Glacial ecosystems are essential to understanding biodiversity responses to glacier retreat

Marek Stibal[1], James A. Bradley[2], Arwyn Edwards[3], Scott Hotaling[4], Krzysztof Zawierucha[5], Jørgen Rosvold[6], Stefanie Lutz[7], Karen A. Cameron[3], Jill A. Mikucki[8], Tyler J. Kohler[9], Marie Šabacká[10], Alexandre M. Anesio[11]

[1]*Department of Ecology, Faculty of Science, Charles University, Prague, Czechia*
[2]*School of Geography, Queen Mary University of London, UK*
[3]*Institute of Biological, Rural and Environmental Sciences, Aberystwyth University, UK*
[4]*School of Biological Sciences, Washington State University, Pullman, WA, USA*
[5]*Department of Animal Taxonomy and Ecology, Faculty of Biology, Adam Mickiewicz University, Poznań, Poland*
[6]*Department of Terrestrial Biodiversity, Norwegian Institute for Nature Research, Trondheim, Norway*
[7]*Agroscope, Molecular Diagnostics, Genomics and Bioinformatics and Swiss Institute of Bioinformatics, Wädenswil, Switzerland*
[8]*Department of Microbiology, University of Tennessee, Knoxville, TN, USA*
[9]*Stream Biofilm and Ecosystem Research Laboratory, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Switzerland*
[10]*Centre for Polar Ecology, Faculty of Science, University of South Bohemia, České Budějovice, Czechia*
[11]*Department of Environmental Science, Aarhus University, Roskilde, Denmark*

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The widespread shrinking and retreat of glaciers and ice sheets drive changes in the biodiversity associated with glacial and glacier-adjacent environments. In a recent meta-analysis of global biodiversity responses to deglaciation, Cauvy-Fraunié and Dangles (1) carefully compiled hundreds of primary studies and presented a compelling analysis of global biodiversity responses to deglaciation. They found increases in the abundance and richness of 'generalist' taxa in glacier-adjacent habitats, as well as a decline in 'specialists', following glacier retreat, and concluded that biodiversity increases locally as glaciers recede. Glaciers themselves were largely considered as abiotic agents, affecting downstream moisture, temperature, and salinity, and their intrinsic biodiversity ignored, while only glacier-adjacent habitats (tidewater glacier fjords, glacier-fed freshwaters, and glacier forefields) were reported for their changes in biodiversity. However, it is now widely accepted that glaciers and ice sheets comprise unique habitats that host distinctive organisms and metabolically active populations that form communities, and facilitate key connections to neighbouring ecosystems (2), all of which may be severely altered, reduced, or lost upon deglaciation (3). **The lack of data on glacial ecosystems in a global synthesis of biodiversity responses to glacier retreat is a warning sign that the biodiversity of glacial habitats is still largely unquantified, overlooked by the broader ecology community, and likely underestimated**. This is especially worrisome given the magnitude of glacial habitat loss anticipated this century.

The **supraglacial ecosystem** at the surface of glaciers and ice sheets comprises several important habitats (4). The upper ice layer is dominated by a group of true glacier specialists – glacier algae. These unique photoautotrophs orchestrate ecosystem processes that have far-reaching implications in the cryosphere, for instance the accumulation of photosynthetically-derived autochthonous organic carbon, which sustains a range of heterotrophic glacial microorganisms (5). Another biological hotspot on glacier surfaces are cryoconite holes, cylindrical depressions formed by the preferential melting of dark debris into the surface (6). Cryoconite holes serve as oases of stability in the otherwise highly dynamic supraglacial environment, and their complex communities consist of microorganisms including bacteria, archaea, algae, and fungi, as well as rotifers, tardigrades, annelids, insects, and crustaceans (7). Furthermore, glaciers are vital part-time habitats for many alpine invertebrates, birds and mammals, some of which forage on other glacier inhabitants or wind-blown material (8). For instance, the Gray-crowned Rosy Finch, the highest-elevation nesting bird in North America, feeds heavily on glacier ice worms while brooding its young (9). Therefore, the supraglacial ecosystem should not be ignored when assessing biodiversity responses to glacial retreat.

The **subglacial ecosystem** at the base of glaciers and ice sheets provides habitats for a wide range of taxonomically and functionally diverse, mostly prokaryotic, microorganisms, capable of metabolising a wide variety of substrates under a range of redox conditions (10). Because sunlight cannot penetrate thick glacier ice, these communities rely primarily on chemical energy derived from the underlying bedrock. The subglacial realm also hosts unique, isolated aquatic habitats, including subglacial lakes and marine brine pools (11,12). These systems are home to thousands of microbial taxa and given their isolation, likely support unique, undescribed species. For example, the subglacial Antarctic Lake Whillans contained representatives of several thousand unique microbial taxa (11). The true breadth of prokaryotic diversity in subglacial ecosystems, however, is virtually unknown.

Temperate and tropical glacier ecosystems are particularly vulnerable, with climate change forcing their rapid retreat and imminent disappearance (13,14). This poses grave ecological concern given our profoundly limited knowledge of their biodiversity, which includes many endemic taxa (15). In a recent synthesis, Zawierucha and Shain (13) concluded that our only option for conserving temperate and tropical glacier biota may be within culture collections, given the impossibility of habitat restoration. Urgent acknowledgement of the impacts of climate warming on these vulnerable but enigmatic ecosystems, and subsequently on regional and global biodiversity, is therefore essential.

As suggested by Cauvy-Fraunié and Dangles (1), upon deglaciation glacial ecosystems will likely be replaced by more diverse non-glacial systems. However, true glacier specialists will disappear, thus negatively impacting total biodiversity at regional scales. Moreover, the shared sensitivity of glacial and glacier-affected biodiversity to climate warming, as well as the interactions between glacial and glacier-adjacent ecosystems means these environments cannot be disentangled and, when possible, should not be considered in isolation. Given the vast, irreversible threat to glacial biodiversity on global scales, we urge the research community to not overlook glacial biodiversity and advocate for an integrative view of ecological changes in glaciated regions. **Thus, we contend that a global synthesis of biodiversity responses to glacier retreat must include glacial ecosystems.**

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