



# Glacial ecosystems are essential to understanding biodiversity responses to glacier retreat

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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<sup>1</sup> 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<sup>2</sup>, all of which may be severely altered, reduced or lost following deglaciation<sup>3</sup>. 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 probably 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<sup>4</sup>. 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<sup>5</sup>). Another biological hotspot on glacier surfaces is cryoconite holes, cylindrical depressions formed by the preferential melting of dark debris into the surface<sup>6</sup>. 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<sup>7</sup>. 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<sup>8</sup>. For instance, the grey-crowned rosy finch, the highest-elevation-nesting bird in North America, feeds heavily on glacier ice worms while brooding its young<sup>9</sup>. 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 metabolizing a wide variety of substrates under a range of redox conditions<sup>10</sup>. As 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<sup>11,12</sup>. These systems are home to thousands of microbial taxa and given their isolation, probably support unique, undescribed species. For example, the subglacial Antarctic Lake Whillans contained representatives of several thousand unique microbial taxa<sup>11</sup>. 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<sup>13,14</sup>. This poses grave ecological concern given our profoundly limited knowledge of their biodiversity, which includes many endemic taxa<sup>15</sup>. In a recent synthesis, Zawierucha and Shain<sup>14</sup> 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<sup>1</sup>, following deglaciation glacial ecosystems will probably be replaced by more diverse non-glacial systems. However, true glacier specialists will disappear, thus negatively impacting total biodiversity at regional scales.

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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 that 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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## Author contributions

M. Stibal, J.A.B. and A.E. conceived of the manuscript and wrote the original draft. All authors contributed to revisions and approved the final version.

## Competing interests

The authors declare no competing interests.

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