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Editorial

Impacts of Human Activities and Climate Change on Freshwater Fish—Volume II

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Introduction

Freshwater fishes are at the center of the freshwater biodiversity crisis [1,2], which is unfortunate as they significantly contribute to global diversity, accounting for 40% of all fish species and 25% of vertebrates worldwide [2,3]. Global pressures such as land and water use changes, pollution, invasive species, and climate change pose significant threats to freshwater ecosystems and the biodiversity they harbor [3–5]. These threats affect freshwater fishes in different ways, altering their phenology, distribution, and population size and dynamics [3,6,7].

Given that these threats are persistent and new emerging threats are continuously being reported (e.g., [5]), it is imperative to shed light on these valuable organisms and how they cope with human-induced changes in order to find solutions that can bend the so-called freshwater biodiversity loss curve [8]. As a follow up on the well-received Special Issue "Impacts of Human Activities and Climate Change on Freshwater Fish" [9], here, we present a second volume, including case studies on various types of human impacts on fishes covering different levels of biotic organization from running and still waters. The papers provide information from areas that are typically less studied, such as tropical, subtropical and arid regions; also, the contributions cover a wide range of aspects of fish ecology and biology, directly or indirectly connected with human-induced changes; and present data from 11 countries in Europe, Asia, and South America. An overview of the main features of each contribution is given in Table 1.

The contributions span from model-based approaches involving species distribution models to experimental and field studies, with the latter being prevalent (Table 1). Most studies were performed at community or population levels. Among the main threats faced by fishes in freshwaters, the majority of the papers dealt with climate change and habitat alterations, followed by non-native species and pollution, and the main focus was on ecology where species and population trophic interactions and/or the response to environmental gradients or habitat preferences were investigated. Four studies used latitudinal/environmental gradients as proxies to assess and forecast the impacts of human-induced changes on freshwater fish populations and assemblages. Among the field studies, five are from riverine systems and three from lacustrine ecosystems, including temperate, Mediterranean, subtropical, and tropical fresh waters (Table 1). Overall, this Special Issue covers a wide range of threats and fish responses and provides valuable insights into the different methods available.

Table 1. Overview of the contributions in this Special Issue.

Contribution No.	Biological Organization Level	Main Research Focus	Connected Human Threat(s)	Country	Ecosystem Type	Type of Study
1	Community	Trophic ecology; habitat complexity gradient	Habitat alteration; climate change	Brazil	Tropical and subtropical upland rivers	Field study
2	Population	Microplastic occurrence and abundance; fish biological traits	Plastic pollution	Argentina	Andean river	Field study
3	Individual	Exposure to Atrazine; behavioral alterations	Pesticides	USA	NA	Experimental study
4	Population	Morphological and genetic variations; latitudinal gradient	Habitat alteration; climate change	Italy	Mediterranean rivers	Field study
5	Population	Critical maximum temperature	Climate change	Thailand	Tropical headwater stream	Field and experimental study
6	Community	Interspecific trophic interaction; native vs. non-native species	Non-native species	Mexico	Subtropical lake	Field study
7	Population	Habitat suitability; species distribution models; forecasting	Climate change	Türkiye	Freshwaters (rivers and lakes) of the Central Anatolian ecoregion	Field and modelling study
8	Community	Beta diversity of fish; latitudinal gradient; habitat disturbances	Habitat alteration; non-native species	Denmark, Belgium, The Netherlands and Spain	Small and shallow lakes	Field study
9	Community	Investigating how body size influences fish diversity across a latitudinal and environmental gradient	Habitat alteration; climate change	Türkiye	Lakes from continental and dry cold steppe to Mediterranean climates	Field study
10	Population	Balitorid fish ecological preferences; responses to habitat alteration	Habitat alteration; climate change	Thailand	Tropical streams and small rivers	Field study

Here, we briefly summarize the methodologies, results, and main conclusions of the papers.

Macrophytes are of key importance in aquatic environments as they provide valuable structural complexity [10], resulting in the great diversity and stability of biotic communities [11]. By offering protection from predators and providing food associated with macrophytes, littoral zones are important spawning and feeding grounds for fishes [12], and plants stabilize the dynamic interactions between fishes and their prey [10,13,14]. Quirino et al. (contribution no. 1) assessed how fish food selection and foraging efficiency, trophic niche breadth, and niche overlap changed along gradients in macrophyte density and diversity. They sampled fishes and macrophytes in 30 macrophyte stands distributed over a 13.7 km stretch of the littoral zone of a river in Brazil. Using generalized linear models, they showed that an increase in macrophyte density favored herbivory and fish foraging efficiency. Beta regressions showed a reduced trophic niche breadth of fishes along the gradient of macrophyte density, while niche overlap increased until a certain extent of plant density, where species started to segregate the niche more strongly. However, the niche breadth responses varied according to the trophic guild considered, with omnivorous and herbivorous fishes generally showing opposite responses. They further showed that macrophyte diversity influenced the food items selected by the fish, shifting from plants, algae, and detritus to insects with increasing macrophyte diversity. Their study highlights the importance of maintaining diverse macrophyte stands for the conservation of fish diversity.

Microplastics (MPs) have been reported in different fish species [15], and they can have several negative consequences for fishes and other aquatic biota, including alterations in swimming performance and digestive tract blockage [16–18]. As such, the determination of plastic load in aquatic organisms is becoming central to monitoring plans; however, some areas and ecosystems such as mountain rivers have so far been less studied. Ríos et al. (contribution no. 2) characterized the MPs present in the gastrointestinal tract of three species—two non-natives (brown trout *Salmo trutta* (Linnaeus, 1758) and rainbow trout *Oncorhynchus mykiss* (Walbaum, 1792) and one native fish (torrent catfish *Hatcheria macraei* (Girard, 1855))—in a mountain river of the Central Andes and assessed the relationship between plastic load and body size. Forty-six specimens belonging to the three species were collected in the central portion of Mendoza River (Argentina), measured, and dissected to extract their gastrointestinal tracts. MPs were classified according to their shape and color and counted. The authors found interspecific differences between species, with brown trout having significantly higher abundances of microplastics than the other two species, with MPs represented only by fibers. There was a preference for blue fibers, suggesting a high probability of ingestion of blue MPs, as also reported in other studies. Furthermore, the authors did not find a correlation between MP load and body size. This study represents a baseline study to assess the ecological quality of these valuable ecosystems and suggests that non-native brown trout and rainbow trout are valid biomonitoring tools in periodical screening for MP accumulation.

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) is one of the most used pesticides in the United States [19,20], but it is also recognized as an endocrine disruptor compound (EDC) that is able to alter proper hormonal functioning by affecting hormone synthesis or target cell receptors [21]. In addition, by altering physiological processes, atrazine exposure can cause behavioral changes that can threaten wild populations, even at low concentrations [22]. MacLaren (contribution no. 3) conducted four sets of experiments to assess the effects of exposure to ecological realistic concentrations of atrazine (1 ppb and 15 ppb plus a control with no atrazine) on the association preferences and overall responsiveness of the sailfin molly *Poecila latipinna*—which is a model organism in studies of animal behavior and ecology and an important indicator species of environmental health within the mangroves along the Gulf Coast of the southeastern US. The author also tested if there were significant changes in the behavior of the fishes associated with boldness and anxiety. Fish responses were monitored through iPad videos by measuring the time spent by each fish on a particular task. The authors found that atrazine influenced the behavior of both females and males, particularly at the moderate concentration of 1 ppb. Females exposed to atrazine showed a reduced responsiveness to/interest in associating with males, favoring avoidance rather than the affiliative behavior. This reduced responsiveness was also observed towards individuals of the same gender, suggesting a more generalized effect of atrazine on affiliative behavior. Therefore, in species like *P. latipinna* that use shoaling as an important anti-predator behavior, atrazine exposure could lead to higher vulnerability to predation. Similarly, males were also found to be less prone to engage in aggressive interactions. Finally, the study revealed significant alterations of boldness and anxiety, and this was particularly pronounced at low concentrations of the pesticide and in females. These results highlight that atrazine can alter the fitness of fish populations, even at low concentrations, and the study provided a simple, practical, and inexpensive protocol for addressing the behavioral impacts of potentially harmful environmental contaminants on fishes.

The morphology of fishes can vary with current temperature increases and changes in other environmental parameters such as salinity and dissolved oxygen [23], whilst genetic diversity, particularly in neutral (i.e., not under selection) DNA regions, such as those commonly used for population genetic studies, typically reflects the historical demographic evolution due to past climatic and geological changes [24]. Nevertheless, both genetic and phenotypic variabilities can be altered via anthropogenic activities such as the introduction of exotic species (e.g., following hybridization [25]) and river damming (e.g., [26,27]). Thus, separating genetic and phenotypic variations induced by local adaptation developed during historical evolution from the variations created by relatively recent events provides valuable insights into both eco-evolutionary processes as seen from a conservation perspective [28]. Quadroni et al. (contribution no. 4) used a latitudinal gradient as a proxy to test the effects of past and present environmental variations on both the genetic and the morphological patterns of three barbel species (genus *Barbus* Daudin, 1805) collected from 17 rivers distributed along the Italian peninsula (about 2.5 north–south latitudinal degrees). They analyzed both morphometric and meristic variations and the mitochondrial DNA diversity of one gene. Overall, the authors found a significant relationship between latitude and the number of private haplotypes compatible with past evolutionary events and weak correlations between both nucleotide and haplotype diversity indices. Their results also suggest an influence of the present environmental conditions at the genetic level. At the morphological level, there was a significant relationship between meristic traits and latitude as well as other environmental variables such as distance from headwater, the ratio between average flow and basin area, and elevation. The results suggest that morphological variation in barbels is more tightly linked to the current environmental conditions than to the genetic structure, highlighting that barbels could be vulnerable to climate changes if these morphological features are the result of local adaptation.

Most fishes are poikilotherms and thus sensitive to changes in the surrounding temperature [29]. Tropical riverine fishes living in a relatively stable environment in terms of temperature and close to their relative upper thermal tolerance limit can be particularly vulnerable to temperature increases [30]. Tongnunui et al. (contribution no. 5) measured the critical maximum temperature (CTmax) in four representative fish species native to Thai rivers to assess their heat tolerance and assess their ability to cope with future global warming. The authors sampled fishes from wild populations in Pakkok River (western Thailand) and exposed them experimentally to temperature increases of 1.0 $^{\circ}C \cdot h^{-1}$ above the acclimation temperature (thermal tolerance) until cessation of respiratory activity. They found that CTmax varied during the wet and dry seasons for all four species, with higher tolerances in the dry seasons when the photoperiod was shorter. These results contrast with results from most temperate and high latitude teleosts, which usually have a higher CTmax during periods of longer daylight. A lower lethal maximum temperature in the wet season may be associated with the rainfall pattern and reproductive seasons rather than the photoperiod in tropical river fishes. The authors modeled the future water temperature increases in Pakkok River in both the wet and dry seasons, and they found that despite a temperature increase, none of the four species are at risk of reaching their relative CTmax this century. The CTmax is thus a useful tool to screen for the vulnerability of fishes to global warming, although heat stress tolerance in fishes is related to a complex genetic architecture underlying thermal tolerance, which should also be considered. Gene expression studies might, therefore, be more useful for detecting plasticity and adaptive responses to this threat.

Fishes are important drivers of food webs in lakes; they occupy a great variety of trophic niches and circulate matter and energy from basal resources to the highest levels of the web [31]. Analyses of the trophic structure and feeding habits of fish communities can provide information on the complex biotic and abiotic interactions in lake ecosystems [32], but so far, few studies are available from (sub)tropical lakes as compared to temperate lakes. Ramírez-García et al. (contribution no. 6) conducted a study on the diet of the fish community and its trophic structure in subtropical Lake Zacapu in central Mexico based on stomach contents and $\delta^{13}C$ and $\delta^{15}N$ stable isotope analyses. Overall, they found good agreement between the results based on diet and isotope analyses. Fish diets mainly consisted of aquatic macroinvertebrates, which were abundant in the lake. Most species were secondary consumers and trophic generalists across the four sites and two seasons, and the results suggest a low trophic position of native species, which had a wide spatial trophic niche and niche width. In addition, they found that the trophic diet overlap was greater between native species than between non-native species.

Climate change will prompt species to adapt, migrate, or face extinction, impacting most species negatively but potentially benefiting some. Hence, identifying winners and losers is crucial for crafting tailored management plans [33,34]. Korkmaz et al. (contribution no. 7) provide insights into the current habitat suitability and forecast habitat alterations for native freshwater fishes within the Central Anatolia Ecoregion (CAE), Türkiye, utilizing species distribution modeling (SDM) and diverse climate change scenarios. The use of SDM, an interdisciplinary tool, allows for a comprehensive understanding of how environmental threats affect the spatial distribution and fundamental niches of freshwater fish, which is crucial for assessing their vulnerability to climate change and habitat alterations [35,36]. The authors predicted the influence of climate change on 16 out of the 43 endemic fish species in the CAE that were suitable for SDM modeling. Their analysis revealed distinct responses among the study species to climate change, with eight species expected to lose their suitable habitats in the changing climate and four facing a high risk of complete extinction. Conversely, eight species could potentially expand their climatically suitable habitats. In addition to climate change effects, extensive land and water use [37] will significantly affect freshwater systems, making freshwater fauna highly vulnerable, and this underscores the urgent need for conservation measures and policy frameworks. The authors conclude that such measures are vital to mitigate threats and preserve the CAE's endemic freshwater fish fauna.

Latitudinal diversity gradients are some of the most noticeable biogeographical patterns on Earth [38], but how and why these patterns exist are still debated [39,40]. It is recognized that species diversity generally peaks at lower latitudes and declines towards the poles. It is well established that beta diversity among lakes in general is affected by natural environmental sorting, dispersal constraints, and anthropogenic disturbances, but their relative contributions are debated and may vary along a climate gradient and geographical distance. Menezes et al. (contribution no. 8) used generalized dissimilarity modeling to assess the relative importance of geographical distance, climate, and environmental heterogeneity for fish beta diversity across Denmark, Belgium/The Netherlands, and Spain. The authors tested whether differences in beta diversity changed between lake types (e.g., clear vs. turbid lakes and lakes with vs. without exotic fish) within regions and across latitudes. They found that beta diversity increased from Denmark to Spain and that geographical distance and climate variability were the main drivers of community change across latitude; however, the rate of change varied between lake types. At the within-region scale, factors such as turbidity, lake size, and presence of exotics had varying impacts on the beta diversity (i.e., increasing, decreasing, or no effect) across the three regions. The authors concluded that understanding the effects of environmental disturbances on beta diversity requires consideration of both biogeographical and local factors.

Body size is a key trait in ecology that affects trophic position [41] and determines competitive ability and predator–prey interactions [42]. Thus, body size has several functional attributes and plays a key role in structuring communities, trophic interactions, and food webs [42,43]. Size diversity might, therefore, be a proxy for functional diversity [43,44] that potentially complements traditional taxonomic diversity measures. Boll et al. (contribution no. 9) elucidated the key variables controlling the size diversity, geometric mean length, and number of size classes in the fish community based on a dataset of fish communities from 40 lakes in Türkiye, covering a wide environmental gradient and continental to dry cold steppe to Mediterranean climates. A generalized linear model analysis revealed that both the size diversity and the number of sizes were strongly related to taxonomic diversity and richness. Furthermore, fish size diversity decreased with decreasing annual precipitation, while the number of size classes increased with increasing lake area but decreased with increasing salinity. They further found that the geometric mean length of fishes decreased with total nitrogen and increased with altitude. Finally, they identified the inter-relatedness between the number of size classes and lake area, which suggests an increase in fish niches with an increasing ecosystem size, while fishes are smaller and have fewer size classes in lakes with a higher salinity. They concluded that size measures provide valuable integrating information on lake fish diversity that may complement, but not replace, more traditional taxonomic fish measures.

Balitorids are widely distributed in Eurasia, but their ecology is poorly documented, and in Thailand, many species have been redescribed or newly established. Thus, filling in the gaps on balitorid ecology is critical to document their responses to ecological disturbances and the potential impacts of climate change. Tongnunui et al. (contribution no. 10) monitored species richness, relative abundance, distribution, and habitat preferences of the river loach family (Balitoridae) in 95 sites in eastern Thailand, characterized by a gradient of alteration from relatively pristine to heavily degraded sites. The authors found that the balitorid occurrence and diversity were negatively associated with high ammonia levels and river temperatures but positively related to dissolved silica. Ammonia was related to the human footprint (i.e., industrial and municipal effluents, agriculture, and shrimp farming). Dissolved silica was found to be particularly low in most of the degraded sites, and this may be an indicator of heavy metal (e.g., iron) pollution in rivers that can co-precipitate with dissolved silica. Temperature may increase ammonia toxicity due to an increased dissociated behavior of ammonia ions and an elevation in aerobic metabolism. Therefore, the authors concluded that balitorids are vulnerable to both climate warming and pollution and the consequent habitat deterioration, and they recommend a reduction in anthropogenic pressure, heat emissions, and warming to preserve the freshwater habitat of these species.

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