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EDITORIAL

Diversity and Distributions WILEY

Biological traits, geographic distributions, and species conservation in aquatic ecosystems

1 | INTRODUCTION

Aquatic ecosystems (both marine and freshwater) have long served as model systems for exploring the role of environmental stressors on organismal performance and survival, the biogeographic distributions of populations and species, and ultimately the diversity, functioning, and stability of ecosystems (Adams, 2002; Forbes, 1887; MacArthur & Wilson, 2001; Paine, 1969; Somero et al., 2017). Climate change, alien species invasions, land use change, urbanization, and other anthropogenic impacts have all been demonstrated to impair aquatic ecosystems at multiple levels of biological organization within aquatic ecosystems (Karr, 1991; Doney et al., 2012; Harley et al., 2006; Poloczanska et al., 2013). Consequently, approaches that include biological traits (e.g., physiological, behavioural, phenological, and functional) at multiple spatial–temporal scales are critical for forecasting responses of aquatic ecosystems to future environmental changes; from individual organisms to entire ecosystems (Deutsch et al., 2015; Dong et al., 2022; Sunday et al., 2014). A merger of different biological scales has great potential for the development of approaches to quantitatively evaluate and forecast ongoing and future responses to climate change and human activities.

The focus of this special issue is on studies that explore how best to incorporate biological traits into conservation biogeography and specifically the temporal and spatial scales over which we must measure both environmental conditions and biological responses in space and time (Miatta et al., 2021). We compile 16 articles on trait-based approaches to conservation biogeography of a number of aquatic taxa, including epiphytic algae, insects, molluscs, turtles, fish, water birds, and mammals across freshwater and marine ecosystems from wetlands, streams, and lakes to mangroves, coral reefs, and the open sea (Table 1). The topics covered by these articles focus on fundamental questions in biological conservation using various traits (Figure 1) and can be generally categorized into the three following themes: (1) species sensitivity and resilience; (2) development of conservation tools (impact, risk and vulnerability assessment); and (3) relating biodiversity, functional traits, and ecosystem functioning. Here, we summarize the main findings of this collection of papers.

2 | SECTION A: SPECIES SENSITIVITY/RESILIENCE

Because biological traits can relate to the ecological fitness of organisms, it is feasible to evaluate the sensitivity and resilience of individuals, species, and communities to environmental and anthropogenic stressors (Miatta et al., 2021). Physiological traits (e.g. critical thermal limits, metabolic index, and cardiac performance) have emerged as having high predictive capacity under various warming and cooling scenarios and have been widely applied to the thermal sensitivity of marine species (Cheung et al., 2015; Deutsch et al., 2008; Liao et al., 2021; Massamba-N'Siala et al., 2022; Sunday et al., 2011, 2014). Community-level thermal deviations from local temperatures have also been applied to assess the sensitivity of marine species to warming and predict the warming-related loss of species from present-day communities in the future (Stuart-Smith et al., 2015). Functional traits can be defined as the morphological, physiological, and phenological attributes of an organism that impact fitness indirectly through their effects on growth, reproduction, and survival, shaping its functional response to environmental change (Violle et al., 2007).

Our special issue contributes to the field by identifying key linkages between physiological and other traits. Finn et al. (2022) assessed the sensitivity of phenological traits (emergence timing and duration) to heat accumulation (i.e. cumulative degree-days) of the four most abundant, spring-emerging species from the orders Ephemeroptera, Plecoptera, and Trichoptera during the emergence period in six headwater streams with different elevation in the Lookout Creek basin, Oregon. They found that several streams have different thermal regimes (indicated by the mean daily water temperature) across the 6 years of the study period (2009–2014). The authors also observed highly variable phenological responses among different populations and species, indicating three clearly different phenological patterns with different thermal regimes among four aquatic insect species. Finn et al. (2022) hypothesized a trade-off between a complex phenological response that synchronizes emergence among heterogeneous sites and other traits such as adult longevity and dispersal capacity. This work sheds new light on the complexity of phenological responses of aquatic insects to water

TABLE 1 Summary of objectives, taxa, habits, and traits of articles included in this special issue

Objective	Taxa	Habitat	Trait	Reference
Section A: Species sensitivity/resilience				
Phenological response to temperature	Aquatic insects	Streams, Oregon	Emergence timing and duration	Finn et al. (2022)
Physiological adaptation and formation of biogeographic break	Limpet	Rocky shore, South East Pacific	Morphometric and physiological traits	Rodríguez-Romero et al. (2022)
Spatial distribution of marine fish	Billfish	Indian Ocean	Physiological traits	Thoya et al. (2022)
Habitat use and movement	Loggerhead turtles	North Pacific Ocean	Diet, body size, reproductive output	Okuyama et al. (2022)
Section B: impact, risk and vulnerability assessment, and mapping diversity hotspots				
Assessing ecological gradients among the mining-controlled and natural headwaters	Freshwater macroinvertebrate	Headwaters, northern Peruvian Andes	Physiological and ecological traits	Mercado-Garcia et al. (2022)
Effect of environmental variables and urbanization on taxonomic and functional diversity	Fish assemblage	Sandy beaches, Southeast Brazil	Functional traits and diversity	Shah Esmaeili et al. (2022)
Cause and rate of spread of alien invasive species	American bullfrog	Jiangsu, China	Breeding call	Wang et al. (2022)
Invasion risk of freshwater fish	Freshwater fish	Laurentian Great Lakes, North America	Functional traits	Campbell et al. (2022)
Climate change vulnerability assessment	Otter	Himalaya	Species occurrence data	Jamwal et al. (2022)
Influence of invasive free-floating macrophytes on epiphytic algal communities	Macrophytes and epiphytic algal	Freshwater lake, Southern China	Macrophyte traits and allelochemical contents	Lv et al. (2022)
Section C: Biodiversity and ecosystem functioning				
Functional and isotopic structure from two biogeographic regions	Mangrove fishes	Caribbean and Pacific coasts of Panama	Taxonomic composition; Functional traits; Functional isotopic metrics	Stuthmann et al. (2022)
Functional role of marine vertebrates on reef ecosystems	Marine vertebrates	Atlantic Ocean reefs	Species-level functional traits	Waechter et al. (2022)
Role of non-random assembly in shaping regional diversity	Waterbird	Wetlands, North China	Taxonomic β-diversity and functional β-diversity	Li, Wang et al. (2022)
Relationship between biodiversity and ecosystem functioning	Demersal fish	Shelf sea, China	Taxonomic and functional diversity indices	Li, Ma et al. (2022)
Prioritized to protect desirable properties of biodiversity	Coral reef	Global	Functional and phylogenetic diversity	Ng et al. (2022)
Taxonomic resolutions for ecosystem assessments	Benthic macroinvertebrates	Paute River Basin, Ecuador	Functional Diversity, rRao index	Sotomayor et al. (2022)

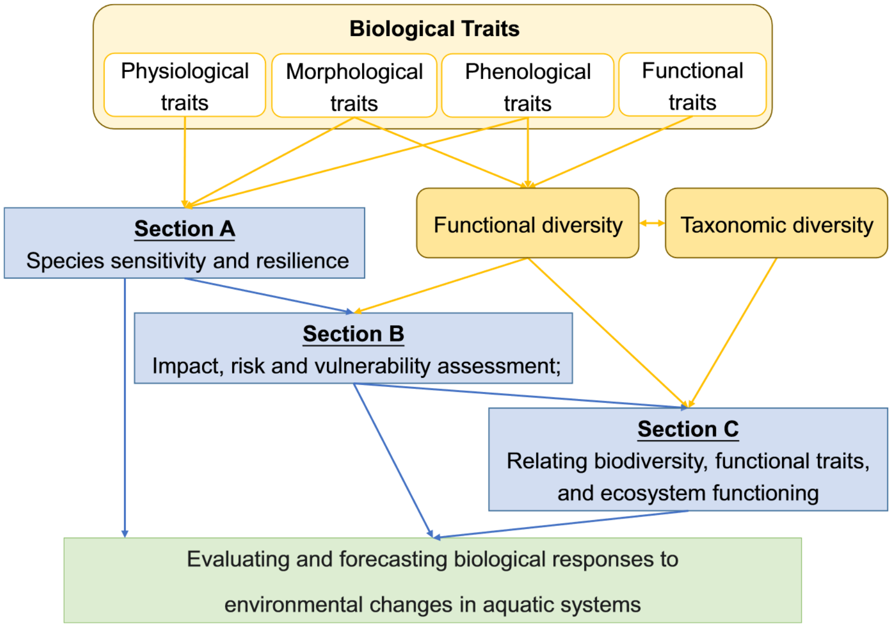

FIGURE 1 Structure of this special issue, including the main traits and questions on which the selected articles focused

temperature and climate change and indicates key directions for future research.

To understand how spatio-temporal environmental variability across a major geographic break (30–32°S) in the South East Pacific (SEP) coast affects physiological tolerance and biogeographical pattern, Rodríguez-Romero et al. (2022) took a multifaceted approach, combining morphological and physiological traits to investigate the stress tolerance and phenotypic variations among populations. Specifically, the authors focused on a limpet (*Scurria araucana)* and determined the morphometric (shell length, total buoyancy weight, dry tissue weight, and shell weight) and physiological (e.g. oxygen consumption rate, cardiac activity, and thermal performance curves) responses to local environmental conditions (temperature and pH/pCO_2) and to simulated ocean acidification scenarios. The scaling relationship between buoyant weight and length showed that individuals from the central part of the break (30°S) had a higher variability in buoyant weight per unit of shell length compared to the individuals from either side of the biogeographic break, indicating the existence of potential morphometric effects of natural spatial variability of SST and pH/pCO_2. They report inter-population differences in thermal physiology (metabolic rates and performances) across the biogeographic break in the SEP coast, and the populations from the central part of the biogeographic break (30°S) show higher thermal performance than limpets from populations from either side of the break. These physiological differences are aligned with the thermally heterogenous seascape along the biogeographic break in the SEP and implicate the role of physiological traits in evaluating the species distribution and sensitivity to environmental factors.

Both Thoya et al. (2022) and Okuyama et al. (2022) identified sensitivity of marine vertebrates to stressors like overfishing or bycatch based on physiological and functional (e.g., diet) traits. Thoya et al. (2022) used physiological tolerances of billfish species in the Indian Ocean to develop hypotheses for species distribution models, which they then used to relate the distributions of the Indian Ocean billfish community to fishing effort and stock status. For example, the authors characterized the temperature and salinity associations of the poorly known shortbill spearfish (*Tetrapturus anguistirostris*), identifying its potential vulnerability to high fishing effort in the southwestern Indian Ocean despite its currently unknown stock status.

Okuyama et al. (2022) used both satellite tracking and stable isotope analysis of diets to characterize within-population trait variability of loggerhead turtles (*Caretta caretta*) that can inform conservation and management of this species in the north Pacific Ocean. These authors found that loggerhead turtles that nest on beaches in Japan disperse to forage in either the Pacific Ocean (oceanic) or in the east China Sea (neritic) and that these habitat choices are highly associated with differences in traits like diet, body size, and reproductive output. Oceanic loggerhead turtles are planktivores that achieve smaller body sizes and lower reproductive output than larger, neritic benthivores that disperse and forage in the east China Sea. Okuyama et al. (2022) identify the east China Sea component of the loggerhead turtle population as a conservation priority given the high reproductive output of these turtles and possible vulnerability to bycatch in a complex, cross-political jurisdiction ecosystem.

3 | SECTION B: IMPACT, RISK, AND VULNERABILITY ASSESSMENT

Trait-based approaches for the analysis of impacts, risk, and vulnerability from environmental change are gaining momentum in ecology (Aubin et al., 2016; Degen et al., 2018; Green et al., 2022; Williams et al., 2008). As a surrogate of organismal performance, biological traits confer a mechanistic perspective to vulnerability assessment by providing information on the characteristics that preclude or allow species to tolerate environmental change (adaptive capacity) and the degree to which they are affected by those changes (sensitivity), which can then be used to predict responses to disturbance across levels of biological organization from populations to ecosystems (Laughlin et al., 2020; Schmitz et al., 2015; Vandewalle et al., 2010).

Several papers in this special issue provide practical examples on the use of trait-based approaches for impact, risk, and vulnerability assessment. In one example, Mercado-Garcia et al. (2022) assess the impact of mining in a watershed on the functional changes of freshwater macroinvertebrate assemblages in the northern Peruvian Andes. They find clear ecological impairment (less macroinvertebrate diversity and changing phenotypic trait composition) of parts of the watershed impacted by mining relative to those that are not. Importantly, the observed ecological degradation occurred in spite of the fact that the water discharged by the operating mine is classified as excellent according to regulatory physicochemical water quality assessments. This suggests that the existing regulatory assessments for large-scale mining operations do not adequately cover the ecological requirements of Andean freshwater ecosystems and shows how trait-based approaches can effectively be used to complement existing freshwater quality assessments on impacts from mining operations.

Similarly, Shah Esmaeili et al. (2022) provide another illustrative example of how complementing traditional taxonomic assessments with functional trait-based analyses can provide useful information to improve conservation and management practices to preserve a diversity of organisms and functional traits integral to productive beach ecosystems. Using data from 77 sites along 150 km of coastline in southeast Brazil, they analysed how environmental factors and urbanization affect taxonomic and functional diversity of fish assemblages in sandy beach surf zones. Increased wave breaker height and proximity to urban areas were found to be the two main factors structuring these fish assemblages by reducing taxonomic and functional diversity to a few generalist predatory fish species, which can effectively forage in the more exposed and less diverse habitats. Based on these results, the authors recommend an integrated management approach to maximize taxonomic and functional diversity across the region, focusing on the conservation of pristine beaches with low wave height, harbouring communities taxonomically and functionally more distinct, but including also high-wave urban beaches where some generalist groups, such as piscivorous fishes, are more abundant.

Risk assessment of alien or invasive species is also informed by trait-based approaches. Wang et al. (2022) reveal a novel way that species traits can inform risk assessment and management of invasive species. These authors used the distinctive, loud call of invasive bullfrogs (*Lithobates catesbeianus*), relative to the quieter calls of native amphibians in China, to survey citizen scientists or community members on the sequential arrival of bullfrogs over time in a spreading population. In this case, a distinctive trait of an invasive species allowed for accurate, post hoc mapping of its spread rate, as well as the ability to assign causes of this spread. Specifically, Wang et al. (2022) found that land use change drove bullfrog spread as urbanization replaced suitable bullfrog habitat at its introduction site with unsuitable habitat, causing the frogs to preferentially disperse to nearby wetlands and rice paddies. In this case, traits inform not only our understanding of impacts of invasive species but provide a mechanism to monitor and measure spread that may inform management against this species in urbanizing landscapes. In addition, this work implies that the ability of rapid range expansion to more suitable habitat may be an important trait of the invasive bullfrog in response to anthropogenetic land use change, which warrants future investigations using more taxa.

Trait-based approaches are also particularly relevant for assessing impacts from climate change in terms of invasion risk. Warming and other variables continue to modify the abiotic filters and biotic resistance in natural ecosystems, hence redefining the pool of species that can remain or become established in a community. Campbell et al. (2022) assess the effect of future climate change on invasion risk of 34 failed introduced freshwater fish species, common to the live-trade pathway (i.e. aquarium trade, food trade), in the Laurentian Great Lakes. Based on the changes in functional distances of these failed non-native species to all other resident species, they estimate that 12–15 of the 34 species have a higher probability of establishment success, while approximately two-thirds of them have an increased probability of high impact on those communities today compared to those at the time of their initial failed introduction in the lakes. Importantly, the study shows that this tendency will further exacerbate in the future as climate change continues to make environmental conditions more suitable for these non-native species. Using a climate-match approach, the study finds that 14 species are expected to experience an increased climate match between the Laurentian Great Lakes region and their native range by 2050 under all future climate-change scenarios. Of these species, half have an increased probability of establishment success, including five species that have high ecological impact compared to their initial period of introduction. Given the extreme costs and technical difficulty associated to the eradication of invasive species, projecting their future risk of establishment provides important information to help prioritizing resources to prevent their establishment.

Trait-based studies also inform vulnerability assessments by quantifying the functional responses of species and communities to multiple disturbances. In this special issue, Jamwal et al. (2022) use the Climate Niche Factor Analysis (CNFA) framework (Rinnan & Lawler, 2019) combined with species distribution models to evaluate the vulnerability of three species of Himalayan Otter (*Lutra* spp.) to the combined exposure to future climate and land use changes in the Himalayan region. They found that the combined exposure to both stressors by midcentury is projected to result in an overall loss of their current range of 6–15%, depending on the species and emission scenario followed, with land use change projected to exert far more severe effects than climate change. Among the species, the most specialist *L. perspicillata* showed the highest vulnerability relative to the most generalist *L. lutra*, evidencing a larger contribution of sensitivity (determined as the range of environmental conditions a species experiences throughout its current range), relative to that of exposure (defined as the degree of environmental dissimilarity between present and future conditions within the species habitat). These results highlight the importance of accounting for species-specific components together with common measures of climatic exposure.

The final article in this section highlights the importance of combining more traditional and biochemical traits in invasion impact assessment for invasion impacts. Lv et al. (2022) study the effect of free-floating macrophytes, including two invasive species (*Eichhornia crassipes* and *Pistia stratiotes*) and one native species (*Hydrocharis dubia*), on the abundance of epiphytic algae with macrophyte traits (biomass and coverage) and the allelochemical contents (i.e., alkaloids, amines, esters, organic acids, and phenols) as traits (Lv et al., 2022), and found that the macrophyte traits were the main factors explaining the epiphytic algal abundance in both the field investigation and mesocosm experiment. The allelochemical contents secreted by invasive macrophytes were significantly higher than those secreted by native species, and the composition of allelochemicals was another factor that drove the decrease in epiphytic algal abundance. This study provides new information about the ecological impacts of invasive macrophytes on freshwater communities.

4 | SECTION C: RELATING BIODIVERSITY, FUNCTIONAL TRAITS, AND ECOSYSTEM FUNCTIONING

The functional diversity of communities provides an additional dimension of biodiversity that complements more traditional taxonomic measures such as species richness and evenness. Moreover, functional diversity may also provide insights into ecosystem processes due to the role that species play within ecological communities. Several articles in our special issue develop and add to the growing understanding that biodiversity underpins ecosystem functioning in aquatic systems.

First, our special issue highlights the importance of local environmental characteristics in shaping coastal marine fish communities with the importance of trophic level as a key driver of variation in community structure and function. For instance, Stuthmann et al. (2022) compared the taxonomic composition and functional and stable isotopic structure of the mangrove fish communities of the Caribbean and the Eastern Pacific. These two coasts of the Isthmus of Panama have been separated for ~3 my, and the formation of the Isthmus of Panama has changed the flora and fauna in the Eastern Pacific and the Caribbean Sea coasts. The species compositions in the two regions are distinctive and the functional divergence and isotopic richness in the Caribbean Sea were higher than those in the Eastern Pacific. Moreover, Waechter et al. (2022) conducted an assessment of the functional structure of Atlantic Ocean reefs with a compilation of six species-level traits of marine vertebrates, including 224 species of marine mammals, sea turtles, sharks, rays and bony fish, to understand the functional roles of marine vertebrates on reef ecosystems (Waechter et al., 2022). Their results confirmed the crucial roles of mesopredators (e.g. *Acroteriobatus annulatus*, *Caranx crysos*, *Epinephelus adscensionis*, etc.) on the functional structure of vertebrate assemblages due to the high proportion of threatened species and importance in the regulation of trophic cascades of mesopredators.

Several articles in this special issue identify key links between biodiversity and ecosystem function. Using taxonomic (species richness and variance) and functional diversity (functional richness and functional evenness) indices of the demersal fish assemblages in the shelf sea of Shandong Province, China, Li, Ma et al. (2022) revealed a significant relationship between biodiversity and ecosystem functioning (BEF) and the seasonality of BEF. These results highlight the importance in considering BEF and its seasonality in ecosystem-based fisheries management.

An example by Li, Wang et al. (2022) investigates the role of non-random assemblage processes in shaping the regional waterbird diversity in wetlands generated by underground coal mining in the North China plain. The authors combine taxonomic and functional β-diversity to show that non-random assemblage processes, for example, environmental filtering played an important role in structuring the waterbird communities in these wetlands and suggest that increasing habitat diversity should be applied for protecting waterbirds in subsidence wetlands.

Mapping spatial patterns of different dimensions of biodiversity can help identify areas of conservation concern. Ng et al. (2022) compiled a species-level phylogeny and trait (morphology, biomechanics, physiology, and reproduction) dataset and compared the phylogenetic diversity (PD) and functional diversity (FD) to perform spatial prioritization of reefs for coral reef protection. The results supported that the PD-maximizing strategy is a better approach in protecting the functional diversity of reef corals in data-deficient circumstances.

Due to limitations in time, funding, and natural history expertise, trait-based approaches to community ecology may be more tractable in many applications than taxonomy-focused approaches. For example, Sotomayor et al. (2022) collected macroinvertebrate samples from 22 locations within the Paute River Basin in Ecuador to investigate taxonomic resolutions using functional trait (rRao index) and cluster analyses using the K-means algorithm in the freshwater benthic macroinvertebrates in the South American. The results indicated that the family-level identification using the functional trait approach was suitable in assessing the macroinvertebrate community of these rivers.

5 | CONCLUSION

Aquatic systems are experiencing rapid changes in structure and function as a result of accelerating climate change and other human stressors. Testing the applicability and accuracy of trait-based approaches using both ecological and biological traits is crucial for evaluating and forecasting sensitivity across levels of organization, assessing risks, and mapping hotspots for biological conservation. This special issue addresses these fundamental questions from freshwater, intertidal, and marine systems using various biological and functional trait-based approaches. We hope these studies can shed light on the application of trait-based approaches for biodiversity and conservation.

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CONFLICT OF INTEREST

None declared.

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PEER REVIEW

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