyncratic and habitat dependent (Lenoir *et al.*, 2020) and these differential species responses to warming promote and will continue to promote reshuffling of communities and consequent cascading effects on food webs and ecosystem functioning, affecting regional availability of food for humans, particularly in developing countries (*e.g.* local fisheries, Ojea *et al.*, 2020).

Besides increasing water acidification (Thomas *et al.*, 2022), climate change alters freshwater ecosystems and their biodiversity by changing (1) temperatures, (2) water availability and (3) flow regimes through changes in precipitation (Doll and Zhang, 2010; Knouft and Ficklin, 2017) and/or temperature (Blöschl *et al.*, 2017). Increased water temperatures often lead to progressive shifts in the structure and composition of assemblages because of changes in species metabolic rates, body size, migration timing, recruitment, range size and interactions (Parmesan, 2006; Scheffers *et al.*, 2016; Pecl *et al.*, 2017; Rosenzweig *et al.*, 2008; Daufresne *et al.*, 2009; Myers *et al.*, 2017). There is already evidence of regional and continental shifts in freshwater organism distributions following their thermal niches (Comte *et al.*, 2013; Mouton *et al.*, 2022), local extirpations through range contractions at the warm edges of species' ranges (Wiens, 2016), body size reductions (Daufresne *et al.*, 2009), and increased incidence of emerging infectious diseases (Reid *et al.*, 2019; Borgwardt *et al.*, 2020). Warmer water temperatures also enhance microorganism metabolism and processing of organic matter (unless dissolved oxygen is limiting), promoting eutrophication when nutrient levels are high (Carpenter *et al.*, 2011; Mantyka-Pringle *et al.*, 2014), and greater omnivory. Warming also induces phenological mismatches between consumers and resources in highly seasonal environments, potentially destabilizing food chain structure (Woodward *et al.*, 2010; Shipley *et al.*, 2022). Moreover, increase in water temperature and streamflow alterations by climate change may interact with land-use modifications to increase autotrophic productivity (Bernhardt *et al.*, 2022) and the dominance of species that prefer warm- and slow-water habitats, reorganizing the structure of freshwater communities (Comte *et al.*, 2021).

Scenarios of climate change (*e.g.* the four Representative Concentration Pathways scenarios (RCPs) 2.6 (most optimistic), 4.5, 6.0, 8.5 (most pessimistic); van Vuuren *et al.*, 2011) on global freshwater ecosystem biodiversity and functioning were reviewed by Settele *et al.* (2014). The strongest temperature increases are projected for eastern North America (0.7–1.2 °C for RCP 2.6 and 8.5 for 2050s), Europe (0.8–1.2 °C), Asia (0.6–1.2 °C), southern Africa (>2.0 °C for RCP8.5) (van Vliet *et al.*, 2016) and Australia (https://soe.environment.gov.au/theme/built-environment/topic/2016/increased-extreme-weather-events#table-BLT5). Moderate water temperature increases (<1.0 °C) are predicted for South America and Central Africa (van Vliet *et al.*, 2016). Changes in water temperature are projected to lead to local or regional population extinctions for cold-water species because of range shrinking especially under the RCP 4.5, 6.0 and 8.5 scenarios (Comte and Olden, 2017). Most lowland-tropical freshwater species are expected to tolerate warmer conditions where water is sufficient (Comte and Olden, 2017).

Decreased water availability and altered flow regimes reduce habitat size and heterogeneity. This increases population extinction rates because the probability of species extinctions increases with reduced habitat size (Tedesco *et al.*, 2013; Barbarossa *et al.*, 2021). Climate change also alters flow regime seasonality and variability (*e.g.* Döll and Zhang, 2010; Blöschl *et al.*, 2017) and increases flow intermittence (Pyne and Poff, 2017). This leads to decreased food chain lengths through loss of large-bodied top predators (Sabo *et al.*, 2010), altered nutrient loading and water quality (Woodward *et al.*, 2010), and/or pushing taxa into novel trajectories from which they may not recover (Bogan and Lytle, 2011). However, whatever the RCP scenario, impacts on the timing of seasonal streamflow are found to be generally small (Eisner *et al.*, 2017), minimizing the possible future impact of this driver on freshwater biodiversity. On the other hand, relative to water availability and according to the wet-wetter/dry-dryer mechanism (Held and Soden, 2006; Gudmundsson *et al.*, 2017; Wang *et al.*, 2017) more severe water stress in current drylands is expected in the future. Although water availability distributions will change little under RCP 2.6 by the end of the 21st century, RCP 4.5, 6 and 8.5 scenarios project substantial drainage shrinking where semi-arid and Mediterranean climates currently occur. Reduced water availability in those regions, including shifts from permanence to intermittence, will generate population extirpations of all types of freshwater organisms (Jaeger *et al.*, 2014), leading to global net biodiversity losses because endemism is usually high in those regions. For example, projected fish extinction rates from drainage shrinking under the SRES A2 scenario (comparable to RCP 8.5) in 1010 river basins worldwide showed that among the 10% most-altered basins, water availability loss will increase background extinction rates by 18.2 times in 2090 (Tedesco *et al.*, 2013). Also, in glacier-fed high-mountain ecosystems, significant changes to snow and glacier melt regimes, including glacier retreat or disappearance, have already been observed (Leadley *et al.*, 2014) and are expected to continue (Kraaijenbrink *et al.*, 2017). This currently, but temporarily, leads to increase the species richness of generalist taxa in glacier-adjacent habitats (positively impacting biodiversity at a regional scale), as well as extinction of endemic ≪ glacier specialist ≫ taxa (negatively impacting total biodiversity at the global scale) (Cauvy-Fraunié and Dangles, 2019).

4 Current and future land-use and water pollution threats

Land-use, especially croplands, mining and urbanization, affect freshwater ecosystems and associated biodiversity through two main pathways. First, water and groundwater withdrawals decrease habitat (water) availability for freshwater organisms leading to increased population extinction rates in rivers and lakes or direct extinctions from riparian zones, wetland, floodplains, and peatland conversions (Gardner *et al.*, 2015; Minayeva *et al.*, 2017), the problem being exacerbated in semiarid regions where water withdrawals lead to some rivers and lakes routinely drying and consequent species extinctions (Foley *et al.*, 2005). Second, water quality is usually degraded by land-use. Intensive agriculture increases sediment, nutrient (N-rich fertilizers) and pesticide loads to ground and surface waters (Peñuelas and Sardans, 2022). Urbanization and industries also substantially degrade water quality mostly through organic, pharmaceuticals, microplastics or phosphorous loadings, especially where wastewater treatment is absent. Mining leads to increased loadings of toxic metals, salts and acids (Johnson and Hallberg, 2005). Part of these chemical cocktails also promote freshwater salinization (Cunillera-Montcusí *et al.*, 2022; Hintz *et al.*, 2022). Such pollutants lead to direct local mortality, impaired individual development and health through bioaccumulation particularly in top predators (Carpenter *et al.*, 2011), altering the structure of biological communities and, consequently, the functioning of aquatic systems (Muturi *et al.*, 2017). For example, (1) pharmaceutical pollution may compromise development and reproduction of aquatic animals by altering behavior and feeding rate of individuals (*e.g.* Brodin *et al.*, 2013) or feminize populations (*e.g.* Kidd *et al.*, 2007); (2) freshwater salinisation may compromise the performance of organisms by causing osmoregulation stress (*e.g.* Cunillera-Montcusí *et al.*, 2022); (3) ingestion of microplastics can cause adverse impacts on growth and development and feeding or reproductive behavior in a range of aquatic biota such as fish, zoobenthos, zooplankton and mollusks (*e.g.* Meng *et al.*, 2020); (4) Nutrient loadings progressively increase eutrophication, depleting oxygen, killing animals, extirpating submerged macrophytes and producing algal blooms (including toxic varieties of cyanobacteria; Paerl and Paul, 2012) and were the leading cause of hypoxia across European lakes since 1850 (Jenny *et al.*, 2016).

Furthermore, deforestation, a key component of land-use change, severely disrupts flooding, thermal regimes, organic matter processing and food web dynamics (Sweeney *et al.*, 2004), exacerbating the establishment and spread of pests and pathogens, especially in tropical regions (Morris *et al.*, 2016). Finally, the loss of lateral hydrological connectivity between rivers and their floodplains through flood-control infrastructures (*e.g.* levees) to satisfy human demand for freshwater and infrastructure development, not only decreases habitat availability but also affects food webs and threatens species that benefit from facultative ontogenetic niche shifts between floodplain and main channel, jeopardizing at the end the entire ecosystem productivity (Opperman *et al.*, 2009; Stoffels *et al.*, 2022).

Concerning freshwater habitats, future RCP projections predict an increase (in order of diminishing importance RCPs 2.6, 6, 8.5) or a decrease (RCP 4.5) in cropland area, an increase (RCP 8.5) or a decrease (in order of diminishing importance RCPs 6, 4.5, 2.6) in grassland area and an increase (RCPs 4.5, 6) or a decrease (RCPs 2.6, 8.5) of natural vegetation area (van Vuuren *et al.*, 2011), but see Alexander *et al.*, (2017) for slightly different projections. The RCP 4.5 scenario, predicting a decrease of land-use area globally, minimizes future freshwater biodiversity disturbances, followed by RCPs 2.6, 6.0 and 8.5 in decreasing order. However, global scenarios mask continental dissimilarities. For example, projections of future primary vegetation show major decreases in western and middle Asia (scenarios 2.6, 6.0 and 8.5), Australia (only RCP 2.6) and North America (only RCP 8.5; Settele *et al.*, 2014).

Concerning water pollution, this anthropogenic pressure has been considerably reduced during the last decades in Australia, North America and Western Europe (Vörösmarty *et al.*, 2010), except for pharmaceuticals, biocides and microplastics because of ineffective treatment currently available (Eerkes-Medrano *et al.*, 2015; Ebele *et al.*, 2017; Wilkinson *et al.*, 2022). Reduced water pollution will benefit freshwater biodiversity whatever the scenario. However, Sinha *et al.* (2017) projected increased eutrophication induced by increased precipitation from climate change in some regions, and Olivier *et al.* (2017) noticed no decrease in nutrient concentrations (except a slight decrease in total nitrogen) for most Northeast U.S. lakes between 1990 and 2013 despite attempts to reduce diffuse pollution. If there is little technology transfer to developing countries, then water pollution will increase worldwide, particularly in tropical regions because of increased human density notably in Asia and Africa, which is expected to account for over half of global population growth between 2015 and 2050 (United Nations, 2015). Under RCP 2.6–if much agricultural, mineral and bioenergy production relocates from high-income to low-income regions, pollution, freshwater biodiversity and aquatic ecosystem functioning will further worsen in those regions (Albert *et al.*, 2021).

5 Current and future habitat fragmentation threats

Dams provide the most characteristic example of anthropogenic fragmentation.

This stressor alters rivers, floodplain lakes, wetlands and estuaries. Dams transform river basins by creating artificial lakes locally, fragmenting river networks, and greatly distorting natural patterns of sediment transport and seasonal variations in water temperatures and flows (Latrubesse *et al.*, 2017; Flecker *et al.*, 2022). Altered flow seasonality in rivers has led to less diverse fish assemblages, decreased inland fisheries production, less stable bird populations and lower riparian forest production (Jardine *et al.*, 2015; Kingsford *et al.*, 2017; Sabo *et al.*, 2017; Ngor *et al.*, 2018). Sediment retention by dams leads to delta recession (Luo *et al.*, 2017; Kondolf *et al.*, 2022) and to degraded coastal fisheries and tropical mangrove forests due to consequent coastal erosion (Ezcurra *et al.*, 2019). Dams also prevent upstream-downstream movement of freshwater plants (*e.g.* Jansson *et al.*, 2000) and animals (e.g. Pess *et al.*, 2014), facilitate settlement of non-native species (Johnson *et al.*, 2008), and increase risks of water-borne diseases and cause local species extirpations by modifying productivity in created reservoirs (Poff and Schmidt, 2016). The fragmentation of river corridors by dams also reduces population sizes and gene flows of aquatic species, increasing species extinction risks (Dias *et al.*, 2017; Brauer and Beheregaray, 2020). Dams are mainly concentrated in highly industrialized regions, but future hydropower development will be concentrated in developing countries and emerging economies (Zarfl *et al.*, 2015; Winemiller *et al.*, 2016; Moran *et al.*, 2018; Schwarz, 2020). Hydropower is expected to expand worldwide whatever the RCP scenario. Most hydropower plants are currently situated in regions where considerable declines in streamflow are projected, resulting in mean reductions in usable hydropower capacity (Turner *et al.*, 2017; van Vliet *et al.*, 2016). Those regions may increase dam building to compensate for the losses unless other energy options are implemented (Zarfl *et al.*, 2015). Also, population density is continuously increasing and will reach around 10 billion in 2050 (United Nations, 2015). This will increase demands for hydropower globally, and especially in tropical regions (Winemiller *et al.*, 2016) where freshwater biodiversity is concentrated (Tisseuil *et al.*, 2013).

6 Current and future non-native species introduction threats

Although policies have been implemented to prevent new introductions globally, the increase in numbers of non-native species shows no sign of saturation over time (Seebens *et al.*, 2017). Non-native species may compete with and/or prey upon native species, generating occasional local population extirpations (Carpenter *et al.*, 2011). Non-native species may also alter ecosystem structure and function (*e.g.* Non-native species are currently changing the functional traits structure of most freshwater fish assemblages worldwide, which may affect ecosystem properties; Blanchet *et al.*, 2010; Toussaint *et al.*, 2018), spread infectious diseases and sometimes may degrade ecosystem services and economies (Leung *et al.*, 2002). They are a key contributor to biotic homogenization of freshwater ecosystems globally (Villéger *et al.*, 2011). Many non-native species are predicted to spread worldwide in the next decades, mainly because of climate change, accelerated economic exchanges among countries, construction of new transportation corridors and increased aquaculture (Seebens *et al.*, 2017).

Anthropogenic disturbances (including climate change) coupled with introductions of non-native species have been associated with native species extirpations and/or range reductions in lakes, reservoirs and rivers (Bell *et al.*, 2021; Zhang *et al.*, 2022). Because both pressures are expected to persist in the 21st century, further threatening of aquatic species is expected.

However, whether non-native species, when introduced, will become invasive (and thus potentially harmful for native communities) or not, is highly context dependent (*e.g.* Manchester and Bullock, 2001).

7 Current and future harvesting threats

Current estimates of inland fisheries harvest are greatly underestimated (Deines *et al.*, 2017), but inland fisheries provide food for billions and livelihood for millions of people worldwide (FA0, 2016), especially in developing countries. Low-income food-deficient countries account for ~80% of the total reported harvest from inland capture fisheries (Lynch *et al.*, 2016). Most global harvesting is concentrated in 16 countries, which have annual inland catches >200,000 tons and together represent 80% of the world's total (FAO, 2016). Asian countries represent 63% of global total catches and African nations >13%. Harvests in African and Asian water bodies are already declining, probably because of environmental degradation and overexploitation (FAO, 2016). Given expected human population increases in Africa and Asia, increased harvesting is expected in both continents in the future. As harvesting decreases population densities and large-bodied species, increased fishing pressure will lead to local extirpations of these species and will alter population (including evolutionary genetic; Czorlich *et al.*, 2022), community structures and food web dynamics (McIntyre *et al.*, 2016). These effects will be magnified by interactions with other anthropogenic stressors, including climate change. Rural economies in developing countries will be the most affected as contributions of inland fisheries to economic security are inversely proportional to development level.

8 Perspectives

As reviewed above, anthropogenic factors and associated processes responsible for the decline of freshwater biodiversity are clearly identified since decades and several existing solutions, either technological, nature-based or policy-based, could be applied globally to halt and/or reverse this rapid decline. These solutions can also benefit climate change mitigation and human well-being (Pörtner *et al.*, 2021; Shin *et al.*, 2022; Smith *et al.*, 2022). Some few examples of potential solutions focusing on improving water quality, restoring freshwater connectivity and protecting freshwater systems globally are given below (see, *e.g.* Tickner *et al.*, 2020 and Harper *et al.*, 2021 for a more extensive list of solutions).

8.1 Improve water quality to sustain aquatic life

Options include:

(1) Improving wastewater treatment technologies and water reuse to reduce pollution from domestic and industrial point sources as well as maintaining sustainable water resources (*e.g.* Bailone *et al.*, 2022). Regarding wastewater treatment plants, a special attention should be given to

pharmaceutical and microplastic pollutions that pose a global threat to both biodiversity and human health (Eerkes-Medrano *et al.*, 2015; Wilkinson *et al.*, 2022). New technologies are now available and can be applied to reduce the level discharged (*e.g.* an advanced membrane bioreactor technology (Lares *et al.*, 2018) can remove up to 98% of microplastics concentration in effluents (Meng *et al.*, 2020)); (2) Improving urban development and agricultural practices by stopping wetlands and peatlands conversion for urban development and agriculture expansion and favoring maintenance of riparian zones at the periphery of all water bodies. Indeed, wetlands, peatlands and riparian zones act as buffer areas able to cool water temperature (riparian zones) and to improve the chemical and biological quality of water through filtering nutrients and stopping erosion and consequent sediment loadings (*e.g.* Engle, 2011); (3) Reducing the use of nutrients (nitrogen and phosphorous), pesticides, herbicides and fungicides applied to land as fertilizers or pest management and improving livestock systems and aquaculture practices by reducing the use of veterinary medicines (antibiotics and growth hormones), which move from lands through freshwater ecosystems. For example, water pollution from nutrients (*e.g.* leading to ecosystem eutrophication and consequent hypoxia) occurs when fertilizers are applied at a greater rate than they are fixed by soil particles or exported from the soil profile by plant uptake. Optimizing nutrient inputs to satisfy plant uptake only, should strongly minimize the export of nutrients to freshwaters and associated environmental and biological impacts. In the same way, manure from livestock production should be stored and treated (*e.g.* through anaerobic fermentation), which can produce organic fertilizers and soil conditioners, decreasing at the same time the need for chemical fertilizers; (4) Favoring efficient and well-managed crop irrigation schemes (*e.g.* drip irrigation, Grafton *et al.*, 2018) which can, besides decreasing the amount of water withdrawal, reduce water return flows and therefore the migration of fertilizers and pesticides to adjacent water bodies.

8.2 Safeguard and restore freshwater connectivity

Hydropower is a leading component of current and future renewable energy portfolios in many countries worldwide and construction of large dams is booming in many countries, particularly in developing countries (Zarfl *et al.*, 2015; Winemiller *et al.*, 2016; Moran *et al.*, 2018). However, the hydropower industry needs to recognize the unsustainability of current common practices for biodiversity and people's livelihoods by including in its strategies the negative social and environmental possible impacts where dams are planned (*e.g.* Moran *et al.*, 2018 ; Peters *et al.*, 2021).

Several solutions exist for reducing the loss of functional connectivity for riverine communities due to dam infrastructures (see, for example, results from the *Adaptative Management of Barriers in European Rivers* (AMBER) project – https://amber.international/about/). Some are listed below: (1) Strategic siting of new infrastructures can be made prior to the construction phase by using multi-objective optimization frameworks to identify least impactful projects by balancing, for example, connectivity maintenance with hydropower generation (*e.g.* Almeida *et al.*, 2022; Flecker *et al.*, 2022). For example, Flecker et al. (2022) recently developed a tool to assess a set of environmental parameters for an optimization analysis helping to find the combinations that can achieve energy production targets while minimizing environmental costs in the Amazon basin; (2) New technical solutions for hydropower dams, such as in-stream turbines, can be privileged, when possible, to maintain the natural dynamic of the fluvial system (*e.g.* connectivity, sediment transport, seasonal river flows; Moran *et al.*, 2018 ; Chaudhari *et al.*, 2021); (3) Systematically designing technical solutions (*e.g.* fish passes) to maintain the fluvial system connectivity for aquatic biota for dams of all sizes (Albert *et al.*, 2021); (4) Systematic dam removal can be considered in regions with aging dams render them unsafe or economically not viable (Foley *et al.*, 2017). When removal is not possible, the natural flow regime baseline of riverine ecosystems should be maintained or restore (*e.g.* Acreman *et al.*, 2014). However, hydropower dams represent only a small fraction of artificial barriers disrupting riverine system connectivity, small instream infrastructures such as weirs, culvets and fords actually constituting the main cause of connectivity loss (*e.g.* Belletti *et al.*, 2020). Many of these small barriers are old and obsolete and can thus be removed to restore connectivity, without major technical difficulties nor strong expected conflict between local stakeholders (but see Blanchet and Tedesco, 2021 for a counter-example).

8.3 Expand the network of protected areas

Protected areas (PAs) play a fundamental role in conserving genetics, species and ecosystem diversity, and in ensuring delivery of ecosystem services from natural habitats. Currently around 17% of global inland surface waters are covered by PAs (Bastin *et al.*, 2019), which is in phase with the Strategic Plan for Biodiversity of the Convention on Biological Diversity (CBD), to conserve by 2020 at least 17% of terrestrial and inland water areas. However, current protected areas are far from being geographically uniform (Bastin *et al.*, 2019) and recent proposals converge around protecting 30 per cent of inland water areas by 2030, with appropriate prioritization (*i.e.* geographical and ecological representability, and connectivity) and management improved (https://www.cbd.int/article/draft-1-global-biodiversity-framework). This strategic expansion of PAs could be realized through a consistent framework allowing to identify, in an objective, transparent, and scientifically rigorous way, important areas contributing significantly to the global persistence of biodiversity (*e.g.* Key Biodiversity Areas (KBAs) –https://www.keybiodiversityareas.org/). As protected areas are most often essentially terrestrially defined, protected area networks are also not fully appropriate for managing freshwater ecosystems (*e.g.* Leal *et al.*, 2020) so that it will be important to (1) design these protected areas for the particular spatial and temporal complexities of freshwater ecosystems (Albert *et al.*, 2021), (2) elaborate management plans harmonising nature conservation and human uses objectives (*e.g.* Abarca *et al.*, 2022).

9 Conclusion

The selected potential solutions listed above – most of them well-known since a long time – are largely achievable and several recovery plans and management Agendas to halt and reverse the rapid decline of biodiversity have been recently proposed (*e.g.* Tickner *et al.*, 2020; Harper *et al.*, 2021; van Rees *et al.*, 2021; Maasri *et al.*, 2022). However, success will require systemic changes across public policy. These changes are far from being insurmountable if there is a sufficient political will to do so. In the same way as for climate change, decision makers need to move urgently beyond well-intentioned speeches as it is now time for concrete and decisive actions.

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