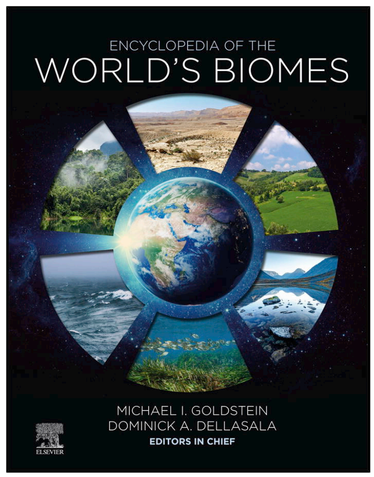

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Arctic Ocean Islands

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Abstract

The Island archipelagos of the Arctic Ocean support the most extreme examples of Arctic-adapted plant and animal communities. Compared with much of the planet, they have seen relatively little human disturbance. Their current faunas and floras have been strongly influenced by the degree of isolation of the different island groups and by Pleistocene glaciations and post-Pleistocene sea-level changes. Faunal interchange with adjacent continents has been modified by the annual connection via winter sea-ice. Current trends towards warmer temperatures and shorter sea-ice seasons in the Arctic may eventually result in the loss of seasonal ice-bridges, isolating some archipelagos and preventing colonization by southern faunal elements. Understanding and protecting these islands is the key to preserving the current remnants of the Pleistocene fauna and flora.

Introduction

The Arctic Ocean, along with the adjacent Kara, Barents, Laptev, East Siberian, Chukchi and Beaufort seas, and circumscribed by the northern extremities of Greenland and the Eurasian and North America continents, contains several important island groups. The largest of these are Svalbard (Norway), Novaya Zemlya, Franz Josef Land (*Zemlya Frantsa-Iosifa*), Severnaya Zemlya, the New Siberian Islands (*Novosibirskiye Ostrova*), and the comparatively isolated Wrangel Island, along with its small companion, Herald Island, all in Russia, and the Canadian Arctic Archipelago (**Fig. 1**). The Canadian islands include some very large ones situated close to the North American mainland (e.g., Baffin, Victoria, Banks islands) which are ecologically indistinguishable from the adjacent mainland. Consequently, for this review, I deal only with the Queen Elizabeth Islands to the north of the Parry Channel—Viscount Melville Sound—M'Clure Strait waterway at about 74°N (**Fig. 2**). These islands are more comparable, ecologically, to the other Arctic Ocean archipelagos than those farther south. For some purposes, I will discuss the Palearctic islands in two groups: (1) the islands of the Barents and Kara seas (**Fig. 3**), which experienced only brief and limited connections to continental Eurasia during the last glaciation and (2) the East Siberian Sea islands (**Fig. 4**), which for most of the last glaciation stood within a broad coastal plain extending hundreds of kilometers north of the current coast of Siberia.

Pleistocene and Holocene Histories

All of the islands under consideration were strongly affected by events during the last ice age (Pleistocene) and especially by the last glacial advance (Wisconsinan/Weichselian) and by postglacial (Holocene) events, especially sea-level changes. Many of the islands were entirely, or almost entirely covered by ice at the peak of glacial periods and consequently their terrestrial ecosystems tend to be

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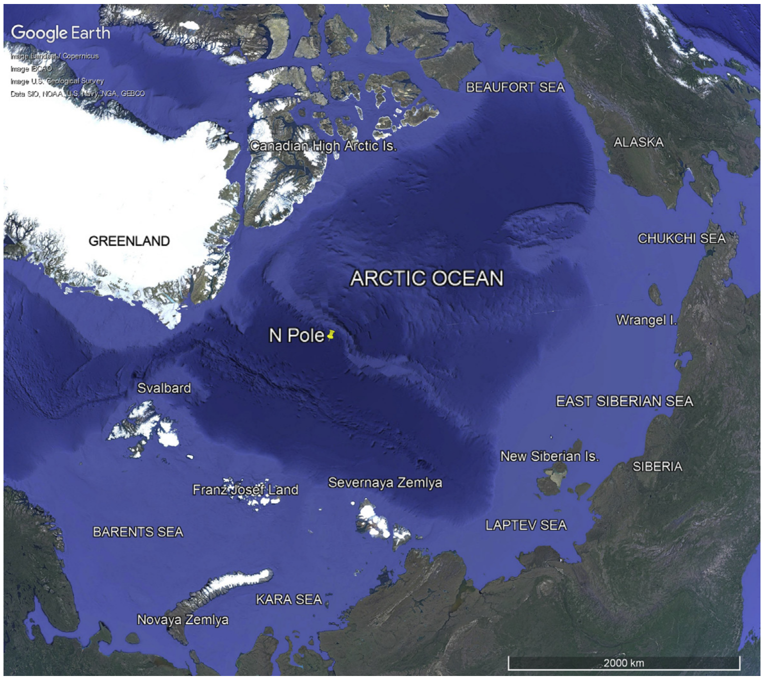

Fig. 1 The Arctic Ocean and the surrounding archipelagos and islands (Google Earth Pro, 2018).

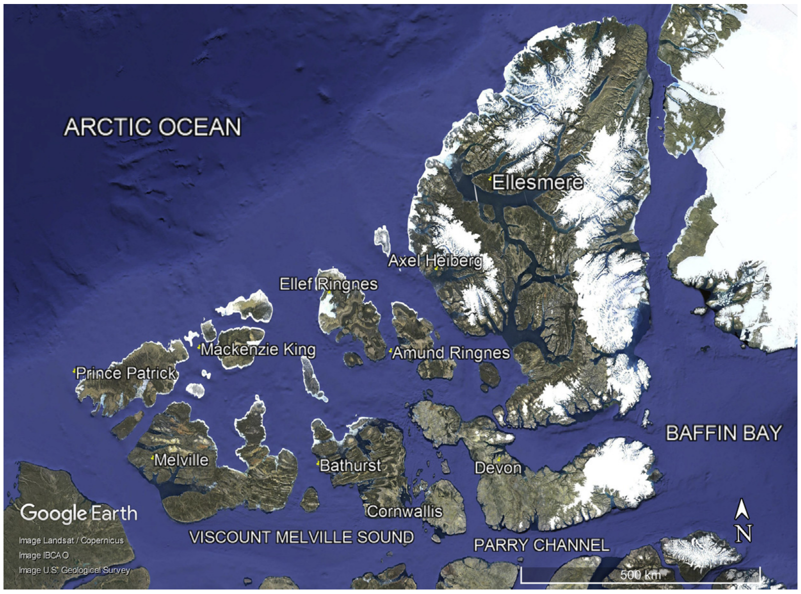

Fig. 2 Islands of the Canadian Arctic Archipelago, north of the Parry Channel—Viscount Melville Sound—M'Clure Strait waterway (Google Earth Pro, 2018).

very young, dating from the period of Wisconsinan deglaciation ~10,000 years ago. The only exceptions were Wrangel Island and parts of the New Siberian Islands and the northwesternmost of Canadian high Arctic islands, none of which was glaciated. As well, the reduced sea-levels of the glacial period exposed large areas of additional land around all of the archipelagos, especially Severnaya Zemlya and the islands of the East Siberian Sea, all of which had long-lasting land connections to the mainland of Asia during Pleistocene sea-level minima (Tolmachev, 1970; Formana et al., 2004; Jakobsson et al., 2012). These low-lying areas would have supported additional periglacial land which would have been home to a continental fauna and flora, components of which later became marooned after postglacial sea-levels rose (Andreev et al., 2009). Remnants of Pleistocene ice sheets remain on Devon, Ellesmere and Axel Heiberg islands, in Canada, on all the major islands of Svalbard and in Franz Josef Land, Novaya Zemlya and Severnaya Zemlya in Russia. Isostatic uplift, following the decay of major ice sheets, has affected most of the islands previously glaciated, leading to the creation of extensive raised beaches (Fig. 5).

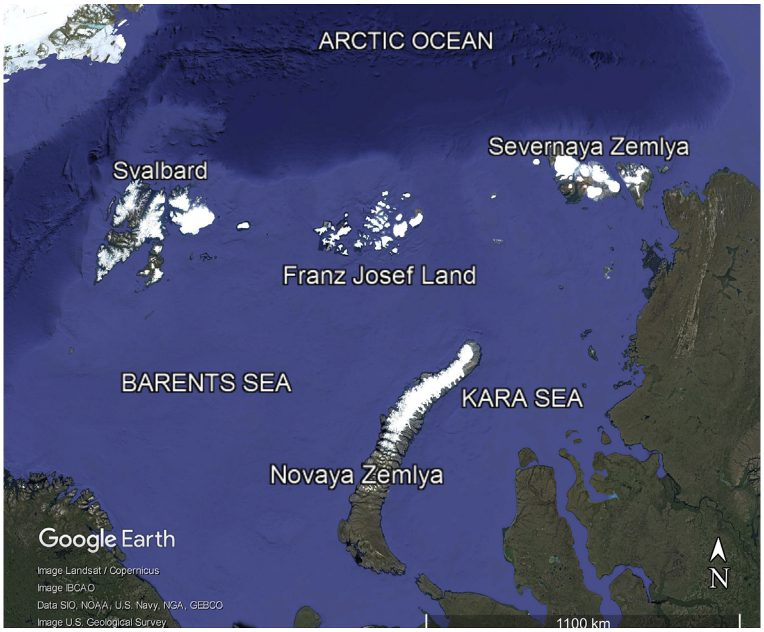

Fig. 3 Islands of the Barents and Kara seas (Google Earth Pro, 2018).

Fig. 4 Islands of the East Siberian Sea (Google Earth Pro, 2018).

Terrestrial Ecosystems

Flora

The vegetation of all the Arctic Ocean islands consists predominantly of graminoid and prostrate dwarf shrub tundra (G1 and G2, CAV Team, 2003) and lichen and moss-dominated cryptogram barrens (B1, B2). All these communities are characterized by plants of very short stature. The archipelagos fall within seven floristic provinces (clockwise from Wrangel I.): West Chukotka (Wrangel I.), Yana-Kolyma (E Siberian Is.), Taimyr (Severnaya Zemlya), Polar Ural (Novaya Zemlya), Svalbard-Franz Josef, Ellesmere-N Greenland (Ellesmere and Axel Heiberg islands and eastern Devon I.), Central Canadian Arctic (western Queen Elizabeth Is.). Provinces are defined on the basis of taxonomic affinities resulting from post-Pleistocene colonization processes, but the genera involved show much overlap (Daniëls et al., 2013). The most diverse and widespread families are Caryophyllaceae, Cruciferae, Cyperaceae, and Saxifragaceae and the most diverse genera *Carex*, *Draba*, and *Saxifraga*. There is a relatively low incidence of endemism, presumably because of the relatively short time since deglaciation. Significantly, highest endemism is found at the unglaciated Wrangel Island, where 35 vascular plants endemic to the Arctic are present (33% of all Arctic endemics; Daniëls et al., 2013). Wrangel Island also has a greater total diversity of vascular plants (315 species) than either Ellesmere Island, in Canada (199 species), or Svalbard (211 species), both considerably larger (Cf. Petrovskii and Yurtsev, 1970).

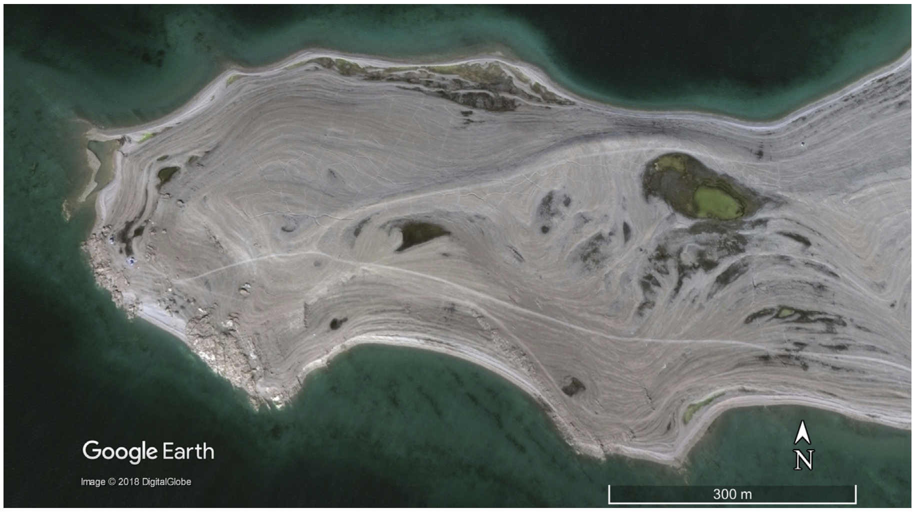

Fig. 5 Raised beach deposits behind shorelines near Resolute Bay, Nunavut, Canada (Google Earth Pro, 2018).

Vegetation throughout the Arctic Ocean archipelagos is very sparse, and few plants grow above 200 m altitude, apart from prostrate mosses and lichens. Above ground plant biomass is predominantly less than 50 g m^{-2} (CAV Team, 2003). Soils throughout are underlain by permafrost, impeding drainage and encouraging the creation of tundra polygons and bogs (**Fig. 6**), but as most precipitation falls as snow, there are few permanent watercourses. Many of the islands experience little rainfall and are regarded as polar deserts. Vegetation is frequently restricted to seasonal drainage channels (**Fig. 7**). The main factors controlling plant growth and the consequent vegetation communities in the high Arctic are summarized by Aiken et al. (2018):

- "Climate, which imposes a major temperature-based zonation, modified by local climates or microclimates;
- Drainage, which controls the summer water regime and has some effect on frost action;
- Nutrients, that are in limited supply in most arctic soils;
- Local soil type, which, along with climate and drainage, influences soil stability and fertility;
- Snow cover, which controls the duration of the growing season."

Despite the generally very low productivity of terrestrial biomes on the archipelagos, small areas exist where local conditions of moisture and soil types combine to create much lusher areas, sometimes termed "high Arctic oases" (Edlund and Alt, 1989). Examples in the Canadian islands include Polar Bear Pass on Bathurst Island (Sheard and Geale, 1983; **Fig. 8**), Lake Hazen on northern Ellesmere Island (**Fig. 9**), and Truelove Lowland, on Devon Island (Bliss, 1977; **Fig. 10**, Cf. **Fig. 11**) and. These areas typically support a much higher density of grazing mammals, hence also of wolves, than areas of lower productivity.

Fig. 6 Ice-wedge polygons on lowland tundra, Wrangel Island (Google Earth Pro, 2018).

Fig. 7 Braided drainage with vegetation concentrated along drainage channels, Khuzny Island, Novaya Zemlya (Google Earth Pro, 2018).

Fig. 8 Polar Bear Pass on Bathurst Island, a "high Arctic oasis" with a concentration of ungulates, loons, shorebirds, jaegers and snowy owls (Nettleship and Smith, 1975).

Oceanography

All the island archipelagos fall within Arctic waters, but the southeastern coasts of the Canadian islands and the west coast of Svalbard are affected by milder waters originating from the North Atlantic (Tang et al., 2004; Wassmann et al., 2006). To a small extent this is also true of Wrangel Island, where a plume of warm water, originating from the Bering Sea, moves westwards towards the east coast (Ahlnäs and Garrison, 1984). The waters surrounding all archipelagos are currently 100% covered by sea ice in winter but break up along the west coast of Svalbard occurs in May and in June in Baffin Bay and Lancaster Sound, south and east of Devon Island, and in the Kara Strait, south of Novaya Zemlya. Break-up in waters surrounding the other island groups occurs in July or later and in some years sea ice remains year-round adjacent to parts of Franz Josef and Severnaya Zemlya, giving these archipelagos very cool summers.

Fig. 9 Lake Hazen, a glacier-fed lake on northern Ellesmere Island (Google Earth Pro, 2018).

Fig. 10 Truelove lowlands and lowlands near Cape Sparbo, two "high Arctic oases" on the northeast coast of Devon Island (Cf. **Fig. 11**; Google Earth Pro, 2018).

Terrestrial Vertebrates

The terrestrial vertebrate fauna of the various archipelagos largely reflects their isolation from continental landmasses. Both Wrangel Island and the New Siberian Islands were connected to the Asian mainland during periods of low sea levels which persisted into the postglacial period, so that they supported a diverse fauna including woolly mammoth, wild horses and musk oxen (Boeskorov, 2004). The birds and mammals of the Canadian islands, with a maximum water barrier of 48 km separating them from the North American mainland (Gaston et al., 2012), are similar to those of mainland North American Arctic ecosystems, while those of the other archipelagos vary in their diversity, with Svalbard and Franz Josef Land, the most isolated groups, being the most depauperate. Svalbard supports only 15 species of nonmarine birds, compared to 36 species in the Canadian islands (Ganter and Gaston, 2013). Moreover, there are no wholly freshwater fishes in Svalbard (anadromous Arctic Char *Salvelinus* sp. is present).

Fig. 11 North-central Devon Island—dry upland area with low moisture and little vegetation (Google Earth Pro, 2018).

Mammals

Arctic fox and polar bear occur on all the Arctic archipelagos. Traveling and living on the sea-ice, as they do in winter, they are capable of reaching all land masses in the Arctic ocean. Otherwise, all of the archipelagos have supported at least one species of terrestrial mammal (Fig. 12), but the most isolated (Svalbard, Franz Josef) support only reindeer/caribou *Rangifer tarandus* (reindeer became extinct on Franz Josef more than a millennium ago Zale et al., 1994). Within the Canadian Arctic, caribou routinely move across sea ice over distances of up to at least 84 km (Miller et al., 2005). This suggests that herds on Novaya Zemlya, Severnaya Zemlya and the New Siberian Islands should be capable of interchange with Siberian mainland populations. Wrangel Island

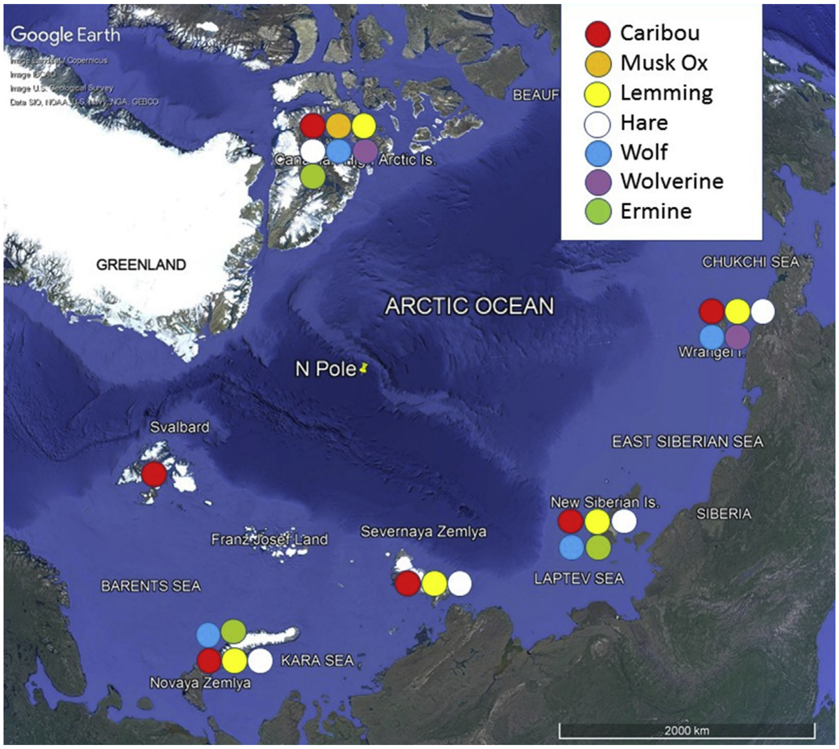

Fig. 12 Distribution of terrestrial mammals on Arctic Ocean archipelagos (data from Gaston et al., 2012).

(140 km from the Siberian mainland), Franz Josef (367 km from Novaya Zemlya) and Svalbard (220 km from Franz Josef, and 640 km from mainland Norway) may be outside the normal over-ice dispersal range for caribou. Populations on those archipelagos, only one of which persisted into historic times, may have colonized those islands during the Pleistocene when lower sea-levels would have reduced over-ice distances. The current isolation of Svalbard caribou is emphasized by their low genetic diversity (Cronin et al., 2006).

Diversity of mammals is greatest on the islands of the Canadian archipelago, where all the "Arctic specialists" can be found. It is the only group of islands supporting Musk Ox *Ovibos moschatus* and the Arctic hare *Lepus arcticus* is found on most islands, whereas its congener in Eurasia, the mountain hare *Lepus timidus* only reaches the southernmost islands of Severnaya Zemlya, Novaya Zemlya and New Siberian Islands. Lemmings, *Dicrostonyx* and *Lemmus* spp., are found on all the larger islands in the Canadian Archipelago, on Novaya Zemlya, Severnaya Zemlya, the New Siberian Islands and Wrangel Island, but not on Franz Josef or Svalbard, presumably because of their isolation (**Fig. 5**).

Among carnivores, wolf *Canis lupus* is found on most of larger Canadian islands, except the westernmost, where caribou are also rare, and on all the Russian archipelagos except Franz Josef, although only an occasional visitor on Severnaya Zemlya (Gaston et al., 2012). The ermine *Mustela erminea* occurs on all the larger islands where lemmings occur, while the wolverine *Gulo gulo*, although very sparse, has been recorded on several of the Canadian islands, but is absent from the Palearctic archipelagos apart from Wrangel Island (**Fig. 12**).

Birds

Being able to fly allows birds to readily colonize distant islands so that their distribution is less affected by the periodic availability of land connections. Many high Arctic species have circumpolar distributions, (e.g., red-throated loon *Gavia stellata*, willow and rock ptarmigan *Lagopus lagopus*, *L. mutus*, gyrfalcon *Falco rusticolus*, snow bunting *Plectrophenax nivalis*, Lapland longspur *Calcarius lapponicus*). However, geese and shorebirds tend to be confined either to the Nearctic (e.g., Ross's goose *Anser rossii*, semipalmated, white-rumped, western and Baird's sandpipers *Calidris pusilla*, *C. fuscicollis*, *C. mauri*, *C. bairdii*, or the Palearctic (e.g., pink footed, bean and barnacle geese *Anser brachyrynchus*, *A. fabalis*, *Branta leucopsis*, dotterel *Charadrius morinellus*), little and red-necked stints *Calidris minuta*, *C. ruficollis*, curlew sandpiper *C. ferruginea*).

In contrast with terrestrial mammals, diversity of waterfowl and seabirds among the Arctic Ocean islands, is highest on Svalbard, the most remote archipelago (**Figs. 13 and 14**), perhaps because of lack of terrestrial predators and competitors. The reverse is true of rodent-eating birds because most Arctic raptors depend on lemmings to provision their young and consequently most are absent from Svalbard and Franz Josef (**Fig. 15**). Shorebirds diversity is fairly similar among archipelagos (**Fig. 16**), with the exception of Franz Josef, where only a single species breeds (purple sandpiper *Calidris maritima*). Shorebird diversity may relate principally to the extent of suitable habitat—for most species lowland wet tundra with sedge meadows—rather than to isolation.

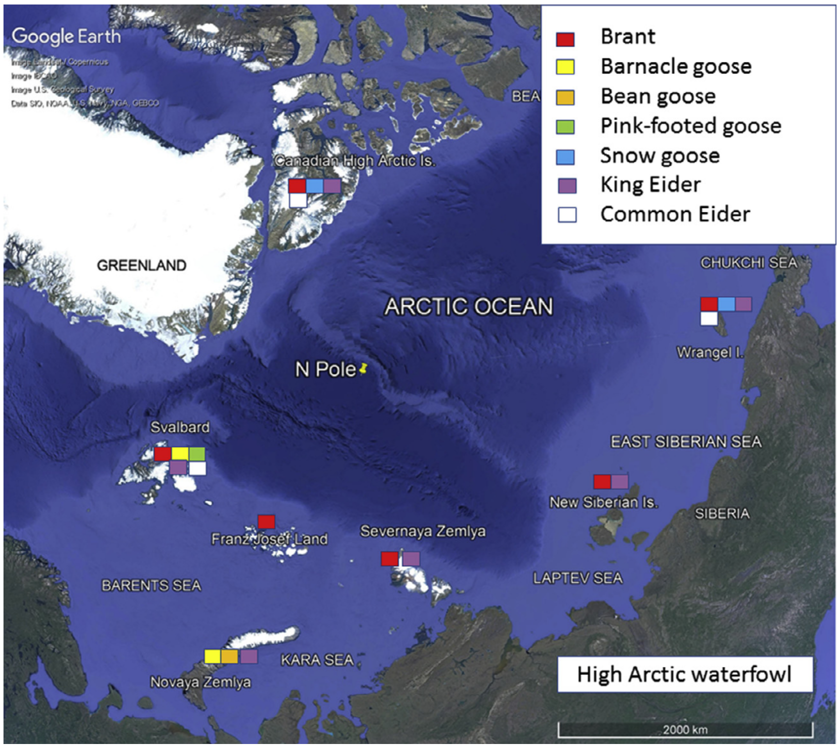

Fig. 13 Distribution of breeding waterfowl among Arctic Ocean archipelagos. Data from Portenko (1972), Cramp (1977, 1982, 1983, 1985), De Korte et al. (1995), and Ganter and Gaston (2013).

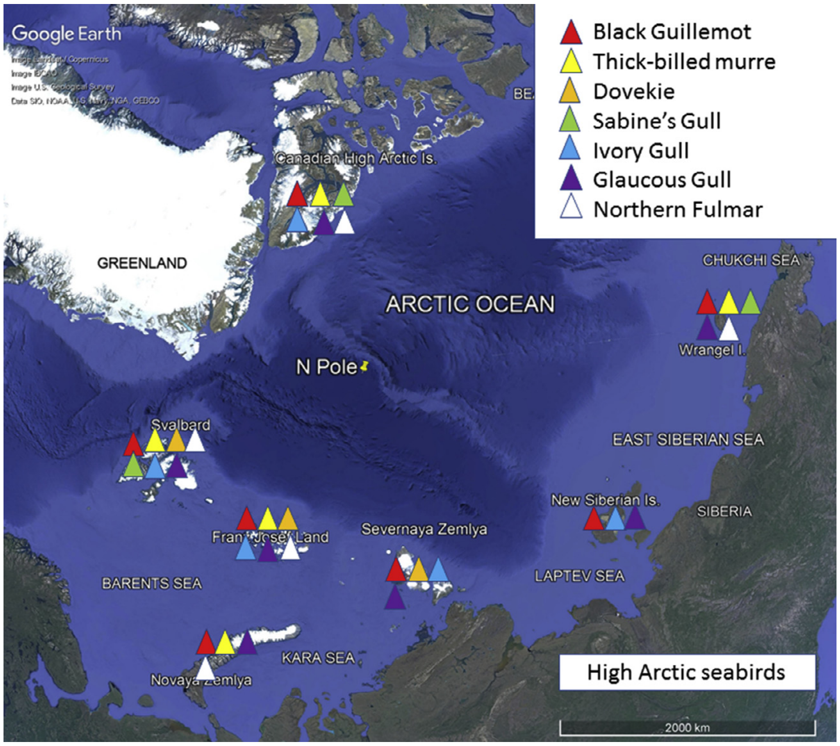

Fig. 14 Distribution of breeding seabirds among Arctic Ocean archipelagos. Data from Portenko (1972), Cramp (1977, 1982, 1983, 1985), De Korte et al. (1995), and Ganter and Gaston (2013).

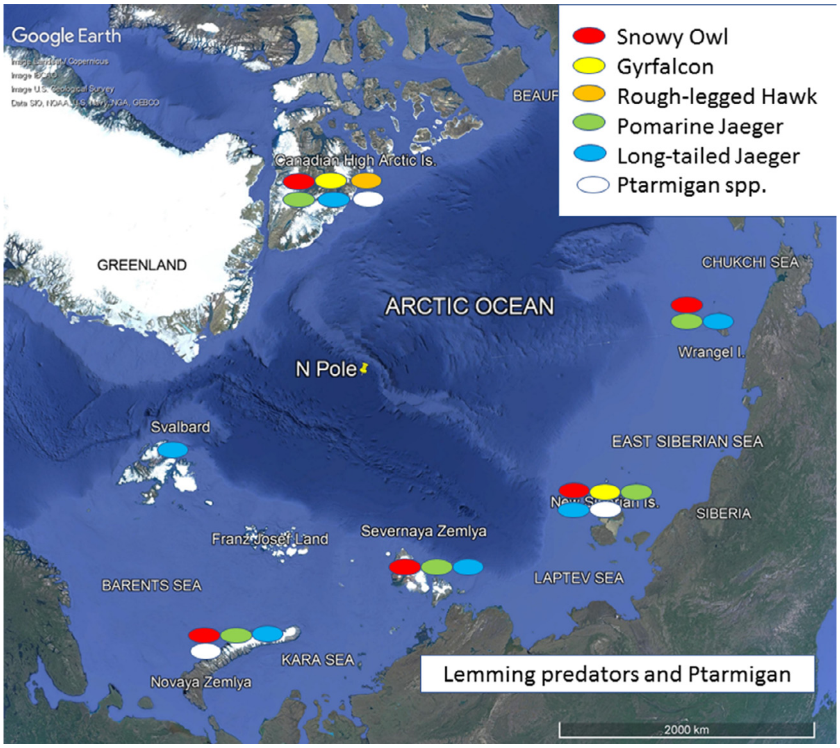

Fig. 15 Distribution of breeding raptors and ptarmigan among Arctic Ocean archipelagos.

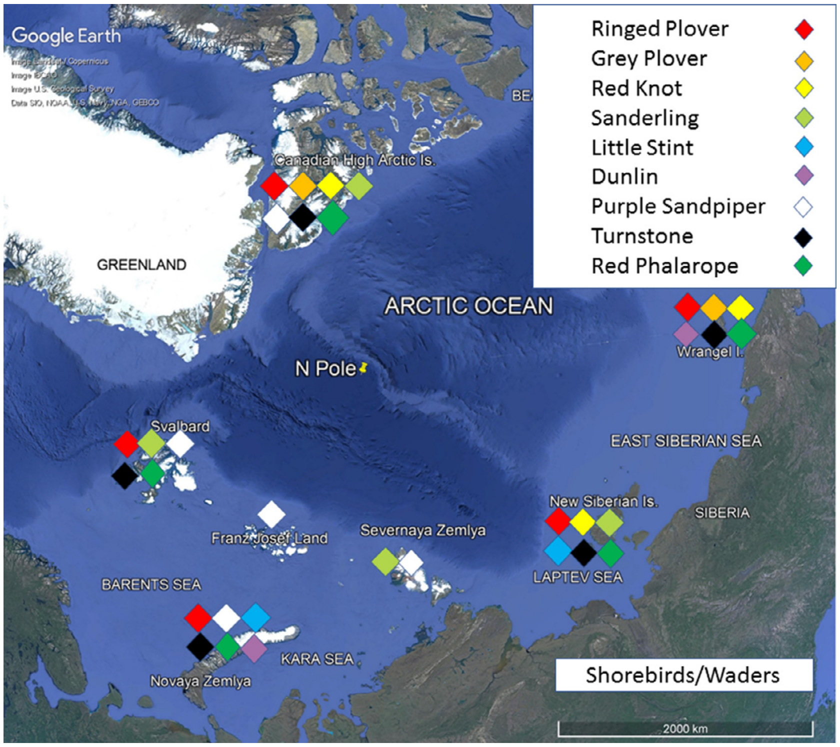

Fig. 16 Distribution of breeding shorebirds/waders among Arctic Ocean archipelagos. Data from Portenko (1972), Cramp (1977, 1982, 1983, 1985), De Korte et al. (1995), and Ganter and Gaston (2013).

Marine Ecosystems

Mammals

The islands of the Arctic ocean play an important role in marine ecosystems by providing breeding and hauling out opportunities for marine birds and mammals. Among mammals, the Arctic Ocean islands are particularly significant for polar bears *Ursus maritimus* and walrus *Odobenus rosmarus* which are found on all the archipelagos, although walrus are absent from the western and northern Queen Elizabeth Islands.

Walrus haul out on sea-ice when it is present, but once the seasonal ice has gone, they haul out on shore in dense aggregations which can number thousands of animals. They persist in areas of extensive winter ice cover by exploiting polynyas—areas of water kept open by strong currents and upwellings, but some populations are migratory, particularly the Pacific subspecies (*O. r. divergens*), which commutes between winter in the Bering Sea and summer in the Arctic Ocean, when large numbers occur at Wrangel Island (Aug–Oct; Fay, 1982). Despite this very large biomass of marine animals coming on land periodically, walrus have little impact on terrestrial ecosystems. Their droppings are deposited very close to the high-water mark and are mostly washed into the sea. They may provide prey for polar bears and carcasses, either killed by bears or other causes, may provide food for scavengers, such as ravens and gulls.

In contrast, polar bears may have significant impacts on terrestrial ecosystems. While ashore in summer, after the retreat of sea ice, they feed on grasses and forbs, as well as on birds' eggs and nestlings, on lemmings and caribou and on freshwater fishes. They frequently congregate in the vicinity of walrus haul-outs and kill smaller animals, especially dependent pups. Females frequently dig maternity dens on shore, in persistent snow drifts, usually within a few kilometers of the coast (Stirling, 1988).

The existence of the Arctic Ocean islands extends enormously the area of the Arctic Ocean accessible to both walrus and polar bears. The islands give access to haul-out and denning sites and, with their indented coastlines, provide excellent habitat for ringed seals *Pusa hispida*, the primary prey of the polar bear, as well as creating the type of narrow straits through which tidal currents maintain year-round polynya necessary for overwintering walrus.

Seabirds

Some species of seabird breed in dense colonies which not only provide opportunities for land-based predators, but also affect the local terrestrial ecosystems by importing large quantities of marine nutrients (**Fig. 17**) into the terrestrial environment (Klimowicz et al., 1997; Jónsdóttir, 2005; Zwolicki et al., 2013). The most common species breeding on the Arctic Ocean islands are the northern fulmar *Fulmarus glacialis*, thick-billed murre *Uria lomvia*, black-legged kittiwake *Rissa tridactyla*, dovekie *Alle alle*, and black guillemot *Cepphus grylle*. The murre and kittiwake normally breed on very steep coastal cliffs. Consequently, much of their droppings wash into the sea. However, dried feces, along with discarded food remains, are frequently blown up the cliffs by strong

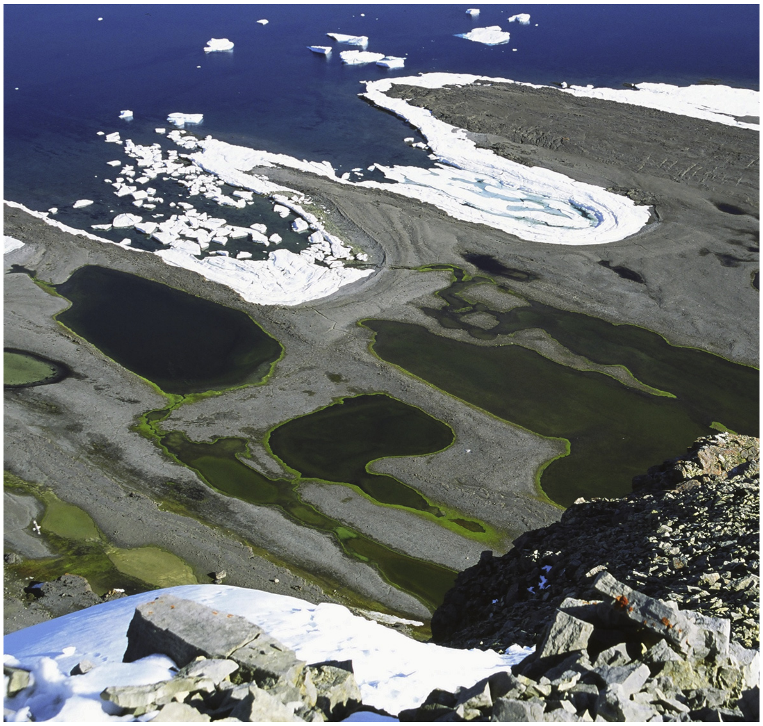

Fig. 17 Freshwater ponds at the base on the Northern Fulmar colony at Cape Vera, Devon Island. The bright green margins show the effects of nutrient enrichment by the Northern Fulmar colony on the cliffs just inland of the ponds. Photo: Mark Mallory.

winds and are deposited in a zone which may be up to a kilometer wide inland from the cliff edge. Enrichment of the vegetation in this zone is clearly apparent at many colonies (e.g., Gaston and Donaldson, 1996). The effects of dovekie manuring can be more extensive, because their colonies are often situated some kilometers inland and the effects of manuring are found over the intervening area (Zwolicki et al., 2013). Similar effects can be seen on small islands where dense aggregations of common eider *Somateria molissima* breed.

Biogeography

The Arctic Ocean archipelagos share many physical characteristics related to their harsh climates and remoteness and many plants and animals occurring in the high Arctic archipelagos have circumpolar distributions. In the case of less widespread taxa, the flora and fauna of the Eurasian archipelagos are dominated by plants and animals of Palearctic affinities, whereas those of the North American sector include a greater proportion of organisms with Nearctic affinities. This division is more striking when we consider birds than for other organisms, perhaps because most Palearctic migrants winter in Asia or Africa, whereas most Nearctic migrants winter in the Americas. Some birds in the eastern Canadian high Arctic, however, move eastwards in fall to winter in Europe and Africa, migrations which presumably mirror the pathways by which they colonized the high Arctic after the last glaciation.

Human Influence

Human history in the Arctic Ocean islands goes back to mid-Holocene times on the New Siberian Islands, at Wrangel Island and at some (perhaps all) of the Canadian islands (Sutherland, 1980), including Ellesmere (Schledermann, 1978), Axel Heiberg, Devon and Cornwallis islands. However, Svalbard and Franz Josef Land probably were not accessed by people before being discovered by modern Europeans some time after 1000 CE (Chochorowski, 1991). Perhaps because of a general deterioration of climate during the last millennium, compared with the earlier Holocene, native people were absent from all of the archipelagos, other than Novaya Zemlya, by the time the islands were discovered by medieval and later whalers and explorers.

In the New Siberian Islands, evidence of Mesolithic hunters has been found on Zhokov Island (77 km^2), in the northern part of the archipelago. A site dated at 7900 BP suggests that the hunters killed caribou and polar bears (Pitul'ko, 1993). By that period sea levels were similar to the present day, so these people had the technology to cross substantial water barriers: Zhokov is more than 100 km from Novaya Sibir Island, the easternmost of the larger East Siberian Islands and 38 km from the nearest potential "stepping stone" island.

Discovery of the Arctic archipelagos by Europeans may have begun with contact between Vikings and Inuit on Ellesmere Island, some time after 1200 CE (Schledermann, 1980). Vikings may well have discovered Svalbard, as well, but the discovery is generally attributed to the Dutch explorer Willem Barentsz who saw the islands in 1596. Thereafter the archipelago was used as a base for whaling (mostly Bowhead *Balaena mysticetus*) until stocks were more or less exhausted in the early 18th century (Woodby and Botkin, 1993). Surprisingly, considering the extent of activities on Svalbard, the Franz Josef archipelago was not discovered until the late 19th century, although it is possible that walrus hunters were familiar with it earlier. The Canadian high Arctic group was first sighted by William Baffin, who saw both Devon and Ellesmere islands, searching for the Northwest Passage in 1616. The islands were not seen again by Europeans until the renewal of attempts to find the Northwest Passage in the 19th century. Unlike the other island groups, New Siberian Islands were discovered by land and ice crossing in 1712 by a Cossack company. Herald Island, adjacent to Wrangel Island, was sighted in 1849 but the first people to land were probably the crew of USRC Corwin in 1881 and Severnaya Zemlya was the last archipelago to be discovered, by Russian icebreakers in 1913 (Wikipedia, 2018).

The archipelagos of the Arctic Ocean comprise some of the remotest and most physically challenging places on earth. The combination of high latitude, proximity to the frigid waters of the Arctic Ocean and the presence, in many places, of mountains and remnant ice-caps, combine to make these some of the coldest places with permanent settlements. Recent permanent habitation on the archipelagos, excluding military installations and weather stations, occur on the Canadian islands, on Svalbard and on Yuzhny Island (the southern island of Novaya Zemlya). The population in the Canadian islands comprises two small Inuit communities: Resolute Bay on Cornwallis Island (~200 people, Fig. 18), and Grise Fiord on the south coast of Ellesmere Island (~120 people, Fig. 19). There are five permanently occupied settlements on Spitzbergen, the largest island of the Svalbard archipelago, with the main town, Longyearbyen (Fig. 20), supporting a permanent population of about 2000 people and four other settlements currently occupied year-round, of which two are mines and one is the research facility of Ny-Ālesund, on the shore of Kongsfjorden. They support an additional 500 people year-round. In Novaya Zemlya, there are several settlements on Yuzhny Island (the southern large island), most near the southern end, with the largest town, Belushya Guba (Fig. 21), supporting about 2000 people and with several hundred more resident in the other hamlets.

The coldest settlements are the Canadian villages, which are Canada's northernmost settlements. They experience only 3 months when the mean daily temperature exceeds 0°C; the mean maximum temperature in July is only 7°C and the maxima in January–March are below −30°C. The monthly mean minimum and maximum temperatures at Longyearbyen are −21°C and −13°C (Feb) and +3°C and +7°C (Jul) and at Belushya Guba, −19°C and −11°C (Feb) and + 3°C and + 12°C (Jul). These two towns are among the warmest places in the Arctic Ocean islands.

In addition to the permanent settlements, temporary camps come and go throughout the islands, weather stations exist on all the archipelagos (e.g., Eureka, Canada; Fig. 22) and minor military facilities exist in the Canadian islands, as well as on all of the Russian archipelagos, but not on Svalbard, which has been declared a demilitarized zone (Koivurova and Holiencin, 2017). Novaya Zemlya, a former nuclear weapons test site, still supports substantial permanent military bases. Recently, Russia has enlarged military facilities on Alexandra Land, Franz Josef, stationing year-round, combat-ready troops there (RFE, 2015).

Conservation

The Arctic being among the most remote places on Earth does not confer immunity from human activities that threaten ecosystem maintenance. Because existing terrestrial ecosystems on the Arctic Ocean islands have very low productivity, they will take a long to

Fig. 18 The settlement of Resolute Bay, Cornwallis Island, Qikiqtaaluk Region, Nunavut. The airport and associated logistics base of Polar Continental Shelf Project is 5 km northwest of the village (Google Earth Pro, 2018).

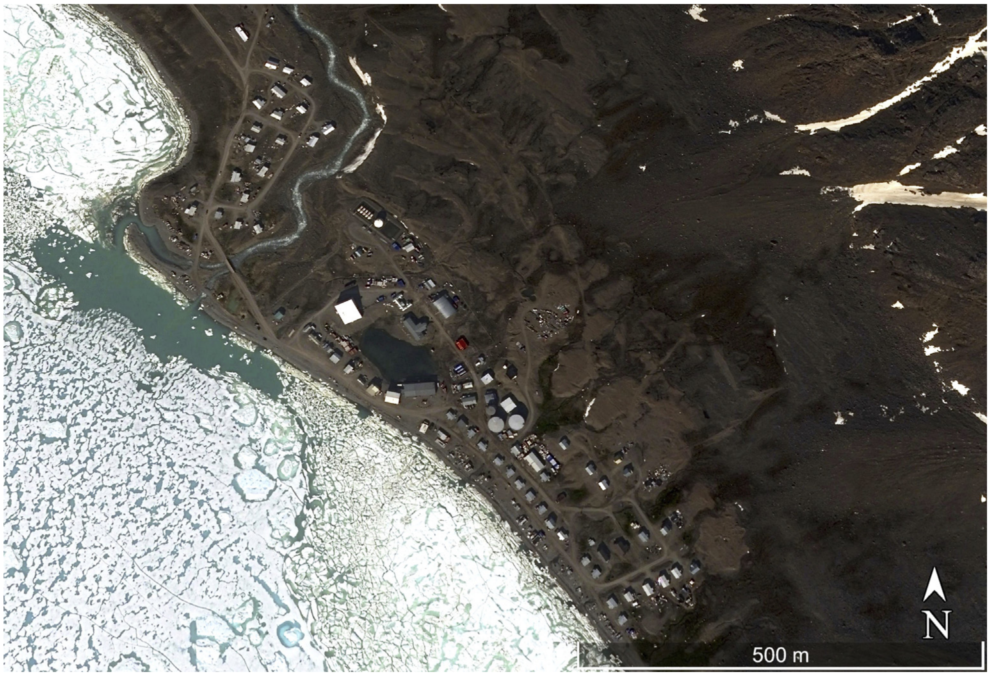

Fig. 19 Grise Fiord, Ellesmere Island, a small community in the Canadian high Arctic (Google Earth Pro, 2018).

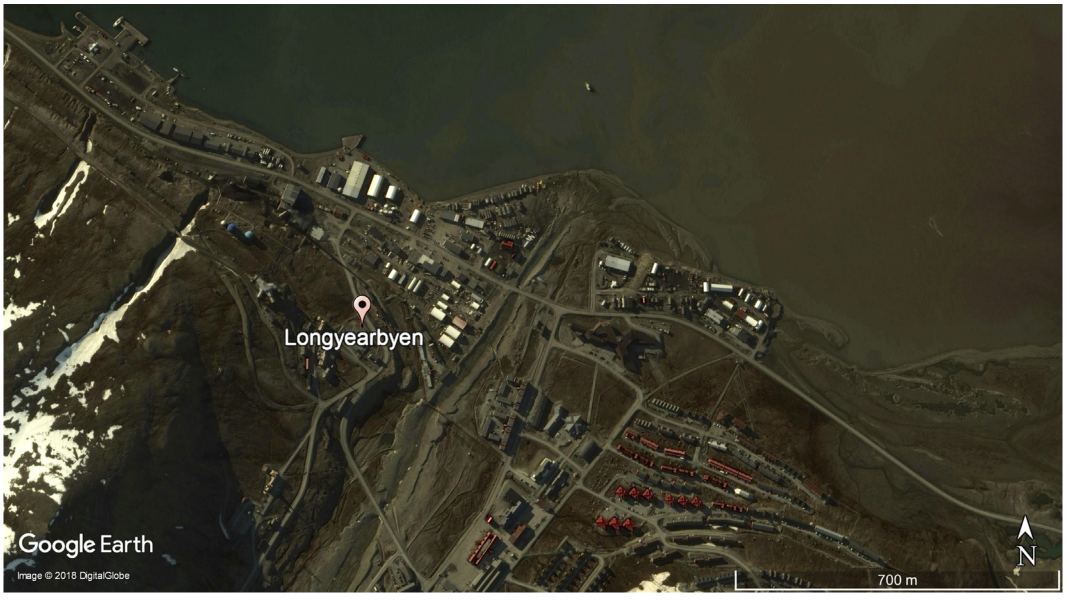

Fig. 20 Longyearbyen, Spitzbergen, the largest settlement in Svalbard (Google Earth Pro, 2018).

recover, once disturbed. Potential sources of disturbance include tourism, oil and gas exploration and exploitation, facilities relating to transportation, especially those relating to the northern Sea route along the Siberian coast, and increased militarization in the wake of increasing East–West tension.

Resource Extraction

Coal mining has been ongoing in Svalbard since the late 19th century and has been the major force in creating a permanent human population there. Russian interests continue to mine coal, although activity is less than in the 20th century. A small amount of mining has been carried out in the Canadian islands, with the Polaris mine on Little Cornwallis Island producing more than 20 million tons of zinc over 21 years. It closed in 2002. As of 2018, a new lead-zinc mine is being developed on Yuzhny Island, Novaya Zemlya by the ARMZ Uranium Holding Co. and is due to begin production in 2023 (Staalesen, 2018).

Fig. 21 Belushya Guba, Yuzhny Island, the main town of Novaya Zemlya (Google Earth Pro, 2018).

Fig. 22 Weather station at Eureka, Ellesmere island *(Google Earth Pro, 2018).

Mining affects the environment through the related disturbance, as well as disruption of drainage patterns. Vegetation characteristics and schedules of snowmelt can be noticeably altered by road dust (e.g., Auerbach et al., 1997), but a Canadian study found few negative effects of mining activities on birds within 1 km of the mine footprint (Smith et al., 2005). Some birds of prey nest on rock faces or infrastructure from mining activities and appear resilient to moderate levels of human disturbance (Swem Jr., 1996). Indeed, some birds of prey may benefit from the artificial lighting, food subsidies and nesting substrate offered by resource extraction infrastructure. Further study is needed to better understand the effects of disturbance and habitat degradation related to mining at local and regional scales.

Potential oil and gas reserves have been identified on or close to all the arctic archipelagos (Meneley, 2008, Craighill, 2015, Klett, 2017, Marex, 2017, Nilsen, 2017). Widespread oil and gas exploration took place in the Queen Elizabeth Islands of Canada from 1968 to 1987 (Meneley, 2008), but despite the discovery of 17 oil or gas fields, no commercial exploitation has ensued. Although exploration was proposed in Baffin Bay, southeast of Devon Island, permission was withheld by Government of Canada on environmental grounds (Davidson, 1981) and the area has subsequently been given protection as part of the Tallurutiup Imanga National Marine Conservation Area (Doyle, 2017). Exploration is currently ongoing in the Barents, Kara and Laptev seas, but to date the only commercial production, in the southern Barents Sea, is far from Svalbard. No commercial wells have been developed on land in any of the islands, but the development of adjacent shelf seas looks very likely.

Oil and gas exploration on land, like mineral exploitation, can significantly degrade both terrestrial and aquatic habitats. The shallow wetlands of the Arctic are sensitive to disturbance of hydrology: Oil and gas extraction can induce subsidence, seismic exploration can lead to channelization and disruption of water flow patterns, and infrastructure and road dust can affect snow melt and permafrost (Jorgensen et al., 2010). Despite technological advancements in seismic exploration, these activities continue to significantly degrade tundra habitats (Kemper and Macdonald, 2009). In addition, industrial activities can lead to locally enriched populations of predators, indirectly impacting local breeding birds (Liebezeit et al., 2009). Birds such as ivory gull and gyrfalcon are known to be affected by low-level aircraft over-flights, such as those associated with oil and mineral exploration (Platt, 1977; Mallory et al., 2008). These and other secondary effects greatly expand the area impacted by resource extraction activities.

Tourism and Other Human Disturbance

Ecotourism is increasing in the Arctic, and human visits to colonies and important breeding areas for birds are increasingly frequent. Disturbance from aircraft, cruise ships, boats, and humans can affect the reproductive success of birds by causing eggs or chicks to fall from breeding ledges on cliffs (e.g., for Thick-billed Murres: Curry and Murphy, 1995) or by leaving eggs vulnerable to predators when parents temporarily desert their nests (e.g., eiders and murres). Likewise, terrestrial mammals may be forced to leave foraging areas. Disturbance of wildlife by aircraft, ships and other vehicles is becoming an increasingly important concern among northern wildlife managers and residents.

Pollution

Most of the harmful pollutants that are released in large quantities at lower latitudes, such as agricultural pesticides, are not used in the Arctic. Industrial chemicals, such as Polychlorinated Biphenyls (PCBs), may be released near communities and development sites, but the effects are usually localized. However, within the Arctic, a substantial risk of pollution comes from chemicals transported over long distances, entering into Arctic environments through atmospheric deposition, ocean currents, and river outlets (e.g., Macdonald et al., 2000; Braune et al., 2005). Through the process of bio-magnification as they ascend the food chain, some pollutants threaten species at the top of the food chain, such as marine mammals, seabirds and especially polar bears (Norstrom et al., 1998).

Some industrial chemicals, such as PCBs, have been regulated since the 1980s but others, such as flame retardants (PBDEs) that are used in computers, car parts and upholstery were not controlled until after 2000. The presence of these compounds in Arctic wildlife is decreasing (Braune et al., 2015a, b), but heavy metals such as mercury and cadmium remain a concern for some species (e.g., Provencher et al., 2014; Braune et al., 2014) and the pathways by which they enter arctic systems are not well understood (Macdonald et al., 2000). In the case of mercury occurring in the Arctic, the most likely source is East Asia, transported by upper atmosphere winds and deposited with precipitation (Braune et al., 2014). Future changes to food webs may affect contaminant exposure, as species adjust their diets and feed higher or lower on the food chain (Braune et al., 2015a). Data exist for only a handful of Arctic species, but the effects of pollutants on arctic wildlife are potentially widespread.

As shipping through the Arctic increases, birds in marine habitats face an increasing risk from chronic oil pollution and accidental spills. Chronic pollution can lead to oiling of individual birds, but may also threaten birds indirectly, through food chain effects (Wiese and Robertson, 2004). Some species, including Common and King Eiders, forage on benthic invertebrates where hydrocarbons may reach dangerous levels (Meador et al., 1995). The risks to wildlife from accidental oil spills are substantial everywhere but are greatest in the Arctic where cold water temperatures, ice cover and periods of darkness limit the dispersal and decomposition of oil and complicate clean-up options (Arctic Council, 2009). When birds or marine mammals concentrate in one place, such as when the entire Canadian population of Pacific common eiders stages in the Southeast Beaufort Sea while on spring migration, risks may extend to whole populations.

Military Installations

Because military arrangements are not usually subject to any local political control, the enforcement of environmental regulations for military bases is more difficult than making the equivalent arrangements for civilian developments. The northern island of Novaya Zemlya, used from 1955 to 1990 for nuclear explosion testing, is still largely under military control. The proliferation of military installations in the high Arctic archipelagos is likely to complicate any future actions for ecosystem protection.

Protected Areas

Currently, the amount of land area within the Arctic archipelagos covered by Protected Areas (International Union for the Conservation of Nature (IUCN) protection categories I-IV) is much higher than in the Arctic as a whole (Huntington, 2013). Both Wrangel Island and Franz Josef Land are completely protected: Franz Josef as part of the Russian Arctic National Park, which also includes northern Novaya Zemlya, amounting to 7% of that archipelago, and Wrangel Island is a State Nature Reserve. Svalbard contains several Protected Areas, amounting to 65% of the land area, while in the Canadian archipelago two National Parks amount to 10% of the total land area. Neither Severnaya Zemlya nor the New Siberian Islands have protection at this level at present, but the area protected for all archipelagos combined is approximately 110,000 km^2, 17% of the total land area, which compares with 11% for the entire area defined as Arctic by the Convention on Arctic flora and Fauna (Huntington, 2013).

Climate Change and the Future of the High Arctic Fauna and Flora

Global warming is especially acute in the Arctic, where air temperatures have risen two to three times as fast as those elsewhere on Earth over the past 30 years (Pachauri and Reisinger, 2007). Arctic glaciers in Greenland and the Canadian islands are in rapid retreat (Rignot and Kanagaratnam, 2006; White and Copland, 2018a, b). Advances in the timing of Arctic spring sea ice break-up (Parkinson and Cavalieri, 2008), and substantial increases in both summer and winter air temperatures at many Arctic stations (Tedesco et al., 2009), are well documented. Arctic-adapted plants and animals may be affected directly, through susceptibility to elevated temperatures and other climatic changes (e.g., Gaston et al., 2002 found heat and water stress caused avian mortality in warm years in northern Hudson Bay, while Anctil et al., 2014 showed that higher rainfall increased nestling mortality of Arctic-breeding Peregrine Falcons *Falco peregrinus*). For most organisms, however, indirect effects, through changes in ecosystem structure (e.g., reduced prey, increased predation, competition, parasitism and disease) are likely to have a greater impact (Ganter and Gaston, 2013).

Although climate change poses a threat to all the world's ecosystems, those of the high Arctic are especially vulnerable because, being limited to the northern fringes of the continents, they have no way to find refuge as distributions shift northwards. However, the high Arctic islands, especially those beyond the swimming range of terrestrial vertebrates (all of those dealt with here), provide a special case where some of the potential effects of climate change may be delayed. Southern predators, of which mammals such as Lynx *Lynx spp.*, red fox *Vulpes vulpes* and various Mustelidae (*Martes*, *Mustela*, *Neovison*, etc.) have the greatest potential for disrupting current ecosystems, may not be able to spread across water barriers. Once seasonal ice cover disappears, they will not be able to access these remote islands unless inadvertently imported by people (Gaston et al., 2012). In this context, increasing tourism, development and military activity pose a real threat to biosecurity and ecosystem integrity.

The most distant archipelagos (Svalbard, Franz Josef) are likely to see only slow and selective immigration of southern plants and insects (Coulson et al., 2002), especially those taxa with low dispersal capabilities (e.g., plants with heavy seeds, nonflying animals). Moreover, the fact that these islands will continue to be surrounded by cool seas will prevent them from experiencing extreme temperatures characteristic of continental land-masses. Consequently, they may provide us with the best opportunity available for protecting the characteristic Arctic fauna and flora.

Unless we decide to deliberately introduce absent species to Svalbard and other remote islands, our best option for the defense of the high Arctic flora and fauna will be in the Canadian archipelago. These islands are the most extensive and have the widest range of native plants and animals among the Arctic Ocean archipelagos. Placing a "*cordon sanitaire*" around them, by rigorous exclusion of potential southern invasive species, may provide the best opportunity to allow the biotic communities of the high Arctic to persist in the face of climate warming. To achieve this goal, awareness of the risk from species invasions and the development of systems for inspection of ships, aircraft and cargoes arriving in the high Arctic islands will be necessary. The time for action is now.

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