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Cascading, interactive, and indirect effects of climate change on aquatic communities, habitats, and ecosystems

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Abstract

Climate-change is rapidly and intensively altering aquatic communities and habitats. While previous work has focused on direct effects of potential drivers, indirect and interactive effects on organisms and ecosystems have received less attention. Here, we give an overview of contributions to a special issue in *Limnology and Oceanography* that addresses this knowledge gap. Contributions covered diverse habitats, from polar to tropical regions, alpine streams to coral reefs. Several studies relied on time-series to identify indirect effects, thus emphasizing our need to maintain high-quality time-series data. Time-series are particularly crucial now that the pace of climate-change on aquatic-ecosystems is accelerating. Another common theme is the role of species-specific characteristics in physiology, behavior or genetics in aquatic ecosystem function. The addition of inter- and intra-specific variability to investigations of climate-change may be challenging particularly since ecosystem studies typically involve a large parameter space of environmental and biological variables across spatial and temporal scales. However, the results demonstrate that inclusion of species-specific dynamics, although challenging, can deliver mechanistic insights into aquatic ecosystem patterns and processes. Some contributions leverage habitat changes from disturbances or climate shifts to document capacity for resilience or recovery of pelagic and benthic communities. Jointly, the results in this special issue document fruitful approaches and provide urgent information needed for deciphering aquatic ecosystem responses to climate forcings. This information is foundational if we wish to tackle the combined effects of climate change and other human impacts with maximum efficacy and minimize unintended consequences for biodiversity and ecosystem functioning.

Motivation

Climate change is rapidly altering aquatic ecosystems on unprecedented scales. Climate-related environmental impacts altering freshwater and coastal habitats often exacerbate other human-induced stressors that negatively affect organisms and ecosystem function, such as urbanization, and persistent pollutants that have permeated the biosphere from freshwater systems to the deep sea. These impacts put species and ecosystems at risk and ultimately endanger humanity's intricate dependence on aquatic ecosystems. These threats also highlight the urgent need to gain mechanistic insights and to improve predictions of how climate change affects aquatic organisms, community structure, and ecosystem function, both now and in future conditions. However, quantifying and predicting the effects of climate change and other human impacts on aquatic organisms remains a major and pressing challenge. Insight into feedbacks and indirect and interactive effects have often been limited by data availability since

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quantifying heterogeneous and variable biotic and abiotic factors adequately is understandably restricted to major campaigns, long-term, and experimental research sites, and time series analyses. Moreover, studies must cover a broad range of scales and levels of organization, so that results can be meaningfully interpreted both in terms of the mechanistic underpinnings at the organismal level, and the resulting impacts at the community or ecosystem level. A multifaceted approach including modeling, controlled laboratory studies and long-term observations is needed with particular emphasis on unraveling nonlinear mechanisms and feedback loops. Such dedicated studies can disentangle the interactive and indirect effects that are essential to make viable predictions about future biodiversity, production rates, and other aspects of aquatic ecosystem structure and function on a changing planet. Parameterizing responses to climate stressors is foundational to predictions of the effects of future environmental conditions. Reduction of emissions of greenhouse gases is urgently needed to combat demonstrable harm of climate change. Additional interventions, including implementation of mitigation and adaptation strategies need to be data-driven and rely on fact-based decision making to avoid unintended consequences and exacerbating negative impacts on aquatic ecosystems and the communities that rely on them. Thus, the need for understanding climate impacts on aquatic ecosystems requires fundamental knowledge of indirect and interactive effects on aquatic communities, species diversity, production, and food web structure.

The goal of this special issue was to coalesce contributions that overcome the challenges of documenting interactive and indirect effects in diverse, heterogeneous, dynamic, and rapidly changing aquatic ecosystems. Our goal was to showcase contributions that document the nature of indirect and interactive effects in diverse habitats and communities, and moreover to highlight fruitful theoretical, experimental, and analytical approaches that can be applied to other habitats and communities. To achieve this goal, we welcomed contributions that investigate climate change effects from empirical research on individual species to whole communities, as well as modeling studies. In particular, we invited manuscripts reporting original hypothesis-driven, process-focused research that documented connections, feedback mechanisms, indirect effects, and linkages across trophic scales. This special issue includes a fascinating and diverse array of studies that provides factual information, inspiration, and guidance so we can collectively continue to make progress on understanding the impacts of climate change on aquatic ecosystems. The diversity of habitats covered highlights differences among freshwater, and marine habitats, that may require unique mitigation strategies. The complexity and scale of the impacts of climate change require that we apply our methodological, empirical, analytical, and theoretical prowess to the problem, so that management decisions and potential mitigation can occur in the most sustainable way.

A diverse array of contributions with common themes

It is a strength of this special issue to be representative of diverse habitats and scales, including alpine streams (Leathers et al. 2023), wetlands of the North American Great Plains (Hu et al. 2023), lakes (Hébert et al. 2023; Katkov and Fussmann 2023; Su et al. 2023), estuaries (Douglas et al. 2023; Franzè et al. 2023), tropical reefs (Lange et al. 2023), and the arctic ocean (Ramondenc et al. 2023), as well as diverse organisms, from single celled algal primary producers (Vrana et al. 2023) to top consumers such as right whales (Meyer-Gutbrod et al. 2023). Moreover, contributions cover ecologically and climate-relevant ranges of scales, including laboratory experimentation lasting days (Bomfim et al. 2023; Carrier-Bellau et al. 2023, Fields et al. 2023), mesocosm experiments of 1-month duration (Katkov & Fussmann 2023; Wang et al. 2023), as well as the paleorecord (Hu et al. 2023). Despite this diversity of habitats and scales, the contributions to the special issue reflect only a subset of breadth, approaches, and geographic coverage; several gaps in contributions of climate-oriented aquatic research are apparent. Importantly, many more contributions are needed to represent habitats and researchers from South America and Africa. To be truly global, data, insights and perspectives from all regions and diverse perspectives are urgently needed.

It is remarkable that despite the diversity in habitats and organisms covered, the contributing articles reflect two common themes that emerged as important in understanding climate change effects on aquatic habitats: the necessity of time series data and the importance of species-specific differences in physiology or ecology, even within the same genus. In terms of direct, indirect, and interacting effects, there may be a third commonality, in that several food web studies report direct effects on lower trophic levels that indirectly affect higher trophic levels.

The power of time series data and analysis

The first theme reflects the power but also vulnerabilities of time series in identifying climate change impacts. Aquatic habitats are dynamic systems subject to many sources of uncertainty. The challenge of unraveling the relative contributions of interactive and indirect effects on environmental or ecological processes in these systems may appear daunting. However, several contributions leveraged continuous and controlled time series observations to overcome this challenge. Analyzing variables in a spatially and temporally discrete manner helps understand their influence on ecosystem processes and biodiversity in varying contexts. Multidimensional analyses help to identify the extent to which variables influence ecosystem processes and biodiversity. Time series observations can identify correlations that can then motivate hypothesis driven experimental examination to identify causation. Additionally, multidimensional analyses contribute to a holistic understanding by considering the interconnectedness of ecosystems and the continuity of global water and elemental cycles.

Freshwater habitats from high mountain streams to Great Plains wetlands can reflect warming trends and changes in the hydrologic cycle. Several studies untangled the interactions between habitat complexity, interannual variability, and a myriad of other biotic and abiotic factors through time series analyses. Leathers et al. (2023) studied the complex and scale-dependent, land-water connections that regulate water temperature change along high-elevation stream networks, which support a diversity of thermally sensitive species. The cascading effects of upstream water warming were propagated downstream, and changed water and habitat quality. In this spatially complex habitat with many interacting properties, temporally resolved analyses allowed the identification of periods of particularly impactful warming. This type of information should guide future management and observational efforts.

Digging into the paleorecord through sediment cores paired with isotope signals, Hu et al. (2023) document that climate impacts on wetlands of the northern Great Plains were unprecedented in over a hundred years. Changes in the community and productivity of primary producers can affect the suitability of this habitat for higher trophic levels, including migrating waterfowl. The observed interactive and indirect effects indicated the unique impact that recent changes in precipitation patterns had on primary production. This result from a wetland is not unlike the impacts of changes in precipitation on estuarine primary producers documented by Douglas et al. (2023). Here, the transition from dry to wet precipitation patterns over a decade elicited an increase in primary production and a shift in the dominant phytoplankton. While it was suggested that observed changes may be connected to the El Niño and the Southern Oscillation climate oscillation, the stochastic nature of the forcing, and changes in seasonal cycles (which were more pronounced in the wet period) further indicate the need for longer-term datasets. In the northern Great Plains wetlands, a recent increase in production of the potent greenhouse gas methane was inferred from changes in benthic and pelagic communities and their trophic interactions (Hu et al. 2023). The identification of the emergence of a new type of wetland habitat by Hu et al. (2023) and the hypotheses generated by the repeat observations by Douglas et al. (2023) highlight the opportunities continuous studies provide for understanding our biosphere, support discovery of new patterns and processes, and possibly help to develop safer and more powerful mitigation strategies.

The power of time series and the complexity of interactions was also evident in a long-term study of heavily utilized subtropical lakes of the Yangtze floodplain. Su et al. (2023) identified impacts on water quality from nutrient concentrations, carp stocking, and phytoplankton abundance. Water clarity reflects particle concentration and affects light availability to planktonic primary producers and benthic epifauna, and thus is often used as a proxy for water quality. A large data set from over 100 lakes helped identify that deterioration in water clarity could not be attributed to increases in macronutrient loading, though eutrophication is certainly an issue. Instead, analysis of two lakes with longer-term and more detailed records, attributed deterioration in water clarity to both climate-related warming and sediment resuspension induced by swimming motions of introduced aquaculture fish. As frequently observed during warming events (e.g., Finkel et al. 2010; Marañón 2015), the cell size of phytoplankton decreased over time. Eutrophication can alleviate nutrient limitation, especially to diffusion-limited larger phytoplankton, while warming can enhance rates of nutrient uptake and drive phytoplankton communities into earlier nutrient limitations. Shifts to smaller species that are superior competitors for nutrient uptake can exacerbate these trends. Remarkably, while the relative contribution of fish, nutrients and climate indicators in the Yangtze flood plain had proportionally similar effects on water quality, the interactive effects differed between the two lakes (Su et al. 2023). Fish stocking had a negative effect on water quality in both lakes, but the effect was exacerbated by nutrients in one lake and warming in the other lake. Disentangling the individual effects of human-induced impacts on lake water quality emphasizes that site-specific responses indicate additional mechanisms may be at play. Thus, accounting for spatial differences may support effectiveness of management tools, such as reduction of nutrient inputs.

By focusing on freshwater clarity as an indicator of water quality, Hébert et al. (2023) used a hypothesis-driven approach to explore how experimental manipulations of dissolved organic matter (DOM), nutrients, and temperature affected freshwater lake communities and trophic transfer. Remarkably, while stocks, including biomass of organisms did change in response to DOM addition, metabolic rates, including rates of primary production and respiration changed to a lesser degree, suggesting the existence of compensatory mechanisms that maintain metabolic activity. Effects that were additive, rather than indirect or interactive dominated the magnitudes of change in the response variables. As commonly observed in the studies included in this special issue (see below), responses depended on taxonomy, with some groups (e.g., bacteria) benefitting from warming, whereas others did not seem to be affected. Remarkably, trophic structure seemed most affected by metabolic processes such as the trophic transfer efficiency. The study by Hébert et al. (2023) supports the common observation that increasing DOM loads in freshwater lakes can exacerbate impacts of other co-occurring factors, such as browning and warming. Remarkably communities as well as food web structure and function are sensitive to even small increases in DOM load. Katkov and Fussmann (2023) used a mesocosm study motivated by longer-term observations to identify that CO_2 and temperature manipulations had mostly direct effects on lake phytoplankton and zooplankton communities, although these authors did not identify strong interactions between the two forcing factors. Interestingly, initial fertilization effects of green algae by CO_2 reversed with time. Such time-dependent transitions highlight the benefit of longer observation periods. The lack of interactive effects in the study by Katkov and Fussman (2023) contrasts with other studies, in which antagonistic, interactive effects were observed. For example, effects of temperature and nutrients on phytoplankton community composition (Anderson et al. 2022) affected predation by single-celled herbivores in a coastal food web; whereby, higher nutrient concentrations reduced grazing rates and trophic transfer with ramifications for secondary production (Franzè et al. 2023).

As is evident in some contributions to this special issue, despite often dizzying amounts of data, involving 100 s of sites or decades of observations, numerous challenges such as periods of data loss nonetheless still limit data interpretability. These vulnerabilities emphasize the need for long-term, secure, and dedicated support for time series that protect the observations and maximize utility for the long term. Moreover, new insights can require post-hoc analyses that might not be anticipated at the inception of time series and the design of the measurement suite. The potential for unforeseen results argues for including broad scopes of parameters and generosity on the part of funders and reviewers when measurements of "luxury" parameters are proposed. As to be expected, funding cycles, instrument failure, logistical constraints, and shifting priorities among institutions result in threats to data coverage and continuity. Future efforts, including instrument development, require a renewed focus on biological information. It is unfortunate that while many chemical and physical parameters can be measured autonomously and with high precision, less than a handful of biologically relevant metrics are routinely measured. Investment in cutting-edge and emerging technologies, such as in-situ image analysis, can make strides toward inclusion of ecologically and organismal information. Amending time series with targeted experiments can illuminate principal interactions and causation that cannot be resolved by correlational analyses alone.

Critical sources of information that need to be elevated are the perspectives and knowledge of indigenous voices that have long term observational records and environmental stewardship. Examples include the recent report that oral traditions of the people from the Swahili coast resolved long-standing questions about the origins of its people (Brielle et al. 2023); and key insights into aquatic systems obtained from mātauranga Māori (encompassing not only Māori knowledge, but also Māori culture, values and worldview; Hikuroa 2017), which have led to sustainable management practices across both freshwater (Kusabs and Quinn 2009) and marine environments (Paul-Burke et al. 2018).

Biological details matter

The second common theme in this special issue was the critical role of biological characteristics, such as species identity, and diversity in physiology and ecology in uncovering drivers of ecological processes. One contribution identified how species-specific differences reflected differences in coral reef capacity to recover and accrete carbon after a bleaching event (Lange et al. 2023). Another showed the significance of pod identity in explaining behavioral differences among subgroups of right whales (Meyer-Gutbrod et al. 2023). Even different life cycle stages of the same species responded uniquely to environmental drivers. Fields et al. (2023) found differences in copepod responses at different developmental stages when subject to manipulated temperature and pCO_2 treatments. These life-stage specific differences have direct implications for the nutritional value of these zooplankton to higher trophic levels. To link species-specific responses to community-level impacts, several studies employed hypothesis-driven laboratory experiments and directed manipulations of communities in natural settings. This approach augments repeat observation and time series studies as experimentation can deliver important information to disentangling causality, and the relative roles of direct, indirect, and interactive effects. Unmanipulated systems may never display the range of conditions necessary to identify causality and parameterize algorithms. Moreover, observations alone might not feature co-occurrence of factors. Similarly, observations may not encompass a sufficient gradient of forcing conditions, which is often required to establish quantitative relationships and develop predictive algorithms. Going forward, pairing ecological theory with experimental examination of that theory can further elevate purely observational studies.

Laboratory-focused studies demonstrated how hypothesis-driven experimentation on organisms can help discern causative relationships. Carrier-Belleau et al. (2023) contribute to the much-needed disentangling of multiple stressor effects on organismal responses and trophic interactions and the resulting impacts on the ecosystem. Their study manipulated the nature, magnitude and combination of potential stressors through the application of gradients in environmental factors. While direct effects on microbial activity and chlorophyll *a* concentration dominated, the study of multiple stressors was necessary to elicit changes in metabolic activity of multicellular, freshwater zooplankton (*Daphnia polymorpha*). In climate-change impact studies, the need to include stressor gradients is particularly urgent to examine quantitative dose response relationships, as well as quantify nonlinear effects and response thresholds. The results allowed Carrier-Belleau et al. (2023) to recommend management strategies that avoid osmotic stress for *Daphnia* due to saltwater intrusions as a particularly impactful stressor. Focusing on the same genus, but very different questions, Bomfim et al. (2023) disentangled a matrix of factors including species-specific differences, predation, competition and temperature. Their study emphasized the need to go beyond mono-specific investigations. A key result was that adaptive advantages of the largest sized zooplankter (*Daphnia magna*) that dominated in experiments without fish predation were rapidly eviscerated by predator preference for the largest zooplankton and greater sensitivity to warming. Vrana et al. (2023) paired the power of long (32-yr) time series with targeted laboratory investigations and discovered that physiological tolerance to warming temperatures (Mediterranean summer time temperatures can exceed 30°C), coupled with shifts in biosynthesis of lipids and pigments likely explain the shifting abundance and species composition patterns of phytoplankton communities. Changes in community composition and elemental composition have substantial ramifications for the suitability of phytoplankton as prey and could alter the role of phytoplankton in biogeochemical cycling. It is true for the study by Vrana et al. (2023), and many studies in this special issue, that changes in prey characteristics have higher-order implications for trophic transfer and need to be considered in an interactive manner, thus increasing levels of complexity. These higher-order effects can be seen, for example, in the change in right whale migration patterns in response to redistributions of their zooplankton prey (Meyer-Gutbrod et al. 2023).

Indirect effects were also considered in the Artic mesocosm study by Wang et al. (2023) who examined pCO_2 effects on gene expression in marine microbes, bridging the gap from genes to ecosystem function. They explored potential effects of future pCO_2 states and the resulting ocean acidification by examining the responses of functional gene structure and diversity in bacterioplankton to elevated pCO_2. Through the use of gene analyses techniques, their experiment revealed that elevated pCO_2 promoted increased abundances and higher evenness in genes involved in metabolic processes. Such adjustments could imply alterations in biogeochemical cycling mediated by these microbes. Changes in gene function contrasted with generally similar bacterioplankton abundances across treatments, suggesting that despite consistency in bacterial biomass, underlying functionality can yet differ.

Two studies, also from the Atlantic, particularly exemplify how species-specific responses can empower understanding across scales and trophic levels. Fields et al. (2023) asked how the direct and interactive effects of potential climate stressors on different life stages of crustacean zooplankton altered vital rates and growth potential. In their two-factor study, temperature and pCO_2 had opposite effects. While warmer temperatures reduced growth and buildup of energetic reserves in the zooplankton, the converse occurred with increases in pCO_2.. Thus, zooplankton reared at elevated pCO_2 and lower temperatures held the greatest nutritional value for higher trophic levels. As highlighted above, such shifts in nutritional value have significant consequences for top predators and can even affect their migration and distribution patterns (Meyer-Gutbrod et al. 2023). Knowledge of changes in carbonate chemistry and sea surface temperatures, particularly in the rapidly warming Northwest Atlantic, along with details of the foraging habitat of right whales elucidated by Meyer-Gutbrod et al. (2023), can be combined with the insights gained by Fields et al. (2023) to anticipate future changes to the prey quantity and quality for right whales. The coastal region of the Northeast United States has one of the fastest rates of warming observed globally, along with substantive changes to biodiversity (Thomas et al. 2017; Blowes et al. 2019). Moreover, the northwest Atlantic has been subject to continuous human utilization including shipping and transportation and, more recently, the establishment (and soon to be significant expansion) of the first offshore wind farm in the United States. Right whales are charismatic and highly endangered residents of this area. In their contribution, Meyer-Gutbrod et al. (2023) utilized two decades of right whale sightings to reveal a northeastward shift in whale distributions. These shifts in whale migration patterns were linked to shifts in zooplankton prey distributions. Knowledge of these migration patterns are necessary for the management of ship traffic, with vessel strikes a major cause of mortality for right whales. On the other hand, misplacing imposed speed reduction zones can unnecessarily delay transportation and limit supply chains, while being ineffective in protecting right whales. The data analyzed by Meyer-Gutbrod et al. (2023) provide insights into the migratory patterns, that is, the when, where, and why right whales are found in specific areas. The results also reveal consistencies between years, such as the destination, though not timing, of reproductive migrations that utilize the same calving grounds irrespective of habitat changes. This type of information is key to setting priorities in habitat management to maximize whale protection that is urgently needed now.

While many studies in this special issue examined the effect of ongoing and persistent climate impacts, Lange et al. (2023) were able to document the effects and subsequent recovery of a coral reef after a short-term disturbance event through bleaching. Species-specificity, repeat observations and carbon budgets were necessary to unravel how bleaching affects coral reefs and their capacity to recover. Encouragingly, all sites were able to recover after bleaching. Crucially, species-specific differences along with habitat quality played a key role in the rate and magnitude of recovery. Interestingly, variance among sampling sites increased over time, indicating differences in recovery capacity and stressing the need for long-term observations. The results of Lange et al. (2023) emphasizing species-specific differences in responses parallel the findings of several other studies documenting species-specific physiology and behavior in zooplankton, including Bomfim et al. (2023), Carrier-Belleau et al. (2023), Ramondenc et al. (2023), and Fields et al. (2023), documenting zooplankton species specific physiology and ecology. Similarly, Meyer-Gutbrod et al. (2023) showed that right whale pod identity is critically important, and Su et al. (2023) concluded that location and species were critical to the differential results in their aquaculture lake study. Biological details do matter. They are expensive to document but we need to do so if our conservation and sustainability efforts are to be successful.

The influence of biological characteristics was also evident in the food web study by Franzè et al. (2023) who measured the impacts of concurrent temperature increases and nutrient additions on herbivorous grazing rates in an Arctic-origin plankton community in the Northwest Atlantic. Franzè et al. (2023) show that nutrient and temperature manipulation had an antagonistic, interactive effect on grazing rate that depended on the relative magnitude of both factors. While temperature effects dominated, both treatments elicited shifts in predator and prey community composition, and changes in grazing rate. Such alterations of trophic transfer can shift the fate of primary production, from higher trophic levels in pelagic to benthic organisms, or to microbial consumers or sequestration. Disentangling these interactive effects facilitates quantifying the relative contributions of and management opportunities for addressing eutrophication. In this study, only by studying predator and prey species composition and metabolic rates in conjunction could interactive and indirect effects be identified.

Ramondenc et al. (2023) investigated the importance of species with observations, in remote and inaccessible Arctic waters through a 16-year time series of zooplankton abundance. Their data allowed identification of the relative influences of seasonal forcing factors, interannual variability, and for some continuously measured variables, longer-term patterns. Ramondenc et al. (2023) show that remote and logistically challenging areas can be fruitfully studied with autonomous instrumentation and long-term deployments, although the remoteness obviously limits accessibility when instrument failures occur. Utilizing sediment trap data, Ramondenc et al. (2023) identified two climatic indices as drivers of zooplankton abundance: the North Atlantic and Atlantic Meridional Oscillations. Through their repeat observations it was possible to identify the coverage and spatial characteristics of sea ice as major forcing factors in zooplankton abundance. Additionally, taxonomy and species-specific migratory behavior played a key role. The results provide critical insights into how future trends in forcing can interact with behavioral responses, and biogeochemical cycling. In a continuously warming ocean, changes in sea ice coverage in polar regions, further intrusion of warmer water, and the potential contributions of different zooplankton taxa to trophic transfer, are all likely contributors to changes in biogeochemical cycling and the biological carbon pump.

Perspective

Contributions to this special issue uncovered many fascinating aspects of climate change impacts on aquatic organisms, their communities, and ecosystem functions. The results also stress how much more we need to know, and the value of combining analytical, experimental, and observational approaches to move forward. Although submissions to a special issue are not representative of community effort, it is noteworthy that many aquatic habitats are not represented here, including the open ocean, although open ocean observational capacity is well established and critically important (Benway et al. 2019). Collectively, results from this special issue clearly mandate that investigations be carried out across broad spatial and temporal scales, from smaller scales relevant to individual organisms to the larger scales needed to examine ecosystem properties. A number of indirect effects were documented, which were only uncovered by multi-factorial investigations. Hypothesis-driven experimentation, motivated by long-term observations, expanded the dynamic range of conditions investigated in several studies and illuminated mechanisms. Such an approach may prove exemplary and vital as we tackle the urgent need for fundamental understanding of climate change effects on aquatic ecosystems, even while the environmental drivers and habitats are rapidly changing. The types of analyses reflected in this special issue provide useful guidance for the study of climate change impacts on aquatic habitats and offer many examples of analyses approaches, which can be applied to other habitats and ecosystems. At the same time, experimental design and observational efforts showcased by these special issue contributions can inform ongoing efforts to work toward intercomparability of time series data and identify larger-scale effects, for example, linking to climate indices. The variety of indirect and interacting effects and the number of discoveries of the contributions to this special issue suggest that such effects are a fertile research area that satisfies critical and time sensitive needs for future study, especially in light of demonstrable impacts of climate change on aquatic habitat structure and function. The power and need for time series was clearly evident in many studies making the maintenance of these continuous observational efforts imperative. The common and recurring theme of the influences of the physiology, ecology, and behavior of individual species is a clear directive to undertake organismal studies in efforts aimed at understanding climate change effects on biological communities and their function.

Data availability statement

This article does not use original data.

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Conflict of Interest

None declared

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