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Editorial: Microbiology of the Rapidly Changing Polar Environments

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Editorial on the Research Topic

Microbiology of the Rapidly Changing Polar Environments

Polar environments are warming at alarming rates (Tingley and Huybers, 2013; Schmidtko et al., 2014). The rapid warming is a threat to the integrity of these ice-influenced ecosystems, where microbes are the dominant life form (Boetius et al., 2015; Cavicchioli, 2015; Pedros-Alio et al., 2015; Mohit et al., 2017). Polar regions play a crucial role in regulating the climate system, and have acted as an anthropogenic CO_2 sink due to combinations of low temperatures and high gas solubility, high winds, extensive winter sea ice cover, and intense biological productivity (Arrigo et al., 2008; Bates and Mathis, 2009). Despite being geographically distant, the Arctic and the Antarctic aquatic ecosystems have much in common. Both regions are subjected to harsh environmental conditions such as low temperatures and darkness in winter, extreme seasonal shifts in solar radiation, high UV exposure in summer, and seasonal changes in ice cover on both lakes and seas. In spite of this apparent inhospitality, polar aquatic ecosystems host diverse and active microbial communities that drive biogeochemical cycles and support higher trophic levels (Cavicchioli, 2015; Pedros-Alio et al., 2015). Since polar regions are more strongly impacted by global change (Yoshimori et al., 2017) than temperate regions, there is an urgent need to understand how these perturbations will affect microbial functions and major elemental cycles, including carbon. Marine and freshwater high-latitude aquatic environments offer an ideal variety of habitats to investigate changes in the community composition and functionality of aquatic microbes, who may be true sentinels of global change. The microbiology across many habitats in these vulnerable ecosystems are the subject of this special topic in Frontiers in Marine Science and Microbiology (Aquatic Microbiology).

The goal of this topic was to bring together contributions that provide a "bi-polar view" of aquatic microbiology. The range of contributions highlights both similar and distinct microbial processes that take place within the two high-latitude extreme environments. This research topic touches upon a wide range of interests to polar microbiologists, and provides a collection of 20 articles, including: a review, *in situ* observations, experiments, technical notes and modeling studies. While most of the articles focus on the response of bacterial communities to environmental changes, several look into the response of microbial eukaryotes, and others take a more biogeochemical approach that includes examining carbon and nutrient dynamics. Finally, we are proud of the high contribution by women to this research topic (the four scientific editors, 75% of first authors, 47% of all authors, 32% of reviewers), which highlights the important contribution of women to polar science in general and microbial ecology in particular.

In contrast to lower latitude regions, annual pelagic primary production in polar ecosystems is constrained by relatively short summers. It is during this brief summer period that light conditions are favorable for the phytoplankton growth, but this only can occur if nutrients are available. Recently, earlier spring-retreat of sea ice, along with the decrease in seasonal sea ice cover especially in the Arctic has led to increased light availability, which could increase primary production. However, increased stratification from meltwater may result in decreased nutrient supply to the euphotic zone. Earlier studies suggested that meltwater itself can sometimes increase nutrient supply to the phytoplankton in the Southern Ocean, and that higher winds across the open water in the Arctic could promote fall blooms. Such changes in phytoplankton phenology could have a cascading effect on other biological activities, potentially perturbing the polar carbon cycle. In this special topic, the review by Deppeler and Davidson concluded that long-term changes in Antarctic phytoplankton dynamics will depend on the magnitude and timing of the climate change induced stressors. In the Arctic, Meshram et al. show that under-ice bloom composition is related to both water mass mixing and local processes. Warming also influences melt water inputs and water column stratification, governing bloom intensities and composition, as reported by van De Poll et al. Current and future environmental changes may shift dominant phytoplankton groups toward smaller species (Paulsen et al.; Onda et al.; Vernet et al.). As changes in the relative size of the dominant primary producers appears to favor small mixotrophic species, tools to assess their trophic interactions and carbon fluxes should be developed. The need to establish baselines was raised by Metfies et al. who propose exploiting preserved sediment trap samples using molecular markers to increase the length of records and facilitate comparisons to more recent data. Looking toward future trends, Vernet et al. used a modeling approach to suggest that community changes could be neutral and perhaps may not impact carbon export budgets.

In polar aquatic ecosystems, the seasonal dynamics of heterotrophic microbial communities are coupled with phytoplankton blooms that produce pulses of labile organic matter. As part of this research topic, several studies report bacterial responses to seasonal and inter-annual variability. Around the western Antarctic Peninsula, seasonal variation in bacterial activities and communities indicate strong coupling with phytoplankton blooms (Kim and Ducklow; Luria et al.). But bacterial heterotrophic production, key to food web functioning, may be fueled by additional sources of carbon (Kim and Ducklow). In the Arctic Svalbard Archipelago, epipelagic microbial communities are also tightly coupled to phytoplankton blooms while seasonal variations do not appear to affect mesopelagic communities (Wilson et al.). Community changes following seasonal ice cover variability were also observed in epishelf and inland lakes where climate change may have major impacts on biogeochemical cycles (Schütte et al.; Thaler et al.). Similar seasonal responses are also observed in alpine glacier ecosystems (Chen et al.). The studies mentioned above, suggest that polar and cold climate microbial communities should be closely monitored as means to anticipate future effects and potential feedback loops on polar ecosystem functioning.

Shifts in heterotrophic microbial communities may also reflect specific community capacities to use seasonal pulses of resources, such as organic carbon and iron, and induce microbial interactions (Fourquez et al.). Vaqué et al. demonstrated that viral infection is more sensitive to climate change and warming compared to grazing, implying that not only variation in community composition and activity, but also bacterial mortality agents will affect the fate of the carbon fluxes through microbial food webs.

Whereas, similar responses to seasonal variability are observed between the Arctic and the Antarctic, future changes may amplify differences between these regions. Compared to the Southern Ocean, the Arctic is largely surrounded by land masses and with large river inputs ($\sim$4,000 km^3 yr^{-1}). These rivers are a source of low-salinity waters, organic matter, and nutrients to the Arctic Ocean and surrounding seas. Moreover, as temperature rises, terrestrial permafrost thaws, which mobilizes ancient carbon that enters the ocean through freshwater discharge. Here, Sipler et al. show that this terrestrial and riverine organic matter is rapidly degraded by bacterial activity even before reaching open waters suggesting a need to revisit the notion that this carbon should be considered as mainly refractory (Kirchman et al., 2009). Nevertheless, phytoplankton derived organic matter remains a major source of carbon fuelling Arctic bacterial production in spring and summer (Paulsen et al.). But as the Arctic warms and freshwater discharge increases, associated pulses of organic matter supplementing bacterial carbon demand (Paulsen et al.; Sipler et al.) may push Arctic microbial communities toward heterotrophy (Paulsen et al.). Increasing riverine input is also associated with changes in bacterial community structure, as specific organisms respond to the terrestrial derived organic matter (Sipler et al.). Hauptmann et al. point out that the transport of freshwater communities into the coastal marine waters could also affect the functioning of the arctic carbon cycle.

Compared to the Southern Ocean, the Arctic Ocean is a semi-closed system, with limited exchanges, through inflow and outflow gateways, with neighboring oceans. Of concern is the recent increase in Atlantic inflow into the European Arctic Ocean (Polyakov et al., 2017), which has been attributed to climate change. The northward intrusion of warmer waters may affect the spring bloom dynamics (van De Poll et al.; Vernet et al.) and favor the establishment of organisms previously absent from these waters, such as the cyanobacterium *Synechoccocus* (Paulsen et al.). Hence, changes in ocean circulation can have major effects on the biology of the pelagic ecosystem.

Lastly, polar benthic ecosystems are not likely to be spared from climate changes as seasonal shifts in surface communities are associated with microbial communities in the sediments (Learman et al.; Franco et al.). An increase in phytoplankton biomass and subsequent carbon export could cause microbial communities in polar sediments to switch from predominantly lithotrophs to organic matter degraders, which will in turn affect benthic elemental cycles (Learman et al.).

While Arctic sea ice extent breaks record lows, and Arctic and Antarctic ice shelves collapse, it is urgent to understand how these dramatic changes will impact the microbial ecology and potentially disrupt the capacity for carbon storage in polar regions. Overall, the studies published in this research topic confirm that major changes already occurring in aquatic polar ecosystems will impact microbial communities, and further suggest that some microbes are potential indicators of these changes. Because most of these studies focus on biodiversity, however, it remains a challenge to unravel how these community changes will alter ecosystem function. Some of the present results hint toward major changes in carbon fluxes and trophic interactions, stressing the need for increased spatial and seasonal coverage, including winter sampling of microbial communities, and continued focus on top-down and bottom up controls of microbial processes. Long-term monitoring is needed to facilitate reliable predictions on how polar aquatic systems will interact with climate and better assess the resilience and adaptation of these fragile ecosystems. Moreover, as polar microbial communities are fundamental to carbon cycling, informed modeling approaches that integrate polar microbial complexity are needed to understand the implications of climate change.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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