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Editorial

Aquatic Carbon Dynamics in a Time of Global Change

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Inland waters are globally significant sites of carbon cycling. They emit high quantities of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) to the atmosphere [1], while simultaneously burying organic carbon at a bulk global rate that is comparable to that of our planet's oceans, despite occupying only a fraction of the surface area [2]. In addition to the intensive processing of imported terrestrial carbon [3], inland waters can also be important sites of primary production, altogether supporting wildlife and human needs around the world. However, global changes currently underway pose multiple potential threats to inland waters. The effect of cultural eutrophication on inland waters continues to be an active and complex area of study [4], and in many ways is compounded by the concurrent multiple effects of climate change on lakes [5]. In addition, new frontiers of research into human impacts on inland waters are continuing to expand, including investigations into the impacts of salt pollution [6], artificial light at night [7], and microplastics [8]. Multiple lines of evidence from around the world point to recent large-scale shifts in patterns of aquatic carbon cycling, whether considering increasing alkalinity [9], changes in greenhouse gas emissions [10], increasing concentrations of dissolved organic carbon (DOC) [11], or shifts in primary production [12]. While evidence mounts of large-scale changes in aquatic system carbon cycling, additional research efforts are being made to identify and close the remaining gaps in our understanding of aquatic systems. These include geographical gaps [13], temporal gaps, whether considering daytime [14] or ice-free season [15] sampling biases, and habitat gaps, considering better integration of the benthic process [16] or carbon cycling in desiccated environments [17]. This Special Issue of *Water*, "The Impacts of Environmental Stressors on Carbon Dynamics in the Aquatic System", was organized with the intent of helping to synthesize and contribute to the closing of some of these gaps in our understanding of how aquatic systems are responding to global change. The articles published in the Special Issue were ultimately successful in this regard, spanning multiple continents and providing new, valuable insights to guide future research efforts in aquatic carbon cycling.

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The largest-scale global patterns in aquatic carbon cycling processes are typically driven by biogeochemical interactions occurring at the microbial scale, so much work in the field attempts to bridge these extremes. In this Special Issue, Sayers et al. [18] use data from satellite remote sensing to calculate trends in phytoplankton primary production rates in eleven of the world's largest lakes (spanning North America, Asia, and Africa) from 2003 to 2018. They provide a methodologically standardized analysis of the majority of the world's available surface freshwater, indicating that climate change, by increasing water temperatures and solar radiation and decreasing wind speeds, can alter patterns in phytoplankton primary production. Khan et al. [19] also adopt a relatively larger-scale approach, comparing four European lakes (in Spain and Estonia) to investigate how eutrophication influences calcite precipitation in lakes. They find that the ratio between calcification and net ecosystem production (NEP) is a powerful predictor of calcite saturation in lakes, indicating that eutrophication may influence lake carbon cycling (and CO_2 fluxes) through its effects on calcite precipitation, particularly in highly alkaline lakes. Considering smaller-scale processes, Fiskal et al. [20] investigate the effects of re-oxygenation and recolonizing macroinvertebrates (associated broadly with lake restoration efforts) on the microbial communities of anoxic sediments from Lake Zurich (Switzerland). Adopting realistic macroinvertebrate population densities and compositions (including both chironomids and tubificid worms) in their controlled 3-month long experiments, they find that the effects of sediment oxygenation strongly surpass the additional (but measurable) effect of recolonizing macroinvertebrates on sediment surface microbial communities. Additionally, at the smaller scale, Page et al. [21] measure the rates of primary production in filamentous algae blooms (FABs) and non-blooming periphyton (attached algae) communities in Bear Lake (Utah/Idaho, USA). They find that large-biomass periphyton communities are significantly less productive than faster-growing low-biomass communities. They furthermore investigate potential causes of the FABs in Bear Lake, identifying climate change, invasive species, and eutrophication as all potentially interacting drivers.

The articles in this Special Issue also help emphasize the importance of under-studied regions or system-types in broad-scale analyses of how aquatic carbon cycling might be impacted by global change. Sayers et al. [18], described above, show that responses of large lakes to climate change are not uniform around the world; two lakes (Great Bear Lake and Great Slave Lake, Canada) featured increasing phytoplankton production, one lake (Lake Tanganyika, Tanzania/Democratic Republic of the Congo/Burundi/Zambia) featured decreasing phytoplankton production, and the remaining eight lakes investigated featured no significant change over time. Thus, given that the environmental stressors associated with global change are varied around the world, it is necessary to account for multiple co-occurring trajectories for aquatic carbon cycles as well. Khan et al. [19], also described above, emphasizes the importance of considering alkaline systems in broad-scale assessments of carbon cycling in lakes, as they represent the majority of the world's lake surface area and yet remain frequently overlooked and understudied. Another article in this Special Issue, Chan et al. [22], reports aquatic CO_2 and CH_4 emissions from reservoirs and rivers in the Kuye River Basin (China). Within this catchment, they find that greenhouse gas (GHG) emissions from reservoirs were dominated by CH_4, compared to CO_2-dominated emissions from rivers, though overall emissions were significantly higher from rivers than reservoirs. This work thus highlights how the construction of reservoirs can change landscape-level GHG emissions to the atmosphere. As this work was carried out in an under-studied arid region of China, the article also features a detailed comparison of how these measured GHG emissions compare to what has been reported from other systems around the world.

Finally, the review paper by Olofsson et al. [23] in this Special Issue criticizes the common approach of inferring the functional importance of an aquatic constituent based solely on its prevalence in a system. Specifically, they argue that low concentrations of some aquatic "cryptic" constituents (for instance, DOC, periphyton, ammonium, or nitrite) can signal high turnover rates or uptake by aquatic food webs. They argue that future studies should account for this possibility through the adoption of tracer methods and mass balance calculations.

The full scope of global changes occurring today goes well beyond the scope of studies included in this Special Issue. However, these articles each provide valuable information for helping us understand the response of aquatic environments to global change. Together, they remind us that inland aquatic carbon cycling is being modulated by climate change [18,21], eutrophication [19,21], and watershed transformations [22], including new restoration efforts [20]. We are also reminded that some of the most important drivers of ecosystem functioning and carbon cycling may be largely invisible [23], highlighting the necessity of understanding detailed ecosystem processes when predicting and interpreting how aquatic systems respond to global change. Altogether, these articles provide insights that are relevant and potentially valuable both to researchers investigating global-scale patterns in aquatic carbon cycling, as well as practitioners focused on managing or restoring specific local aquatic systems. Although these articles show us how variable the responses of aquatic carbon cycling are to environmental stressors, they also highlight that this remains an important area of future research in the face of ongoing global change.

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