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Opinion

A horizon scan for Arctic coastal biodiversity research: understanding changes requires international collaboration

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Arctic coastal biodiversity faces increasing threats from anthropogenic activities and climate change. However, the effects on biodiversity are still poorly understood, hindering actions aimed at mitigating the impacts at a pan-Arctic scale. We present the results of a horizon scan that provides a road map to address knowledge gaps on the influence of anthropogenic activities, from increased shipping and harvesting to consequences of climate change including increasing temperatures, cryosphere loss, and freshwater runoff. Predictions on ecological change, species range expansions, and anthropogenic impacts on Arctic coasts are hampered by the lack of biodiversity data and scarcity of biological long-term monitoring programs. Filling these knowledge gaps will require coordinated international efforts and standardized experiments across the diverse ecosystems characterizing the Arctic.

Highlights

Current knowledge on coastal Arctic biodiversity originates from a small number of study sites, but the Arctic includes more than a fifth of the world's coastlines and its coastal biodiversity is increasingly experiencing pronounced effects of climate change and other anthropogenic influences.

The scarcity of baseline biodiversity data and a lack of large-scale comparative observations and experiments are limiting our capacity to detect commonalities in biodiversity responses to change at a pan-Arctic scale.

A horizon scan identified threats to Arctic coastal biodiversity. Increased pan-Arctic coordination of long-term standardized observations and field experiments is needed to understand the external impacts on ecological processes and to make predictions on coastal Arctic biodiversity on which adaptation and mitigation strategies can be based.

The Arctic coastline

Based on the definition of the Arctic region given by the Conservation of Arctic Flora and Fauna group (Figure 1), one fifth of Earth's coastlines are in the Arctic [1]. The Arctic coastal zone encompasses a wide variety of habitats, including rocky shores, sedimentary beaches, kelp beds, shallow lagoons, and river deltas (Figure 2). These Arctic coastal systems are influenced by a strong exchange of energy and matter with terrestrial and open-ocean ecosystems and the cryosphere [2]. Healthy coastal ecosystems are of great importance to the millions of Arctic inhabitants [3] who depend on them for subsistence food sources and other ecosystem services underpinning their cultures and identities.

Understanding threats to coastal biodiversity in a changing Arctic

Arctic coastal ecosystems are experiencing pronounced environmental changes, with air temperatures increasing three to seven times faster than the global average [4]. Biodiversity is considered to facilitate many ecosystem services and resilience to change, and Arctic biodiversity faces a growing number of anthropogenic pressures, including fishing, mining, pollution, and the multifaceted impacts of climate change. Recent warming has increased melting of glaciers and sea ice, freshwater runoff, and permafrost thaw, which, together with increased storminess, has accelerated coastal erosion [5]. Rivers export large quantities of sediments, organic material, nutrients, and contaminants such as mercury to coastal habitats, and the magnitude and rates of physicochemical changes observed along Arctic coasts [6], which affect coastal species and their interactions at complex spatiotemporal scales, raise concerns about biodiversity responses and

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Figure 1. The Arctic region. No single definition exists for the Arctic region. Given our focus on biodiversity in this article, we follow the definition of the Conservation of Arctic Flora and Fauna group (orange line). Figure modified with permission from GRID-Arendal (https://www.grida.no/resources/8387).

ecosystem functioning. Yet, knowledge of how these different stressors will affect patterns and drivers of Arctic coastal biodiversity is extremely limited.

So far, Arctic coastal areas (defined here as having water depths less than 20 m) have been poorly studied because access is difficult and the large research ships commonly used for Arctic research cannot access shallow waters [7]. Additionally, only a few research stations that include coastal biodiversity monitoring exist across the Arctic (https://www.interact-gis.org). Furthermore, the necessary logistic and safety measures make Arctic research costly and impractical for many institutions. At this time, we are also struggling to predict the response of coastal Arctic biodiversity to emerging stressors because prevailing ecological concepts regarding the regulatory processes of species assemblages are largely based on research done in non-polar environments [8–10] and are virtually untested in the Arctic. Current knowledge on the influences of climate change on coastal Arctic species diversity and ecosystem structure and function rests on studies done at a limited number of sites (i.e., specific shorelines or fjords) (e.g., [11–15]). Although those studies provide essential information on local ecology, our capacity to detect commonalities across the diversity of Arctic

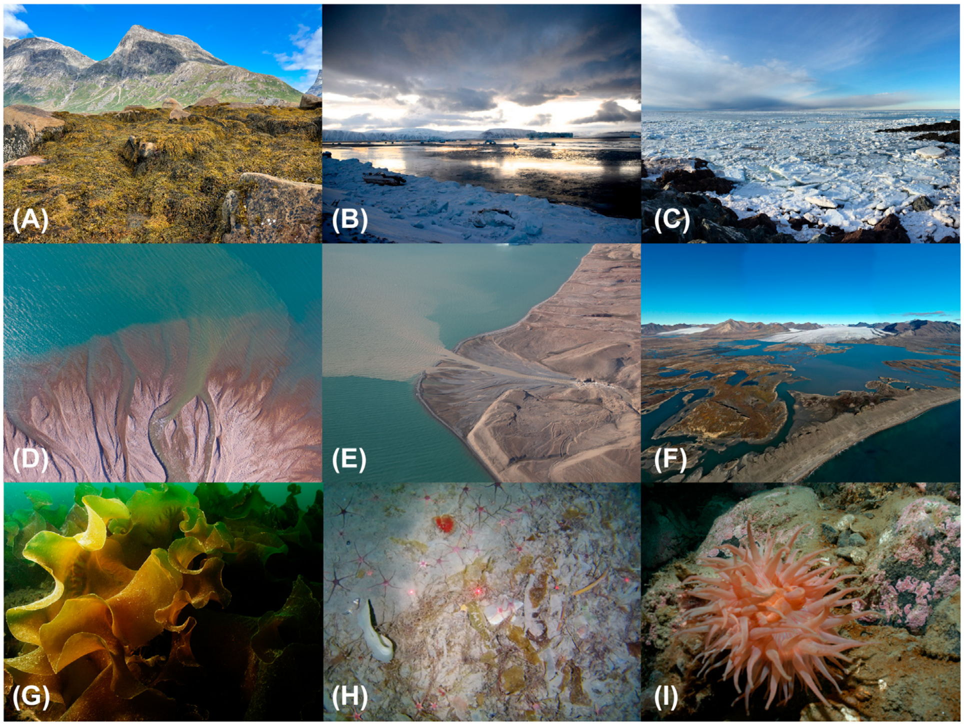

Figure 2. The diversity of Arctic coastal environments. (A) Rocky intertidal shore dominated by macroalgae during summer near Nuuk, West Greenland (photo: Jakob Thyrring). (B) Rocky intertidal shore encrusted in ice (known as the ice foot) during winter near Qaanaaq, West Greenland (photo: Jakob Thyrring). The ice foot protects intertidal organisms from extremely low air temperatures. (C) Sea ice breaking up in the Gulf of St Lawrence coast of Nova Scotia, Canada. The sea ice break-up exposes the surface water to sunlight, stimulating primary production, but it also increases disturbance to the seafloor and intertidal habitats as drifting ice scours substrates (photo: Ricardo Scrosati). (D) Plume of sediment exported from a land-terminating glacier in Young Sound, East Greenland. The plume decreases light availability in the water column and decreases primary productivity (photo: Mikael K. Sejr). (E) Export of sediment from land is increasing delta progradation and thus the extent of soft-bottom habitats across the Arctic (photo: Nikolaj Krog Larsen). (F) Post-glacial lagoon near Eidembukta, Svalbard. Post-glacial lagoons usually form in front of retrieving glaciers, and the lagoon is filled with freshwater and seawater [photo: Jakub (Kuba) Witek]. (G) Subtidal macroalgal meadow, which commonly occurs throughout many Arctic coastal waters (photo: Peter Bondo). (H) Subtidal soft bottom community inhabited by brittle stars and buried infauna (photo: Mikael K. Sejr). (I) Hard-bottom community dominated by encrusting algae and anemones (photo: Peter Bondo).

coastal landscapes remains very limited, and the lack of knowledge on ecological interactions such as predation, competition, and facilitation in Arctic coastal communities seriously hampers our ability to predict biodiversity responses to climate change and increased human activities.

Here, we present the results of a horizon scan conducted at a meeting in Copenhagen, Denmark, in January 2024 aimed at identifying issues of concern for coastal biodiversity across the Arctic region. We followed a well-established horizon scan protocol [16] (see Box 1 for methods). We

Box 1. Horizon scanning methods

The scanning process began in 2023, when experts on the ecology and ecophysiology of polar coastal marine species were invited to a workshop in Copenhagen, Denmark, held in January 2024. Experts were selected to provide a wide expertise in ecology, physiology, genomics, ecological modeling, and food web dynamics. All experts were asked to identify key questions to advance knowledge on current threats to coastal Arctic biodiversity. Fourteen scientists from ten countries attended the workshop. Participants were divided into groups to discuss and prioritize their responses and vote on their priorities. The list of priorities was compiled and discussed in plenum. Through a final round of voting, all participants agreed on a final list. The inputs from the invited Russian colleague were provided through virtual meetings before and after the workshop.

present these issues in no particular order and conclude with a road map on how to address important knowledge gaps across the Arctic region.

Horizon scan results

Lack of benchmark knowledge

Assessing change in coastal biological communities requires biodiversity knowledge obtained through standardized sampling, but few comprehensive pan-Arctic coastal biodiversity datasets exist. The available species records are taxonomically incomplete and spatially and temporally biased towards easily accessible seasons and sites. The resulting partial picture of native species composition defines a key challenge for assessing future changes in biodiversity. Some of the available long-term monitoring programs of Arctic coastal biodiversity – such as in the White Sea [15,17], Svalbard [13,18], and Alaska [19,20] – have demonstrated profound recent changes in Artic ecosystems, but monitoring a few sites will not provide a large-scale understanding of how changing conditions might impact Arctic coastal biodiversity as physicochemical conditions vary across regions and fjords. Reduced data availability may also result from a culture of not sharing data from monitoring programs or research projects. Hence, data sharing, a greater spatiotemporal coverage, and integration of biodiversity data across all Arctic nations constitute an urgent need [21].

Changing cryosphere and intensified land–ocean coupling

Disappearing sea ice threatens the species associated with coastal sea ice ecosystems (from ice algae to polar bears, *Ursus maritimus*), while potentially benefitting other species as conditions change and new habitats become available [22,23]. For example, warming and a prolonged open-water period could facilitate the expansion of foundation species such as mussels, macroalgae, and seagrasses [24,25], enhancing coastal biodiversity [26,27]. However, the increasing runoff from melting glaciers and thawing permafrost locally decreases coastal water clarity due to increased suspended sediments, counterbalancing the effect of a longer ice-free period by reducing the amount of light reaching different depths of the water column, a process termed coastal darkening [28]. Coastal darkening may decrease primary production by macroalgae, seagrasses, and phytoplankton and, thus, reduce the abundance of foundation species that either depend on phytoplankton for food (e.g., filter-feeders) or light as energy source (macroalgae and seagrasses).

Non-indigenous species, parasites, and the emergence of pathogens

Arctic sea ice is becoming thinner and the seasonal sea ice freezes later and melts earlier. Less ice increases ship traffic through the Northwest Passage and the Northern Sea Route ('Northeast Passage'). Together with ocean warming, increased shipping might increase the risk of range expansions of non-indigenous species to the Arctic from the Pacific and Atlantic Oceans, potentially altering species interactions. Recently, species distribution modelling has predicted that Hudson Bay, Labrador, the Chukchi/Eastern Bering Seas, and the Barents/White Seas are particularly vulnerable to future intrusions of non-indigenous species [22,29]. The rate of change may depend on physical barriers, such as island chains, and on the exposure to influx of Atlantic or Pacific waters [30]. North-flowing currents influence some Arctic areas such as Svalbard or the Chukchi Sea, facilitating range extensions of species from lower latitudes, in contrast to a greater isolation of other areas such as the Russian Severnaya Zemlya Archipelago [31].

Invasive species may change coastal biodiversity and ecosystem functioning [32] through changes in food web structure. In the 1960s, the non-indigenous red king crab *Paralithodes camtschaticus* was introduced to the Barents Sea to create a new commercial fishery. Today, the king crab is considered invasive in this region, where it has decreased biodiversity at depths >100 m in Arctic Norway [33]. However, only a few studies have investigated experimentally the importance of biotic interactions in shaping Arctic coastal communities [14,34]. Therefore, limitations in current knowledge preclude predictions about the impacts of non-indigenous species and novel biotic interactions on coastal biodiversity [35].

Warming can also facilitate the range expansion of pathogens such as invertebrate parasites, fungi, bacteria, and viruses, which may alter species composition through species-specific effects. Such pathogens can cause widespread host mortality and population collapse such as those documented from lower-latitude coastal systems [36,37]. Transmissible cancer has previously been reported for a range of bivalve species in Europe and North America [38] and, recently, transmissible cancer cell lineages were detected in blue mussels (*Mytilus* spp.) from the Barents Sea [39]. However, the ecological impacts and associated risks to subsistence communities of such pathogens on their hosts and Arctic coastal biodiversity remain largely unknown.

Biodiversity and the blue economy

Climate change is making the Arctic region more navigable, and the ever-rising human need for food, energy, and minerals means that industry is following the retreating ice northward. Rapid growth of the blue economy in the Arctic has led to projected Arctic investments of more than US$ 1 trillion over the coming decades [3]. Harvesting of living marine resources will inevitably alter biodiversity and habitat integrity. Increased aquaculture activities risk changing local nutrient balance, with direct effects on (harmful) algal blooms and indirect effects through impacts on dissolved oxygen concentration, water clarity, sediment organic enrichment, and heavy-metal concentration. All ship-based activities and oil production itself come with the threat of pollution from oil spills as well as providing vectors for the introduction of non-indigenous species. Man-made structures, such as oil rigs and renewable-energy platforms, are stepping stones for subsequent dispersal and range expansions of northward-moving species [40,41]. Given that most hydrocarbon production projects in the Arctic take place in coastal regions and/or have associated coastal infrastructure (e.g., shipment/trans-shipment terminals), coastal regions are particularly at risk. As we note elsewhere, each of these human impacts can alter the biodiversity of native biological communities through mortality or alterations in food web dynamics, so efforts must ensure that economic development in the Arctic is ecologically sustainable and includes monitoring and spill-response programs.

Impacts of multiple stressors

Workshop participants flagged the importance of understanding how interacting abiotic and biotic drivers affect species distribution and community structure, as these drivers can exert synergistic or antagonistic effects that make it impossible to predict the direction and magnitude of effects without empirical support. For example, exposure to low pH can exacerbate thermal stress effects by increasing the susceptibility of intertidal benthic invertebrates to freezing (synergistic effect) [42]. In addition, when multiple stressors create synergistic effects, they can generate earlier tipping points (zones of rapid change in a nonlinear relationship between a response variable and the intensity of a stressor) in aquatic ecosystems [43]. Yet, very few studies have assessed the combined effects of multiple stressors on coastal Arctic species (e.g., [44–46]), rendering the Arctic severely understudied in this regard. Furthermore, genetic diversity in natural populations enhances the resistance and adaptive potential when facing multiple stressors, and adaptation can enhance their resilience to stress on an evolutionary scale [47]. Thus, understanding the responses of biodiversity to environmental change requires knowledge on the sensitivity to multiple stressors across various levels of biological organization, especially considering that even a moderate increase in environmental stress can alter community structure [48].

Concluding remarks and future perspectives

The scarcity of international and interdisciplinary collaboration represents one of the most important barriers to understanding anthropogenic impacts at greater spatial scales, pointing to the need to synthesize knowledge and coordinate observational and experimental approaches. Such efforts must incorporate local and Indigenous knowledge whenever possible, as it fosters more holistic, ethical and effective outcomes while aligning research and management strategies with the lived experiences and needs of local communities. Furthermore, the current lack of baseline biodiversity data and experimental tests of ecological theory in the coastal Arctic limits our ability to understand community assembly processes in this system (see Outstanding questions). Increased international collaboration and coordinatepan-Arctic monitoring would help to create a benchmark inventory to better understand ongoing and future changes in Arctic coastal biodiversity, identifying mechanistic links related to climate change and other anthropogenic pressures.

The comparison of ecological responses to changing external drivers across regions throughout the Arctic based on monitoring and standardized experiments on different coasts is needed to reveal commonalities in the mechanisms affecting community assembly across the heterogeneous Arctic region (Box 2). Understanding the challenges facing biodiversity requires expanded sampling efforts across Arctic coastal systems ideally spanning different seasons, enabling predictions for geographic areas with the greatest sensitivity to change. The establishment of additional coastal marine protected areas, particularly in areas of high biodiversity, could help to preserve extant biodiversity from increasing human activities. Beyond the threats that human activities impose through pollution, eutrophication, and habitat alteration, human activities also increase the risk of introducing invasive species, and these risks require mitigation. We acknowledge that the global nature of climate change threats to biodiversity is not limited to the Arctic. However, few other systems are so severely understudied while at the forefront of climate change. A wider spatial coverage of Arctic biodiversity will improve efforts to understand global biodiversity patterns, drivers, and improve predictions on which species will thrive or

Outstanding questions

Where are the coastal biodiversity hotspots?

What factors mainly drive regional differences in species interactions and biodiversity patterns in Arctic coastal systems? Are there commonalities in biodiversity responses across different Arctic coasts?

Can local biodiversity responses be up-scaled to achieve a pan-Arctic understanding?

How do the duration and seasonal timing of multiple stressors affect the magnitude and direction of ecological processes?

Can contemporary ecological theory predict the ecological succession of emerging habitats and clarify ecosystem dynamics and future changes in biodiversity?

Box 2. Pan-Arctic standardized long-term monitoring

Researchers are recognizing the importance of coordinated standardized long-term biodiversity monitoring to detect the impacts of human activities and climate change. The patchy distribution of current marine Arctic monitoring programs and differences in methodologies and sampling efforts limit efforts to synthesize these initiatives to gain a more holistic understanding of the effects on Arctic coastal biodiversity. The Arctic Council, an intergovernmental forum promoting cooperation among Arctic nations, has established the Circumpolar Biodiversity Monitoring Programme (CBMP), which is currently developing an Arctic Coastal Biodiversity Monitoring Plan based on science and indigenous knowledge [49]. Although ecosystem-wide monitoring provides pivotal knowledge, the required efforts and associated costs limit their geographical scope to a few sites, often located close to cities or research stations. Thus, integrating low-cost, low-maintenance monitoring tools into ongoing monitoring efforts would enable researchers to track changes in biodiversity across the Arctic over the coming decades. For example, the relatively easy access to rocky intertidal habitats during low tides (when free of ice) together with the monitoring of permanent plots may be particularly amenable to frequently assess changes in community structure and the abundance of ecologically important species. Subtidal biodiversity can likewise be monitored using permanent plots visited by scuba divers or photographed using remotely operated vehicles (ROVs) or drop cameras. Decreasing costs and rapid improvements in sequencing techniques make environmental DNA (eDNA) an easy-to-standardize and noninvasive approach suitable for large-scale monitoring in intertidal and subtidal habitats. However, while eDNA efficiently detects rare and newly established species, the lack of barcodes for Arctic species represents significant gaps for DNA databases and restricts the use of eDNA to supplement visual biodiversity monitoring on a pan-Arctic scale. Finally, remote sensing can track biophysical changes at local to regional scales and, in combination, provide a large-scale perspective on Arctic biodiversity.

decline, refine management efforts, and ultimately help us more effectively to forecast the future of Arctic coastal biodiversity.

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Declaration of interests

The authors declare no conflicts of interest.

References

1. CAFF (2013) *Arctic Biodiversity Assessment – Status and Trends in Arctic Biodiversity*, Conservation of Arctic Flora and Fauna, Akureyri, Iceland
2. Sejr, M.K. *et al.* (2024) Multiple climatic drivers increase pace and consequences of ecosystem change in the Arctic Coastal Ocean. *Limnol. Oceanogr. Lett.* 9, 683–695
3. Atkisson, A. *et al.* (2018) Getting it right in a new ocean: bringing sustainable blue economy principles to the Arctic. Published online November 26, 2019. WWF, https://www.arcticwwf.org/newsroom/reports/getting-it-right-in-a-new-ocean-report/
4. Rantanen, M. *et al.* (2022) The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* 3, 168
5. Overeem, I. *et al.* (2011) Sea ice loss enhances wave action at the Arctic coast. *Geophys. Res. Lett.* 38, L17503
6. Hernes, P.J. *et al.* (2021) Element cycling and aquatic function in a changing Arctic. *Limnol. Oceanogr.* 66, S1–S16
7. Fritz, M. *et al.* (2017) Collapsing Arctic coastlines. *Nat. Clim. Chang.* 7, 6–7
8. Bruno, J.F. *et al.* (2003) Inclusion of facilitation into ecological theory. *Trends Ecol. Evol.* 18, 119–125
9. Silliman, B.R. and He, Q. (2018) Physical stress, consumer control, and new theory in ecology. *Trends Ecol. Evol.* 33, 492–503
10. Menge, B.A. and Sutherland, J.P. (1987) Community regulation: variation in disturbance, competition, and predation in relation to environmental stress and recruitment. *Am. Nat.* 130, 730–757
11. Sejr, M.K. *et al.* (2021) Small scale factors modify impacts of temperature, ice scour and waves and drive rocky intertidal community structure in a Greenland fjord. *Front. Mar. Sci.* 7, 607135
12. Sejr, M.K. *et al.* (2022) Glacial meltwater determines the balance between autotrophic and heterotrophic processes in a Greenland fjord. *Proc. Natl. Acad. Sci.* 119, e2207024119
13. Węsławski, J.M. *et al.* (2010) Increase in biodiversity in the Arctic rocky littoral, Sorkappland, Svalbard, after 20 years of climate warming. *Mar. Biodivers.* 40, 123–130
14. Díaz, M.J. *et al.* (2023) Limited predatory effects on infaunal macrobenthos community patterns in intertidal soft-bottom of Arctic coasts. *Ecol. Evol.* 13, e9779
15. Naumov, A.D. (2013) Long-term fluctuations of soft-bottom intertidal community structure affected by ice cover at two small sea bights in the Chupa Inlet (Kandalaksha Bay) of the White Sea. *Hydrobiologia* 706, 159–173
16. Sutherland, W.J. *et al.* (2024) A horizon scan of global biological conservation issues for 2024. *Trends Ecol. Evol.* 39, 89–100
17. Azovsky, A.I. *et al.* (2023) Long-term dynamics of subarctic intertidal macrofauna: common trends and the role of local environment. *Estuar. Coasts* 46, 740–756
18. Al-Habahbeh, A.K. *et al.* (2020) Arctic coastal benthos long-term responses to perturbations under climate warming. *Philos. Trans. A Math. Phys. Eng. Sci.* 378, 20190355
19. Danielson, S. *et al.* (2022) Monitoring Alaskan Arctic shelf ecosystems with an informal observation network. *Oceanography* 35, 198–209
20. Bonsell, C. and Dunton, K.H. (2018) Long-term patterns of benthic irradiance and kelp production in the central Beaufort sea reveal implications of warming for Arctic inner shelves. *Prog. Oceanogr.* 162, 160–170
21. Thyrring, J. *et al.* (2024) Shallow coverage in shallow waters: the incompleteness of intertidal species inventories in biodiversity database records. *Ecography* 2024, e07006
22. Goldsmit, J. *et al.* (2020) What and where? Predicting invasion hotspots in the Arctic marine realm. *Glob. Chang. Biol.* 26, 4752–4771
23. Pavlova, L.V. *et al.* (2023) The impact of sea ice loss on benthic communities of the Makarov Strait (Northeastern Barents Sea). *Animals* 13, 2320
24. Thyrring, J. *et al.* (2017) Rising air temperatures will increase intertidal mussel abundance in the Arctic. *Mar. Ecol. Prog. Ser.* 584, 91–104
25. Assis, J. *et al.* (2022) Major expansion of marine forests in a warmer Arctic. *Front. Mar. Sci.* 9, 850368
26. Lavoie, C. *et al.* (2024) Living under Arctic kelp forests: linking soft-bottom communities to kelp cover in the Canadian Arctic. *Mar. Ecol. Prog. Ser.* 740, 1–22
27. Cameron, N.M. *et al.* (2024) Global taxonomic and functional patterns in invertebrate assemblages from rocky-intertidal mussel beds. *Sci. Rep.* 14, 26
28. Attard, K. *et al.* (2024) Seafloor primary production in a changing Arctic Ocean. *Proc. Natl. Acad. Sci.* 121, e2303366121
29. Goldsmit, J. *et al.* (2018) Projecting present and future habitat suitability of ship-mediated aquatic invasive species in the Canadian Arctic. *Biol. Invasions* 20, 501–517
30. Krumhansl, K. *et al.* (2023) Permeability of coastal biogeographic barriers to marine larval dispersal on the east and west coasts of North America. *Glob. Ecol. Biogeogr.* 32, 945–961
31. Sirenko, B.I., ed (2001) *List of Species of Free-living Invertebrates of Eurasian Arctic Seas and Adjacent Deep Waters*. *Explorations of the Fauna and the Seas* 51. Russian Academy of Sciences, Zoological Institute

32. Cottier-Cook, E.J. *et al.* (2024) Horizon scanning of potential threats to high-Arctic biodiversity, human health and the economy from marine invasive alien species: a Svalbard case study. *Glob. Change Biol.* 30, e17009
33. Oug, E. *et al.* (2011) Effects of the invasive red king crab (*Paralithodes camtschaticus*) on soft-bottom fauna in Varangerfjorden, northern Norway. *Mar. Biodivers.* 41, 467–479
34. Khalaman, V.V. *et al.* (2016) Algae versus animals in early fouling communities of the White Sea. *Mar. Ecol. Prog. Ser.* 553, 13–32
35. Goldsmit, J. *et al.* (2024) Predicted shifts in suitable habitat of interacting benthic species in a warmer and invaded Canadian Arctic. *Elementa* 12, 00018
36. Mouritsen, K.N. *et al.* (2005) Climate warming may cause a parasite-induced collapse in coastal amphipod populations. *Oecologia* 146, 476–483
37. Hewson, I. *et al.* (2023) A scuticociliate causes mass mortality of *Diadema antillarum* in the Caribbean Sea. *Sci. Adv.* 9, eadg3200
38. Barber, B.J. (2004) Neoplastic diseases of commercially important marine bivalves. *Aquat. Living Resour.* 17, 449–466
39. Skazina, M. *et al.* (2023) Genetic features of bivalve transmissible neoplasia in blue mussels from the Kola Bay (Barents Sea) suggest a recent trans-Arctic migration of the cancer lineages. *Mol. Ecol.* 32, 5724–5741
40. Mayorga-Adame, C.G. *et al.* (2022) Spatiotemporal scales of larval dispersal and connectivity among oil and gas structures in the North Sea. *Mar. Ecol. Prog. Ser.* 685, 49–67
41. Adams, T.P. *et al.* (2014) Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. *J. Appl. Ecol.* 51, 330–338
42. Thyrring, J. *et al.* (2023) Ocean acidification increases susceptibility to sub-zero air temperatures in ecosystem engineers and limits poleward range shifts. *eLife* 12, e81080
43. Carrier-Belleau, C. *et al.* (2023) Tipping point arises earlier under a multiple-stressor scenario. *Sci. Rep.* 13, 16780
44. Beaudreau, N. *et al.* (2024) Using a metabolomics approach to investigate the sensitivity of a potential Arctic-invader and its Arctic sister-species to marine heatwaves and traditional harvesting disturbances. *Sci. Total Environ.* 917, 170167
45. Nielsen, M.B. *et al.* (2021) Freshening increases the susceptibility to heat stress in intertidal mussels *(Mytilus edulis)* from the Arctic. *J. Anim. Ecol.* 90, 1515–1524
46. Diehl, N. *et al.* (2020) Impacts of combined temperature and salinity stress on the endemic Arctic brown seaweed *Laminaria solidungula* J. Agardh. *Polar Biol.* 43, 647–656
47. Meester, L. *et al.* (2018) Genetic adaptation as a biological buffer against climate change: potential and limitations. *Integr. Zool.* 13, 372–391
48. Heaven, C.S. and Scrosati, R.A. (2008) Benthic community composition across gradients of intertidal elevation, wave exposure, and ice scour in Atlantic Canada. *Mar. Ecol. Prog. Ser.* 369, 13–23
49. CAFF (2019) *Arctic Coastal Biodiversity Monitoring Plan*, Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland