CHAPTER 4

Polar Coastal Wetlands: Development, Structure, and Land use

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Contents

1. Introduction

Polar coastal wetlands mostly consist of salt- and brackish/fresh-water marshes, laida (coastal tundra inundated by seawater during storm surges or by freshwater at the time of snow and ground-ice melt), and coastal tundra plains with numerous ponds and shallow lakes in Arctic and sub-Arctic zones affected by permafrost (Figure 1). Vegetated coastal wetlands are found along every northern coastline, although locally they are often poorly developed especially on coasts of polar deserts. The deserts have a very cold climate (less than 10°C average during the warmest month of the year), very low precipitation (less than 250 mm/year to as low as 45 mm/year), and extreme poverty of life (Callaghan et al., 2005).

In the north, coastal marshes are well represented in low Arctic and sub-Arctic lowlands. They may bound wide tidal flats in protected embayments or develop behind coastal barriers partially inundated by tides where fine sediments (mud to fine-grained sand) can accumulate and vegetation grows under waterlogged

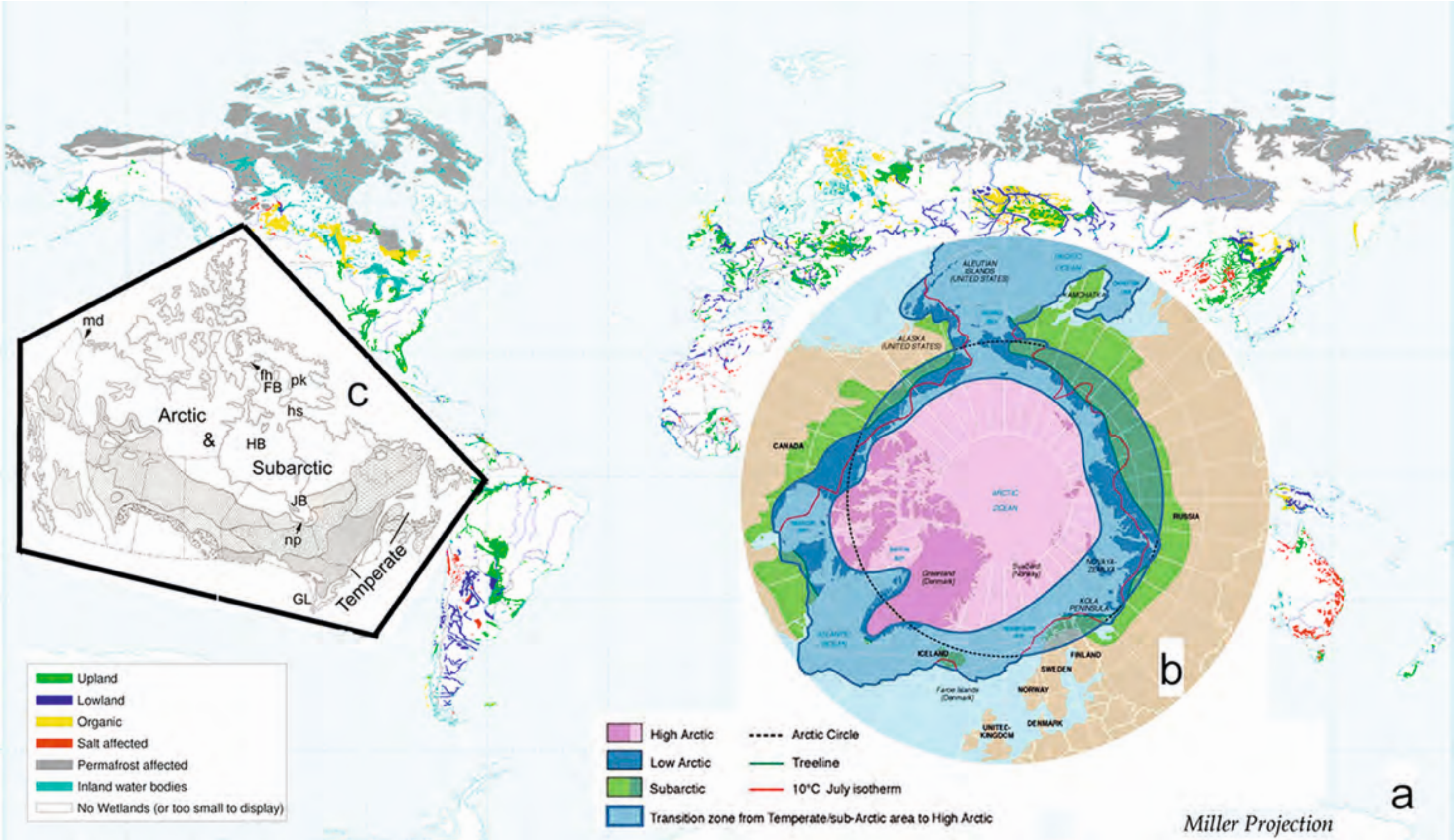

Figure 1 Wetlands. (a) Distribution of wetlands on Earth; polar wetlands are characterized by the presence of permafrost. (b) Distribution of Arctic and sub-Arctic zones in which polar wetlands are located. (c) Distribution of the major types of Wetlands Regions of Canada (the Boreal Wetland Zone is further subdivided into various sectors as indicated in Zoltai, 1980) (FB, Foxe Basin; fh, Fury and Hecla Strait; GL, Great lakes; HB, Hudson Bay; hs, Hudson Strait; JB, James Bay; np, North Point; md, Mackenzie River Delta; pk, The Great Plain of the Koukdjuak). [Compilation of data from U.S. Dept. of Agriculture (1996), UNEP/GRID (2006), Zoltai (1980)].

conditions. Laida and other coastal tundra also develop on low-lying polar coastal plains. Equivalent types of marine coastal wetlands do not develop to any extent in the Southern Hemisphere because few ice-free lands occur south of the Antarctic Circle. In addition, surface marine currents flow latitudinally and, unlike the Northern Hemisphere, do not refrigerate the continents at lower latitudes.

Some of the largest polar salt marshes have developed in the Hudson Bay Lowland, on the coasts of Hudson and James bays. Some of the largest laida and tundra coastal plains occur in the southeastern corner of the Foxe Basin, along the Arctic Coastal Plain of Alaska and Yukon, and along the Russian Arctic coast. Brackish marshes and other coastal wetlands develop extensively on deltas/ estuaries of rivers that flow into Hudson and James bays and the Arctic Ocean, such as in the deltas of the Mackenzie River (Canada) and Lena River (Russia) (Figure 1).

Multiyear, multidisciplinary studies of wetlands and their land uses have been carried out along the western coasts of James Bay (JB) and southwestern Hudson Bay (HB) and to a lesser extent in the Foxe Basin (FB) and some of the Canadian Arctic Islands. Variations in sediment, soil, vegetation, and distribution of infauna and migratory birds were recorded along selected transects from the sea to the upper marshes. Regional physiographic variations of the coastlines along a south–north transect were also examined (Figure 1c). In addition, detailed multiseason analyses of local estuarine areas and selected coasts have been made, such as at North Point (np) in James Bay (Figure 1c), which allow for benchmark comparisons to be made with coastal wetland sites elsewhere.

2. Geology/Geomorphology

The Arctic regions have been affected by several orogenies (mountain-building episodes) and are mountainous over large tracts. A series of terranes (fragments of the Earth's crust) accreted during the Mesozoic in present Arctic areas where mountain ranges developed in northeastern Russia, Alaska (such as the east–west trending Brooks Range (BR)), Canadian Arctic (such as the Richardson Mountains (RM) and Innuitian Mountains), and northern Greenland. Older Caledonian mountain belts developed during the Paleozoic in eastern Greenland, northern Europe, and the central parts of Russia (Ural Mountains) (Figure 2). The Kamchatka Peninsula in northeast Russia and the Aleutian Islands to the west of Alaska are two active tectonic areas where continuing subduction of the Pacific tectonic plate has in the past generated, and is still generating, active volcanoes and rugged terrain. Nevertheless, extensive Arctic lowlands occur in between or in front of these mountain chains along the Arctic Coastal Plain of northern Alaska, in the Mackenzie River delta in NW Canada, and in parts of the Arctic Russian coastal areas west and east of the Ural

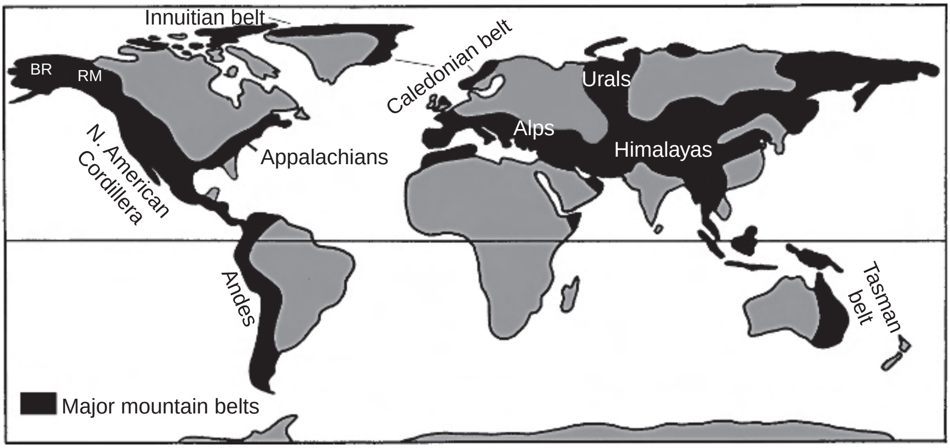

Figure 2 Distribution of major mountain chains on Earth (BR Brooks Range; RM Richardson Mountains).

Mountains. In northeast Canada, other extensive coastal plains occur in Arctic and sub-Arctic zones that extend southward along the coasts of Hudson and James bays bounded by the North American Precambrian Shield and underlain by low-lying Paleozoic rocks of old inland basins.

Most polar areas have been variously glaciated during Late Pleistocene except in a few cold but dry areas in northernmost North America and Russia (Figure 3a,b). The large ice sheets were thicker at their epicenters (domes) and thinned toward saddle and peripheral areas. This had several consequences that still affect polar coastal areas. The weight of the glaciers depressed the Earth's crust, and as the glacier melted, differential isostatic rebound has led to uplifts of more than 200 m. The rebound is still continuing at rates that vary from around 1 m per century where the ice was thicker near the centers of glaciation at mid-high latitudes to minimal rates of uplift in other areas. The isostatic uplift also led to land emersion from large lakes and seas that had formed in front of the glaciers, and subsequently extensive coastal plains developed. Land emersion (regression) continues in areas near former ice domes where the land uplift is more rapid than the present sea-level rise. This occurs along the western coasts of Hudson and James bays, along the Gulf of Bothnia between Finland and Sweden, and in the White Sea in northwest Russia. Where the land uplift was small and is no longer occurring and where there is no active neotectonism, a marine transgression is taking place, such as along the Arctic Coastal Plain of Alaska, northwestern Canada, and parts of the Siberian coastal plains.

The extent of glaciation in central-north Russia is still unresolved: two major hypotheses have been put forward (Grosswald, 1998; Velichko et al., 1997). One hypothesis proposes a wide, thick glaciation during the Late Pleistocene, which could have generated postglacial isostatic uplift similar to that of North America and Fennoscandinavia (mainly Finland, Sweden, and Norway). The other

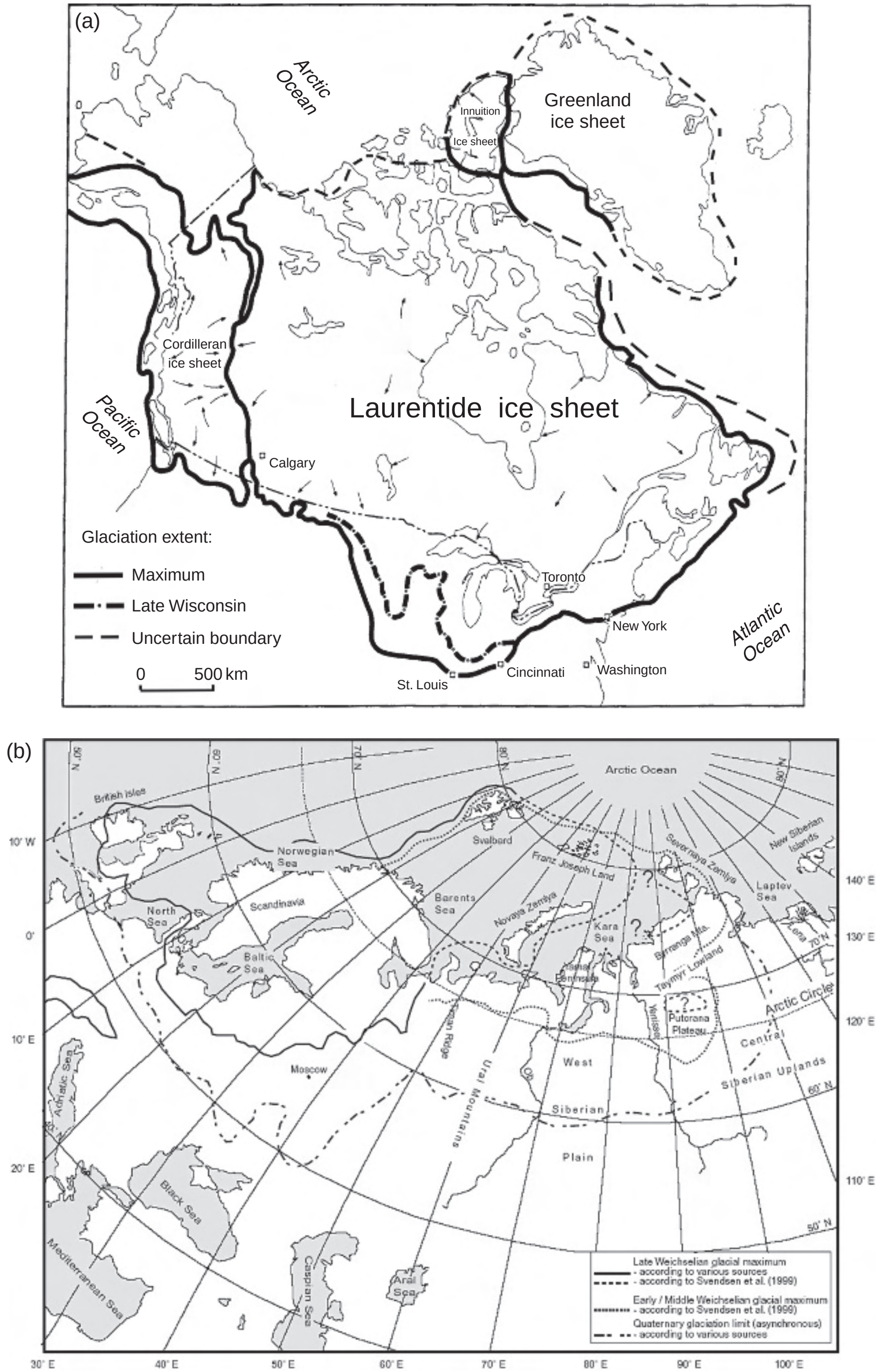

Figure 3 Pleistocene glaciations of northern lands (after Flint, 1971; Fulton, 1989). (a) North America. (b) Arctic Russia; the wide glaciation hypothesis considers the Yamal and Yenissei area to have also been glaciated in Late Pleistocene (late Weichselian) (adapted from Raab et al., 2003).

suggests a restricted glaciation that generated smaller areas of postglacial isostatic uplift. For example, uplift is still occurring in the White Sea area in the Kola Peninsula, northwest Russia (Jeglum et al., 2003).

3. Oceanography

The inshore Arctic seas are generally shallow, particularly along the Russian coasts, Foxe Basin, and James Bay. They and their respective coasts are subjected to a harsh climate and a seasonally variable ice cover that is more severe at the northernmost latitudes where ice is present throughout the year. Sea ice influences marine currents, tides, and waves that, in turn, affect the stability of coastlines although their potential action is limited to a few months of the year.

The marine currents of the Arctic Ocean and the adjoining inland seas are complex (Figure 4). In North America Arctic waters enter the Canadian inland seas from the Fury–Hecla Strait in the northwest corner of Foxe Basin and are carried down into Hudson and James bays to latitudes of about 51° N, cooling off the surrounding lands. Conversely, the northern lands of Fennoscandinavia are warmed by a branch of the North Atlantic Drift current up to approximate latitude of 70° N, well above the Arctic Circle.

The tides of the northern seas are generally microtidal (less than 2 m in amplitude), but several shores experience mesotidal excursions, such as those of Hudson Bay, James Bay, and the Barents Sea. Macrotidal excursions with tides exceeding 5 m and locally 10 m occur in a few embayments, such as Bristol Bay in west Alaska, Bowman Bay in the southeast Foxe Basin, Frobisher (Iqualuit) Bay in southeast Baffin Island, parts of Ungava Bay along the Hudson Strait, Mezen Gulf in east White Sea, and the Gulf of Shelikov in the northern Okhotsk Sea.

The salinity of the Arctic seas may in some places vary drastically from season to season due to the formation and melting of the ice cover and to the variable input of fluvial freshwater during spring–summer freshets (floods). "Unlike tropical oceans, which are temperature-stratified (there is a thermocline), the Arctic Ocean [and adjacent Arctic seas] is [mostly] salinity-stratified (there is a halocline), although at high latitudes the ocean is much less stable. The temperature profile of Arctic waters is nearly uniform at 0° to 1°C"(Linacre and Geerts, 1998).

Brackish-water conditions develop in and near the estuaries of major rivers during the spring–summer freshets, and more marine saline conditions are reestablished later when the river discharge decreases drastically. One dramatic case occurs in the shallow, southern James Bay, where freshwater is injected into the shallow sea by the northward flowing river floods. The anticlockwise marine current of the bay moves these waters northeastward, freshening the eastern coast of the bay significantly more than the western coast.

Figure 4 Marine currents (arrows) in the Arctic Ocean and adjacent seas (north-directed arrows just west of Iceland and Norway represent movement of warm water into the Arctic) (after AMAP, 1998).

4. Climate

Average annual low temperatures and amounts of precipitation decrease substantially from south to north, particularly where polar deserts are present, such as in the northernmost parts of the Russian and Canadian Arctic Islands. The cold climate and the strong variation in day length throughout the year greatly affect assemblages of plant and animal species. There is a particularly low species richness in polar deserts.

A cryosphere has developed in northern areas, which includes ice formation over water bodies and within the ground (permafrost). The distribution of permafrost in northern lands does not regularly follow latitudinal alignments; rather, it is influenced by the heat redistribution brought about by atmospheric movements and marine currents. Accordingly, there is a southern dip of continuous and discontinuous permafrost in continental and mountainous areas of central Asia and, more relevant for this chapter, a latitudinal dip in central-east Canada where anticlockwise marine currents bring cold Arctic waters to low latitudes in Hudson and James bays (Figure 5). The effect of marine currents is dramatically evidenced in James Bay, where warmer fluvial waters are injected into the bay from the south and are moved northeastward along the shore by marine currents, leading to a significant northward shift of the permafrost zones on the east side of the bay.

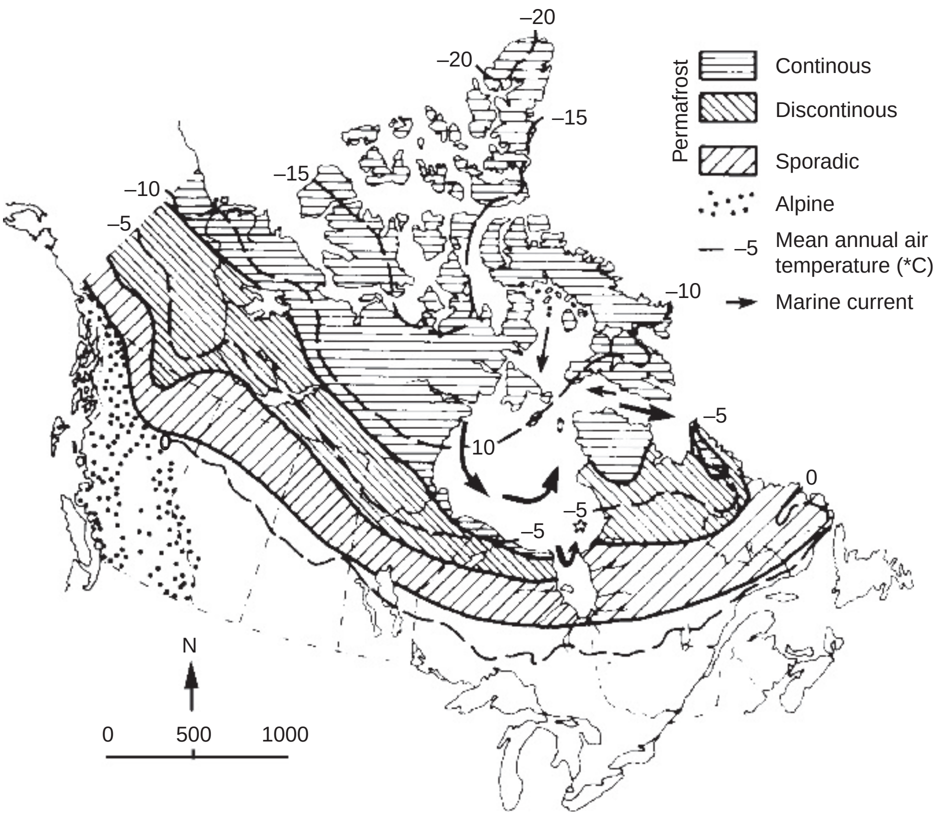

Figure 5 Distribution of permafrost in Northern Canada (after Atlas of Climatic Maps, Canada, 1967).

Furthermore, whereas new (modern) permafrost is actively forming at mid-latitude where the land is actively emerging from the sea, Pleistocene relict permafrost is present in the high Arctic. Such relict permafrost has undergone adjustment to the variable Holocene climates, particularly during the postglacial temperature maximum (approximately 8,000–7,000 years BP) in northwest Canada and northern Alaska, as demonstrated by peat accumulations of that age, but which are now frozen and inactive. This has led to the development of various geomorphologic structures in these landscapes including numerous thermokarst features (Washburn, 1973; Ruz et al., 1992).

Frozen soil constitutes a barrier to free groundwater movement. In the high Arctic, a thin (<1 m) surficial active layer thaws during the summer. Water moves by convection only within this thin layer, as the underlying permafrost for the most part impedes percolation, and, thus, waterlogged conditions are favored (Woo, 2002). Farther south in the discontinuous and sporadic permafrost area of the sub-Arctic, the groundwater movement is less influenced by the ground ice: near-surface water flow is only partially obstructed by locally persistent ice lenses. The groundwater flow is still very slow, though, because of the very low hydraulic conductivity of peat.

5. Structure of Coastal Wetlands

The characteristics of polar coastal wetlands depend on abiotic and biotic conditions. They range from extensive seashore meadows showing a transition from saltwater to freshwater on large coastal plains such as the sub-Arctic and Boreal marshes of James and Hudson bays, to narrow strips of depauperate vegetation in the mid- to high-Arctic where narrow wetlands mostly developed in swales between beach ridges and brackish-water systems in deltaic areas.

Salt marshes are a characteristic landscape feature of low-lying Arctic coastlines (Jefferies, 1977; Macdonald, 1977; Bliss, 1993). The best-developed marshes of the low Arctic to sub-Arctic are those on the southern and western coasts of Hudson and James bays (Jefferies et al., 1979). They have developed in the last 300–400 years as the Hudson Bay Lowland has continued to emerge as a result of the isostatic uplift (Andrews, 1973; Mörner, 1980). Two major types of marsh have formed: one on open coasts and the other in swales on coasts with beach ridges.

1. The widest salt marshes occur inland from open, extensive sand and mud flats (Figures 6a,b), and brackish marshes are formed in estuarine areas and on mainland coasts freshened by fluvial plumes (Figure 6c,d). Less well-developed marshes form on steeper shores with higher waves and low sedimentation rates, where limited fine-grained deposits occur in bouldery areas. The salt marshes open to the sea are much impacted by ice. During the melting season, ice floes are grounded and later lifted and removed by tides, or ice pressure ridges form (Figure 7a). This leads to the removal of marsh

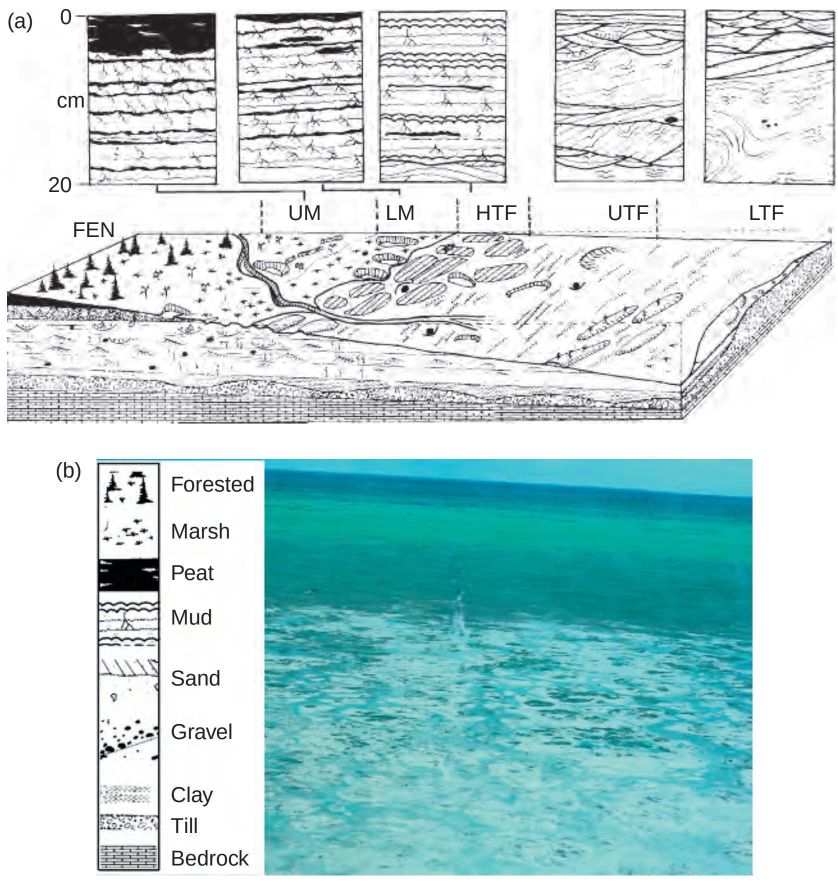

Figure 6 Structure of well-developed sub-Arctic coastal marshes, western James Bay. (a,b) Marsh of open coasts with a well-developed gradation from algal high tidal flats at the shoreline to inland freshwater marshes and peat-bearing fens. The diagrams show a cross section of the substrate stratigraphy, the surficial depositional features (barbed short line indicate sandy ripple marks), and erosional features by ice floes, progressive colonization of the raised coastal plain by grassy vegetation, shrubs, and trees, and, in the top short columns, the stratigraphy of the top 20 cm of the laminated and cross-laminated (inclined lines) recent sediments and peat (symbols of diagrams are explained in vertical profile in "b") (after Martini et al., 2001). (c,d) Extensive brackish- to freshwater marshes on river-influenced coasts. (e,f.) Coast with beach ridges and bilaterally structured coastal wetlands in the interridge swales. (UM, upper marsh; LM, lower marsh; HTF, high tidal flat; UTF, upper tidal flat; LTF, lower tidal flat).

material frozen to the underside of the floes, or to scouring due to ice push. As the land emerges further and becomes more vegetated, typical jigsaw patterns of pools develop reflecting earlier ice action (Figure 7b).

2. Marshes also form in interridge swales that are inundated by high tides, where they acquire a bilateral vegetation distribution pattern with salt species closer to the mid-swale tidal creek and brackish and freshwater species farther

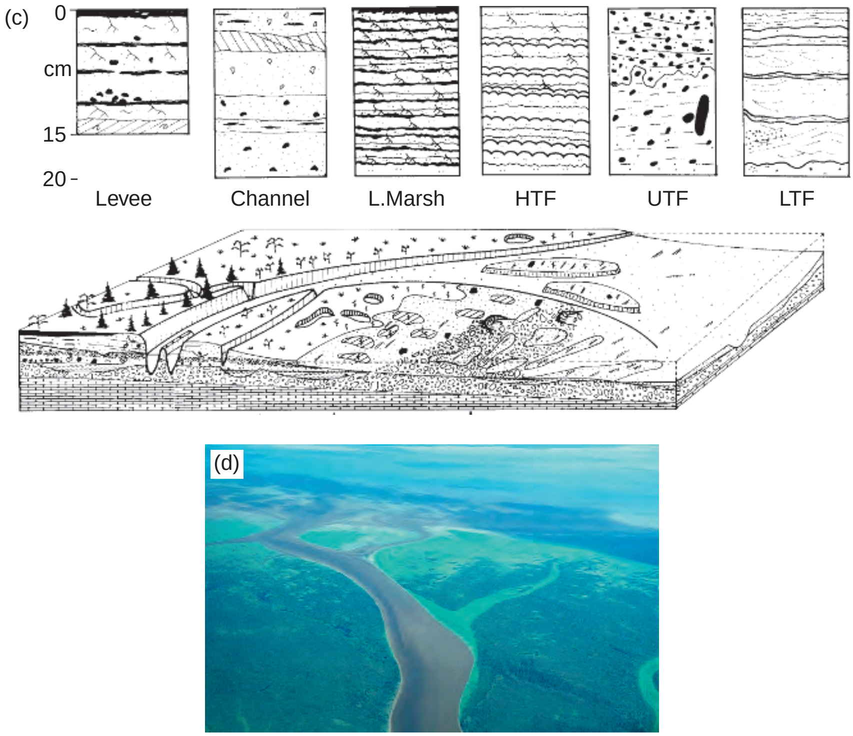

Figure 6 (Continued)

away from it. Locally, the marsh deposits of the swales have well-sorted sand grains (dispersed or in thin lenses) received from the bounding beach ridges, either blown in by strong winds or as a result of washover events during heavy storms (Figure 6e,f).

In low Arctic to sub-Arctic zones, the generally muddy, wet sediments of marshes are modified (ripened) as incipient soils develop. Incipient Bkg to Bg horizons with grayish brown colors (2.5Y5/2) (Protz, 1982) occur in the upper marshes, and ferrans (iron precipitates) may form around plant roots in better-drained parts of the system. Along transects from the shoreline inland, salt-marsh soils show a gradual increase in thickness of the surficial organic layer (never reaching the 30–40 cm thickness to qualify as peatlands), a decrease in sodium and chloride concentrations with an associated drop in electrical conductivity (e.g., from a seasonal average of 6.1 mS/cm in the lower marsh to 2.2 mS/cm in the upper marsh at North Point (np) in southwest James Bay; Figure 1c), a marked decrease in pH in the upper brackish/freshwater marshes, and a decrease in calcium carbonate equivalents. In some cases, a landward salinity inversion occurs with brackish marshes formed near the coast and saltwater marshes developing farther inland (Martini, 2006). Salinity of inshore seawater is often low (about

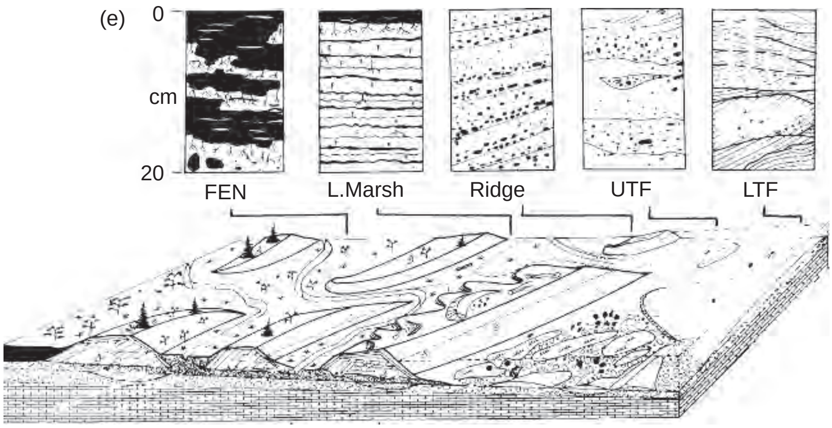

Figure 6 (Continued)

12 g of dissolved solutes per litre of soil solution), because of the inflow of freshwater from large rivers that drain into Arctic seas. The more seaward sections of marshes are less saline than the landward sections where disturbance, lack of tidal cover in summer, and drying out of the terrain can produce extreme hypersaline soils (about 120 g of solutes per liter of soil solution), which are devoid of vascular plants (Iacobelli and Jefferies, 1991). In southern James Bay, the inland more saline marshes located beyond the reach of storm surges derive salt from groundwater desalinating marine argillaceous silts of the substrate (Price and Woo, 1988).

In the mid- to high-Arctic zones, salt marshes open to the sea are generally poorly developed and infrequent. The coasts are affected by storm waves during the period of open seawater and commonly develop beach ridges, spits, and barrier beaches. On the isostatically rising lands, the beach ridges show various height and spacing. They alternate with interridge lows occupied by shallow lakes and ponds (Figure 8). Sparse vegetation grows in these interridge coastal wetlands, which may be described as true oases where they occur in the northernmost polar deserts.

Wetlands with numerous interlaced channels and lakes separated by patterned grounds develop on Arctic deltas, particularly along the Beaufort Sea (such as those

Figure 7 Effect of ice push and erosion on salt marshes. (a) Freshly developed ice push structures in high tidal flats, precursors to a more mature, pond-riddle marsh. (b) Mature salt marsh with jigsaw pattern that has developed because of formation of pools initiated by ice action.

Figure 8 Coastal ridges of Igloolik Island in northwest Foxe Basin, Nunuvut, in the mid-Arctic Zone of Canada.

of the Colville and Mackenzie rivers; Figure 9a) and along the Arctic Russian coast (such as those of the Lena River (Figure 9c,d) and Kolyma River). Pingos (small conical hills with a core of solid ice) develop in shallow lakes where the coastal areas are low lying, such as in the Mackenzie River delta (Figure 9b).

Thermokarst greatly affects Arctic coastal zones, but the change in the landscape differs depending on rates of uplift relative to sea-level rise. For example, the coastal plain of southeast Foxe Basin, the Arctic Coastal Plain of Alaska, and the Mackenzie River delta are characterized by numerous thermokarst lakes. There sea-level rise outpaces any residual postglacial isostatic rebound, and during the ensuing marine transgressions, considerable coastal erosion occurs and the coastal lakes become breached and invaded by the sea (Figure 10c,d; Ruz et al., 1992; Wolfe et al.,

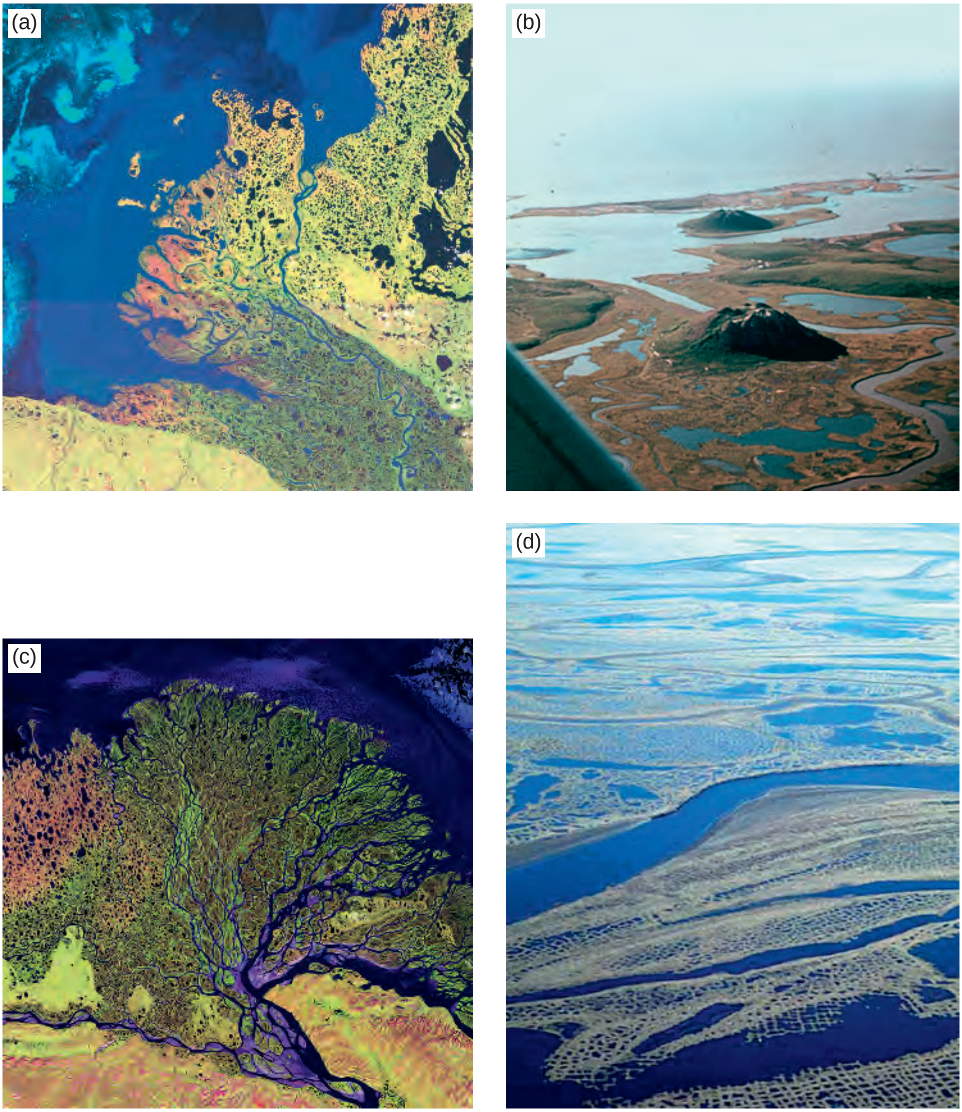

Figure 9 Coastal wetlands associated with polar river deltas. (a,b) Interlaced channels, lakes (several are thaw lakes) in the Mackenzie River Delta, Northwest Territories, Canada [(a) from NASA and (b) aerial view of part of the delta with pingos developed in a coastal lake, from Canadian Geological Survey]. (c,d) Interlaced channels, thaw lakes, and patterned ground of the Lena River delta, Russia [(c) from NASA; (d) aerial view of well-developed patterned ground in interchannel areas, adapted from Williams (1994)].

1998). Local salt marshes can develop inside the newly formed, protected embayments. In the Foxe Basin, instead, the land is still undergoing isostatic uplift and the thaw lakes of the coastal tundra remain isolated and are only locally breached and joined by creeks (Figure 10a,b).

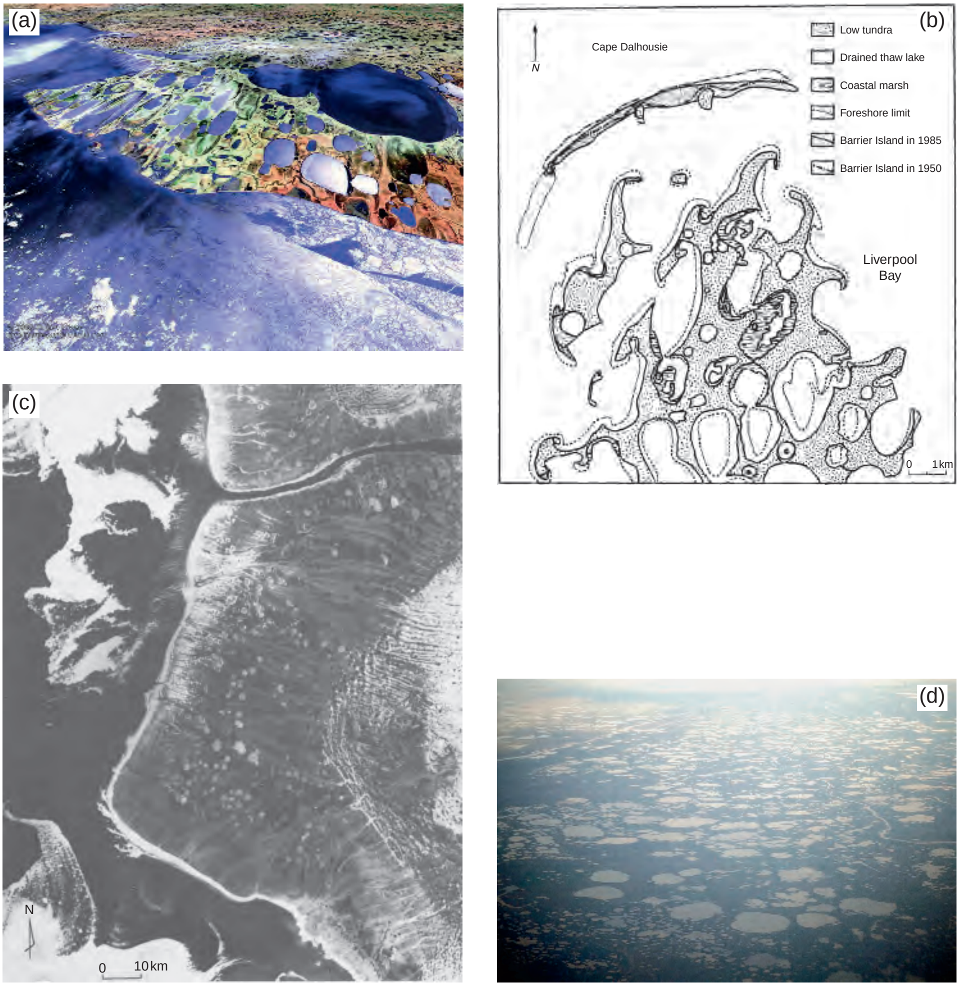

Figure 10 Thermokarst structures in coastal zones. (a) Thaw lakes in the Arctic Coastal Plain, Cape Harlett, Alaska (adapted from Bowen, 2005). (b) Breached thaw lake Mackenzie River Delta (after Ruz et al, 1992). (c,d) Isolated lakes in Great Plain of the Koukdjuak, southeastern Foxe Basin, Nunavut, Canada; (c) satellite image of the entire plain; (d) air view of part of the plain.

6. Vegetation of Polar Coastal Wetlands

Environmental conditions such as cold climate and icy conditions within the immediate coastal zones are often severe enough to restrict species richness. Furthermore, regional development portends a likely future scenario where some low-lying sedimentary coastlines and their associated biota become increasingly vulnerable to rise in sea level and the occurrence of tidal surges associated with global climate change. Other damaging oceanographic changes are likely to occur.

For example, the present mean annual discharge of freshwater to the Arctic Ocean and the Hudson Bay is estimated at 5,250 km^3/year (Shiklomanov et al., 2000), and significant increases (up to 30%) in discharge rates are projected to occur in response to climatic warming (Walsh et al., 2005). These changes in runoff will affect water levels, salinity, and nutrient fluxes in estuarine wetlands, all of which may be expected to alter biological production and biodiversity (Walsh et al., 2005). The extent to which the Arctic biota present at this interface between terrestrial and marine systems can adapt (genetic response) or modify behavior patterns (phenotypic plasticity) to this ongoing change is largely unknown.

Sea ice persists until late spring (mid-June) on many shores, which restricts plant growth in the early growing season. At that time, most sea ice is located at the seaward end of marshes and its presence may protect the lower marsh vegetation from grubbing by geese (Section 7.2.1). Ice rafting is common when the ice breaks free of the shore at melt. The underlying sediment and vegetation are still frozen to the base of the ice and are carried to different locations in melt or tidal water. The remaining exposed sediment may be colonized by inward clonal growth from adjacent intact graminoid swards.

The only studies of the nutritional status of Arctic salt-marsh soils are those conducted in the southern Hudson Bay region, where the results indicate that the soils are severely nitrogen-limited for plant growth (Cargill and Jefferies, 1984; Ngai and Jefferies, 2004). Addition of ammonium or nitrate salts leads to a rapid increase in the aboveground biomass in summer, but quickly growth becomes phosphorus-limited because of a colimitation of this element when nitrogen shortage is alleviated (Cargill and Jefferies, 1984). For the immediate coastal freshwater mires, mostly poor fens, plant growth is limited by both nitrogen and phosphorus (Ngai and Jefferies, 2004).

The plant species richness of Arctic and sub-Arctic coastal salt marshes is low compared to temperate marshes, and prostrate graminoids dominate the vegetation. The common vascular species that colonizes suitable sites along low-lying, muddy seashores throughout circumpolar regions is *Puccinellia phryganodes* (Figure 11a; Hultén, 1968). In Arctic North America, plants are triploid and although they flower, seeds are not produced. In northern Fennoscandinavia and in the White Sea region of the Russian Federation, there are reports of tetraploid races of this grass, but it is not known if seed set occurs (R.M.M. Crawford, personal communication). Hence, at least in North America and northern Russia, plants are dispersed by clonal propagation. Individual leaves, shoots, and tillers are able to establish in soft sediment and develop into plants (Chou et al., 1992). Individuals are extremely resilient to environmental stressors; they can survive encased in pack ice for months and have been grown successfully in an anaerobic jar in an atmosphere of nitrogen for a number of weeks (Crawford et al., 1994; Crawford and Smith, 1997). Another widespread circumpolar species is *Carex subspathacea* (Figure 11b) and this includes the closely related species, *Carex salina* and *Carex ramenskii*, which may be variants of *C. subspathacea*. The species appears to be less salt tolerant than *P. phryganodes* and tends to occur in areas that receive fresh or brackish drainage water from adjacent lowlands. Unlike the grass, *C. subspathacea* can grow in anoxic soils where drainage is impeded. Seed set is episodic and most growth occurs via clonal reproduction. Both graminoids have well-developed

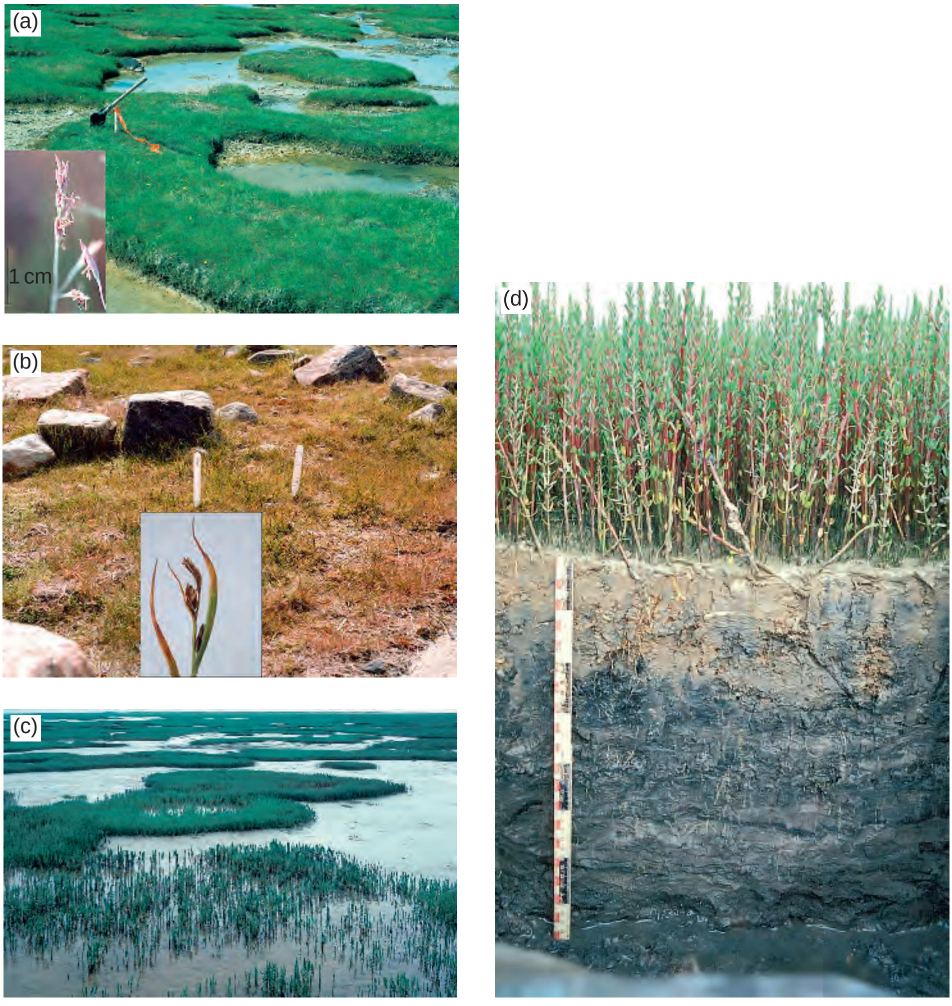

Figure 11 Typical plants of Arctic and sub-Arctic coastal marshes of James and Hudson bays. (a) *P. phryganodes* colonizing plants of salt marsh (inset: inflorescence from Aiken et al., 2003; Dalwitz et al, 2003). (b) *C. subspathacea* (adapted from Aiken et al., 2003; Dalwitz et al., 2003). (c) *H. tetraphilla* brackish marsh. (d) Thick silt deposits trapped by *H. teraphilla*.

rhizomatous and/or stoloniferous systems and the fine root systems are confined to the upper soil layers (<7.5 cm). Other species that are common include *Triglochin palustris* and *Triglochin maritima* (the former grows more seaward than the latter), *Cochlearia officinalis*, *Plantago eriopoda*, *Potentilla egedii*, *Ranunculus cymbalaria*, *Stellaria humifusa*, *Carex ursina*, *Carex maritima*, and *Festuca rubra* (Kershaw, 1976; Jefferies, 1977; Jefferies et al., 1979). All flower infrequently but seed set is uncommon and depends on prevailing local weather conditions. Weather conditions are also important in the previous year when flower buds are laid down in most species. There have been few studies of the seed bank in Arctic and sub-Arctic salt marshes (Staniforth et al., 1998;

Chang et al., 2001). The results show that the composition of the vegetation and the soil seed banks are only loosely correlated (approximately 50%), reflecting the poor contribution of the dominant graminoid species mentioned above to the seed bank. Some species are overrepresented in the soil seed bank compared with their abundance in the vegetation. They are weedy species typical of degraded or disturbed soils. Seed banks in impacted and fragmented sites do not recover quickly (Chang et al., 2001).

The annual growth habit is confined to the low Arctic, generally close to the Arctic/sub-Arctic boundary. Within salt marshes, three species are represented: *Salicornia borealis*, *Koenigia islandica*, and *Atriplex patula*, which mostly grow on an organic substrate in the upper levels of salt marshes or in supratidal marshes (flooded by seawater only during storm surges) but only set seed in favorable years. *S. borealis* does not have a well-developed long-term seed bank, and annuals are not the primary colonizers of exposed mudflats, as in temperate salt marshes. This functional group of annuals is a prime candidate to study the response of plants in the low Arctic to climate change. There are indications that *S. borealis* is spreading north on the Cape Churchill Peninsula, Manitoba in the last decade, but much of this spread may be related to the loss of vegetation and exposure of sediments as a result of goose grubbing (see below). Where salt marshes grade into beach ridges or dunes, *Leymus mollis* var. *arenarius* is common. This ecological equivalent of marram grass (*Ammophila arenaria*) in temperate latitudes is widespread in well-drained, disturbed, sandy habitats in the Arctic. Other species that occur in this type of habitat where there is some soil organic matter include *F. rubra* and the related species, such as *Sedum rosea*, *Parnassus palustris*, *Primula stricta*, *Bartsia alpina*, *Polygonum vivipara*, and *Chrysanthemum articum*.

Because of the large outflow of freshwater from rivers, brackish conditions often prevail in the tidal reaches of the estuaries and on open marine coasts close to the river mouths. The salinity ranges from about 3 g of solutes per liter up to 12 g/L. The range is the result of the movement of the tidal salt wedge along the lower reaches of the rivers. Because of the high rates of sedimentation in some estuaries associated with the deposition of the sediment load from rivers and the brackish conditions that prevail, soft sediments are often available for colonization by plants intolerant of full salinity. In these muddy estuaries, species such as *Hippuris tetraphylla*, *Hippuris vulgaris* (less salt tolerant), *T. palustris*, *Potamogeton filiformis*, *P. pectinatus*, *C. officinalis*, and *R. cymbalaria* readily establish in soft sediment or on shallow river bottoms if the outflow is not rapid. This flora is not confined to the vicinity of river mouths, but can occur in coastal areas beyond the intertidal zone where relict salt or brackish ponds are present as a result of isostatic uplift. *Hippuris* species develop an extensive rhizome system, and the stands of shoots produced by clonal propagation are very effective at trapping soft sediment, leading to a rapid change in coastal topography (Figure 11c,d).

7. Fauna of Polar Coastal Wetlands

Although species diversity in the Arctic is considered relatively low compared to other regions, the Arctic terrestrial fauna nevertheless contains some 6,000 species, which is about 2% of the global total (Chernov, 1995; Callaghan et al., 2005). From an ecological point of view, the fauna of polar coastal wetlands can be divided into two basic categories: an infauna consisting of organisms that live their life cycles within or in close association with the wetland; and a second group, an exfauna that makes use of the resources within the wetland on a seasonal basis, and whose members are migratory or nomadic. Polar coastal wetlands, in fact, play a critical role in the life cycles of many migratory animals, particularly birds; many species of waterfowl and shorebirds use Arctic and sub-Arctic wetlands both for breeding and/or as stopovers on migration to reach their breeding areas. The flora and infauna of the wetlands provide the food resources upon which the birds depend to complete their annual cycles.

7.1. Invertebrate fauna

Among invertebrates, primitive groups are better represented (such as springtails: 400 species, 6% of the global total of species) than advanced groups (such as spiders: 300 species, 0.1% of the global total). Typically, there is a reduction in invertebrate species and families with increasing latitude, and the distribution of some groups, such as spiders, is patchy (Chernov, 1995; Pickavance, 2006). The common invertebrate species in the far north tend to be widely distributed and only a few species may become dominant at high latitudes (e.g., 12 species of springtail in the northern Taimyr, Russia; Chernov and Matveyeva, 1997). Although there has been a steady increase in the description of invertebrate assemblages at site-specific locations within the Arctic, the roles of individual species and functional groups in community dynamics are poorly understood.

Coastal wetlands and their fauna fall into two broad categories: those at or near the shore involving marine or saltwater-influenced habitats, and those occurring slightly inland involving mostly brackish and freshwater habitats.

7.1.1. Invertebrate fauna of coastal saline areas

Marine intertidal invertebrates and other organisms have received limited study in many Arctic and sub-Arctic areas (although they are highly important food sources for a variety of birds, fish, and even mammals). The extent of intertidal areas that develops in different regions will depend on the geomorphology and sedimentary characteristics of the area, and intertidal organisms not only have to survive severe climatic conditions, but are likely to be subjected to annual removal or disruption caused by ice scour, which can affect the flats themselves and the near-shore waters to depths of up to 5 m. In James and Hudson bays, for instance, the bivalve *Macoma balthica* is the most common burrowing mollusk and much of the intertidal stock is removed by ice and wave action during the winter and spring but is replenished by spatfall (larval production) originating from subtidal populations each year. *M. balthica* has an extensive geographic range, inhabiting temperate to Arctic coastal waters in the North Atlantic and North Pacific oceans, and forms a prominent food resource for birds and fish in intertidal areas in Iceland, Hudson and James bays, and Alaska. Densities in James Bay average 2,000–3,700 individuals/m^2, with highest recorded densities in zones of eelgrass *Zostera marina* of up to 12,800 individuals/m^2

(Martini and Morrison, 1987). These densities are consistent with those recorded in other areas: Alaska, maximum 4,000 individuals/m^2 (Powers et al., 2002); St Lawrence Estuary (southeast Canada), maximum 2,700 individuals/m^2 (Azouzi et al., 2002); and Dutch Wadden Sea, 3,250 individuals/m^2 (Piersma and Koolhaas, 1997). Sub-Arctic tidal flats may be characterized as having fairly high densities of infauna invertebrates, but low species diversity. In James Bay, the intertidal fauna consist principally of *M. balthica* and the gastropod *Hydrobia minuta* (Martini et al., 1980), while on the Copper River Delta, Alaska, *M. balthica*, the amphipod *Corophium salmonis*, and the polychaete *Eteone longa* account for over 95% of individuals identified on the mudflats (Figure 12; Powers et al., 2002). Other organisms occurring in James Bay and other sites include gastropods, mussels, limpets, nematodes, oligochaetes, and polychaetes, as well as foraminifera, copepods, ostracods, amphipods, cladocerans, ectoprocta, and barnacles (Martini et al., 1980). Oligochaete worms and Dipteran larvae are numerous along the edge of the short-grass salt marsh (consisting primarily of *P. phryganodes*) and are important food items for shorebirds. Oligochaetes (family Naididae, genus *Paranais*) numerically account for about 63% of the macrobenthos in the salt marshes, and their distribution is strongly correlated with electrical conductivity and the organic carbon content of the sediments. In the coastal ponds, Dipteran larvae of the families Chironomidae, Heleidae, and Tipulidae occur in densities of up to 5,500 m^{-2} (Clarke, 1980).

Intertidal mudflats in high Arctic locations have received less study. It would appear that numbers and variety of organisms are low, as environmental conditions are correspondingly more severe than in sub-Arctic localities. At Zackenberg in central northeast Greenland, coastal mudflats contain low to moderate densities of nematodes, tardigrades, and crustaceans, and these are preyed on by shorebirds during July and August (Caning and Rausch, 2001; Meltofte and Lahrman, 2006). Red knots (*Calidris canutus*) have been observed feeding on crustaceans on intertidal mudflats on the central east coast of Ellesmere Island, Canada, during the postbreeding period, and both knots and ruddy turnstones (*Arenaria interpres*) feed on crustaceans along shorelines in the Alert area on northeast Ellesmere Island, Canada.

At the other end of the globe, there has been little study of intertidal areas in sub-Antarctic wetlands and mudflats. The Atlantic mainland coast of Tierra del Fuego, although surrounded by the sub-Antarctic oceanographic zone, is cool temperate in terms of climate and vegetation, and it does contain important coastal wetlands. At Bahía Lomas, in the Chilean sector of Tierra del Fuego near the entrance to the Strait of Magellan, preliminary investigations of the infauna show that polychaetes, bivalve mollusks, isopods, and amphipods are predominant in sandy habitats, their abundance dependent on sediment size and type (Ponce et al., 2003).

7.1.2. Invertebrate fauna of near-coast, freshwater areas

In areas of inundated less regularly by the tide and farther inland, a rich insect fauna develops. In southern James Bay, Kakonge et al. (1979) identified 318 species of invertebrates (105 families, 14 orders) among which mosquitoes and biting flies were a prominent component. The insects play an important role in ecological processes in the marsh, including contributing to soil fertility through

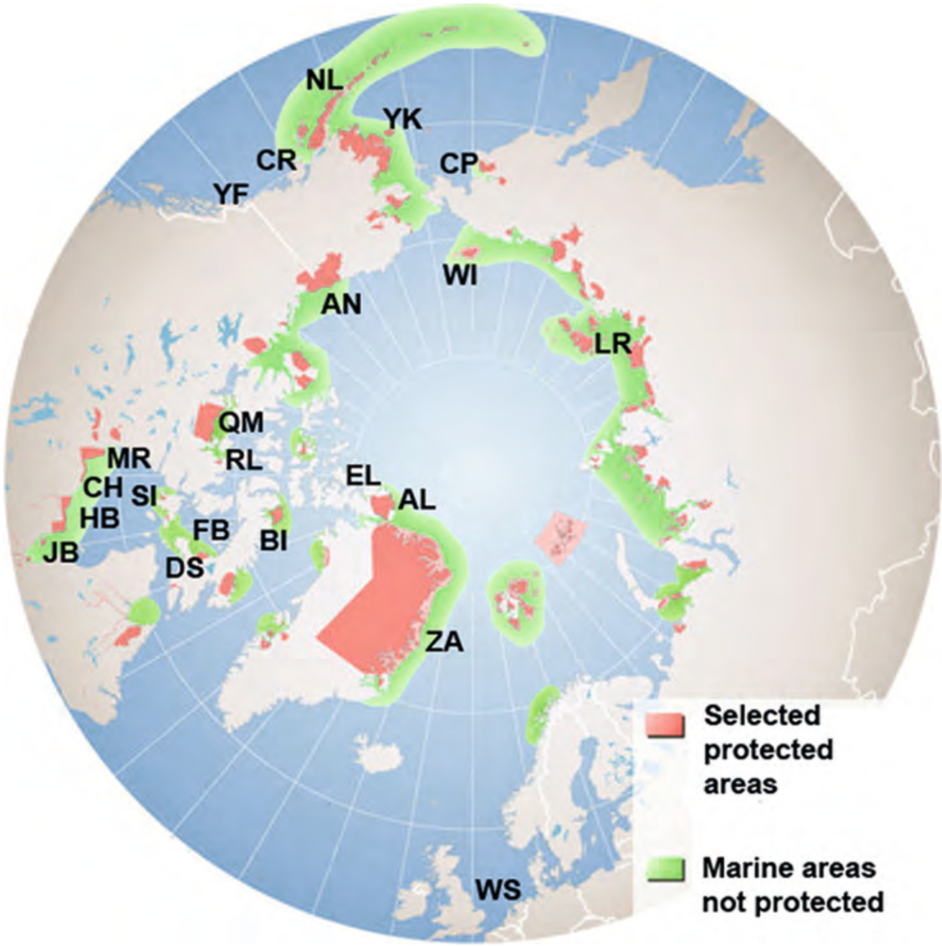

Figure 12 Locations of wildlife places mentioned in the text in the Arctic and sub-Arctic. (AL, Alert; AN, Arctic National Wildlife Reserve, Alaska; BI, Bylot Island; CH, Churchill, Manitoba; CP, Chukotka Peninsula; CR, Copper River Delta, Alaska; DS, Dewey Soper Migratory Bird Sanctuary, Baffin Island; EI, Ellesmere Island; FB, Foxe Basin; HB, Hudson Bay; JB, James Bay; LR, Lena River Delta, Russia; MR, McConnell River Migratory Bird Sanctuary; NL, Nelson Lagoon, Alaska; QM, Queen Maud Gulf Migratory Bird Sanctuary; RL, Rasmussen Lowlands; SI, Southampton Island; WI, Wrangel Island; WS, Wadden Sea; YF, Yakutat Forelands, Alaska; YK, Yukon and Kuskokwim river deltas Alaska; ZA, Zackenberg, Greenland) (after UNEP/GRID-Arendal, 2005).

aeration and transfer of organic particles into the soil, litter breakdown (by springtails, mites, nematodes, rotifers, and some exotic earthworms), the role as major secondary producers, and the function of providing a food resource for migrating birds. Mosquitoes were reported to occur in densities of 5 million per acre (13.35 m/ha) on the coast of Hudson Bay (West, 1951). Chironomids often reach densities of many thousand per square meter in freshwater and brackish water (Pinder, 1983), and they are a major component of the macrobenthos in ponds at northern latitudes (Andersen, 1946; Butler et al., 1981) as well as being an important component of the diet of shorebirds (Summerhayes and Elton, 1923; Holmes and Pitelka, 1968) and waterfowl (Bergman and Derksen, 1977; Danell and Sjöberg, 1977). Arthropod species characteristic of the sub-Arctic and the Boreal forest are frequently transported on southerly winds to the low Arctic where they survive the summer (Danks, 1981).

7.2. Vertebrate fauna using coastal wetlands

7.2.1. Avifauna

Birds form one of the most prominent components of the fauna using coastal wetlands. Most species may be categorized as waterbirds, principally waterfowl such as ducks, geese (12 breeding species), and swans, but also loons, shorebirds, gulls, and terns. Other types of birds including birds of prey (such as owls and raptors) and passerines also use coastal wetlands. Within the Arctic, 450 species of birds, which make up the majority of vertebrate species, have been recorded breeding (Callaghan et al., 2005); the majority are migratory and migrate in winter to southern latitudes and many inhabit coastal wetlands (Schmiegelow and Mönkkönen, 2002). The total number of wetland birds that breed in the Arctic is estimated at between 85 and 100 million individuals (Callaghan et al., 2005).

Polar wetlands not only serve as breeding grounds for many millions of waterbirds, but also play a key role as important migration stopover sites enabling the birds to travel between their breeding grounds and their more southerly wintering areas. The migration systems connecting southern wintering and Arctic breeding areas are generally known as flyways – worldwide there are some 8 recognizable flyway systems for waterfowl (Figure 13) and 10 (nine linking Arctic and Boreal breeding areas with wintering zones and one in South America linking austral

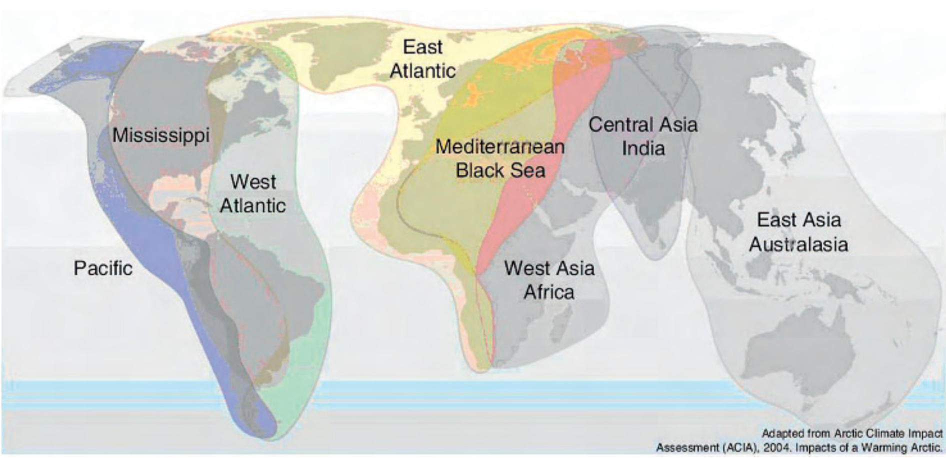

Figure 13 Major global flyway systems used by waterbirds (adapted from ACIA, 2004).

sub-Antarctic, cool-temperate, breeding, and wintering areas) for shorebirds (Figure 14). Some birds travel between Arctic and sub-Arctic wetlands to sub-Antarctic wetlands during the course of their annual travels: the North American red knot (*C. canutus rufa*) (Figure 15a), for instance, migrates from breeding areas in the central Canadian Arctic, through areas along the coasts of Hudson and James bays, through temperate and tropical areas, to wintering areas on the cool-temperate, intertidal areas of Tierra del Fuego at the southern tip of South America (Morrison and Harrington, 1992; Morrison, 1984; Morrison and Ross, 1989). Areas supporting important concentrations of shorebirds worldwide are located near coastal regions of high productivity (Butler et al., 2001).

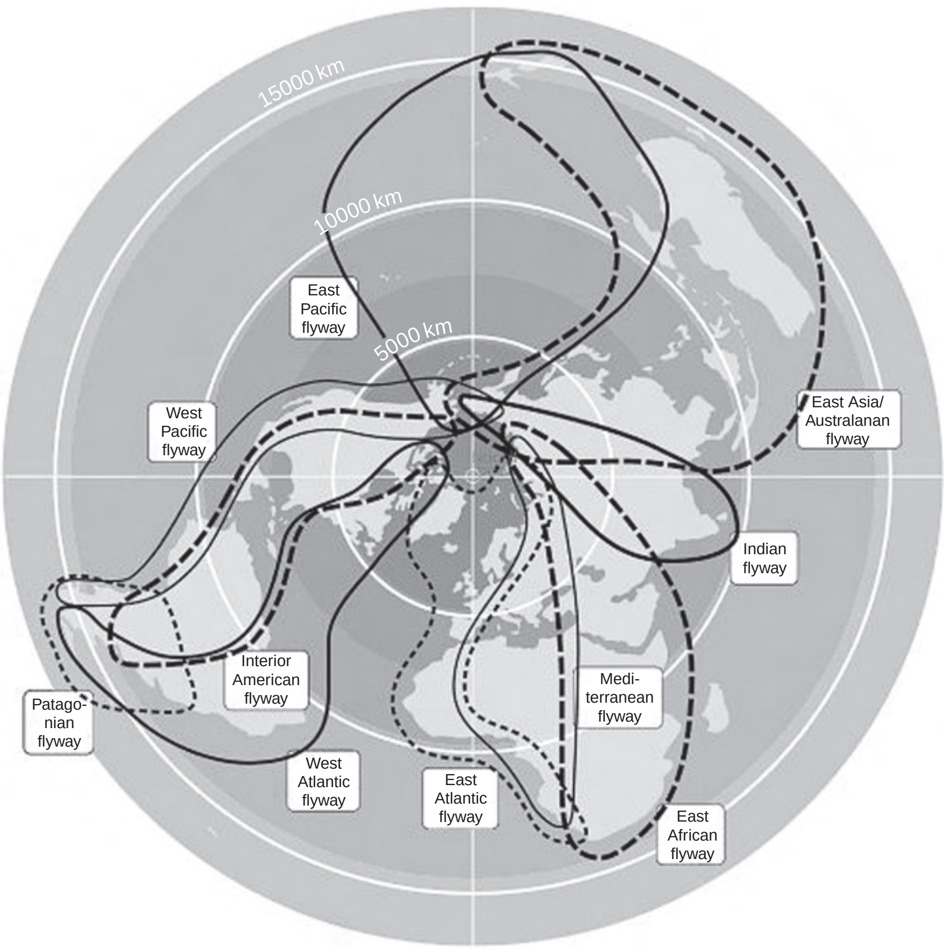

Figure 14 Major global shorebird flyway systems linking arctic breeding wetlands with "wintering areas" some of which are sub-Antarctic wetlands (adapted from Piersma and Lindström, 2004).

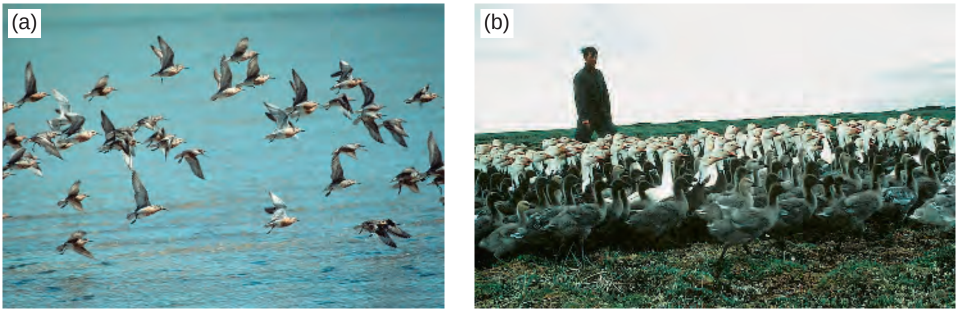

Figure 15 **Birds utilizing the polar coastal wetlands. (a) Red knots in flight. (b) Lesser snow geese, light-colored, flightless adults in the background during breeding period, and darker colored goslings in the foreground.**

Bird breeding areas. Geese form a prominent component of the avifauna using polar coastal wetlands, with populations of six species totaling an estimated 5.7 million birds in the North American Arctic and nine species totaling an estimated 2.5 million birds in the Eurasian Arctic (Zöckler, 1998) in the early 1990s. Some geese occupy a relatively restricted part of the Arctic, while others have a wide geographical distribution. For instance, about 95% of Ross's geese (*Chen rossii*) historically nest in the Queen Maud Gulf Migratory Bird Sanctuary in the central Canadian Arctic (Kerbes, 1994; Ryder and Alisauskas, 1995; Kerbes et al., 2006), whereas lesser snow geese (*Chen caerulescens caerulescens*) breed from northwest Greenland, through the Canadian and Alaskan Arctic, to Wrangel Island and the Chukotka Peninsula in Russia (Mowbray et al., 2000) (Figures 12, 15b). In the North American Arctic, hundreds of thousands of geese and other waterfowl nest in areas such as the Yukon and Kuskokwim river deltas [which support most of the world's emperor geese (*Chen canagica*)], Arctic National Wildlife Refuge in Alaska, the Rasmussen Lowlands, Queen Maud Gulf Migratory Bird Sanctuary, McConnell River Migratory Bird Sanctuary, and Dewey Soper Migratory Bird Sanctuary in the Canadian Arctic. Similar numbers are supported in the Eurasian Arctic in areas such as the Lena River delta in Russia (Gilg et al., 2000) and in sub-Arctic wetlands in Iceland (Rowell and Hearn, 2005) (Figure 12).

Shorebirds also form a prominent component of the breeding avifauna of sub-Arctic and Arctic wetlands. Zöckler (1998) reported 13 species of calidrid sandpipers with an estimated population of 8.1 million individuals that breed in the North American Arctic (including Greenland), while 17 species involving 6.3 million individuals breed in the Eurasian Arctic. When more southerly areas around Foxe Basin, Hudson Bay, and James Bay are included, some 27 species of shorebirds use central areas of Canada (Morrison and Gaston, 1986). Some species nest directly in wetland habitats, such as red phalarope (*Phalaropus fulicarius*) and dunlin (*Calidris alpina*), whereas others, such as ruddy turnstone and red knot, nest in nearby upland habitats. In the latter cases, the upland (tundra) habitats used for nesting are often found in close association with wetter habitats, where the birds feed and raise their young. Shorebirds breed right to the northern limit of land in North America and Eurasia, although it is in the more southerly large wetlands that the highest numbers and diversity are found, such as Yukon and Kuskokwim river deltas in Alaska, Rasmussen Lowlands in Canada, and coastal wetlands in eastern Siberia.

Bird staging areas. During migration, sub-Arctic and Arctic coastal habitats support equally large populations of waterfowl and shorebirds en route to and from the breeding grounds. In many cases, geese and other waterfowl acquire nutrients that they bring to the breeding grounds farther north in the form of body stores, which are used to form eggs or enhance survival (Alisauskas and Ankney, 1992). A similar phenomenon occurs with shorebirds. In Iceland, for instance, red knots en route to the eastern Canadian high Arctic from European wintering quarters, not only accumulate large amounts of fat but also alter their physiological makeup, increasing the size of organs and muscles used for flying (pectoral muscles) and decreasing the size of organs and muscles that are less important during the flight (stomach, intestines, and leg muscles) so that they transform themselves into virtual flying machines (Piersma et al., 1999). Not all the stores are used during the flight, and an important function of the significant amounts of fat and protein that remain on arrival in the Arctic appears to be to enable the birds to retransform their physiological makeup into one suitable for breeding [such as liver, heart (decreased during flight), stomach, and intestines increase in size], or perhaps for survival if early season conditions are difficult (Morrison and Hobson, 2004; Morrison et al., 2005). These aspects of bird migration emphasize the interconnected nature of the Arctic, sub-Arctic, and other wetlands farther south. The ability of birds to acquire the needed stores during migration has important survival implications. Shorebirds departing Iceland in better than average condition were shown to have a higher survival when faced with difficult weather conditions in the Arctic (Morrison, 2006; Morrison et al., 2007), and conversely, shorebirds prevented from reaching adequate departure weights at the final spring stopover area in North America suffered significantly decreased survival (Baker et al., 2004).

Waterfowl also depend on food resources in sub-Arctic wetlands during migration. Examples in North America include the Mid-Continent populations of lesser snow geese and Atlantic brant (*Branta bernicla)* passing northward through James Bay during the spring (Jefferies et al., 2003; Ward et al., 2005) and European populations of brant using Icelandic stopovers en route to the Canadian Arctic (Ward et al., 2005) as well as pink-footed geese (*Anser brachyrhynchus*) using wetlands in northern Norway en route to breeding grounds on Svalbard (Drent et al., 2006; Glahder et al., 2006). In recent decades, habitats in migration and breeding areas used by lesser snow geese and Ross's geese in the Canadian Arctic have been heavily damaged as a result of overgrazing by the geese, which have undergone spectacular increases in population size. On the wintering grounds in southern latitudes, the loss of coastal habitat and freshwater wetlands (associated with changing land use) has led to the birds becoming heavily dependent on agricultural crops, particularly high-yielding crops rich in nitrogen. Some species that have shown geometric population growth, primarily in response to changes in modern agriculture, are the lesser snow goose and Ross's goose in North America (Abraham et al., 1996, 2005) and the barnacle goose (*Branta leucopsis*) in Europe (Van Eerden et al., 2005; Jefferies et al., 2006a). Winter counts of the Mid-Continent population of snow geese increased in a geometric manner between 1970 and 2000, from 0.8 million in 1969 to 2.7 million in 1994, indicating that the entire population was most likely between 4.5 and 6 million in the mid-1990s (Abraham and Jefferies, 1997; Jefferies et al., 2003). At La Pérouse Bay near Churchill on the Hudson Bay coast, the breeding colony increased from less than 2,000 pairs in 1968 to 44,500 pairs in 1997 (Jefferies et al., 2003). The main factors involved appear to be the increased availability of food from agriculture, as well as the availability of refugia from hunting, lower harvest rates, and possible climate change on the breeding grounds (Jefferies et al., 2003; Kerbes et al., 2006). The birds have, in effect, escaped from density dependence in the coastal marshes, and hunting losses (where hunting is permitted) have not been able to keep pace with the increases in the population sizes of the different species (Abraham et al., 1996).

With numbers of lesser snow geese exceeding 5 million, the large population may be expected to have adverse effects on Arctic coastal vegetation, depending on the densities of the birds and their foraging behavior (grazing, grubbing, shoot pulling of sedges), which is related to bill size and shape. Grubbing, in which the geese pull up the roots and rhizomes of the plants, and shoot-pulling lead to destruction of the vegetation and often total loss of the selected graminoid plants. The resulting physical and chemical changes in the exposed sediments and the continued exposure to geese foraging alter habitat succession and recovery (Abraham et al., 2005). Coastal wetland sites in the sub-Arctic in North America are particularly vulnerable to such disturbance because they serve as sites for both staging and breeding. During both of these phases of the annual cycle, the birds need to feed heavily, especially in early spring, to regain resources expended during migration and maintain or increase reserves for breeding. In North America, the Mid-Continent population of the lesser snow goose that breeds in the eastern Canadian Arctic has had a dramatic impact on coastal wetland plant assemblages and soils at a large spatial scale (Jefferies et al., 2003): vegetation loss has been so extensive that it can be readily detected by remote sensing (Jano et al., 1998, Jefferies et al., 2003; Didiuk and Ferguson, 2005, Jefferies et al., 2006b; Alisauskas et al., 2006). The loss of vegetation is triggered by geese grubbing for roots and rhizomes in thawed ground in early spring. However, it is the subsequent abiotic changes, including the development of hypersalinity, loss of organic matter, and compaction of sediments that limit the potential for recolonization. This is compounded by biotic factors such as loss of the seed bank, the absence of sexual reproduction in *P. phryganodes* (at least in North America), and irregular seed set in *C. subspathacea*. Because of the cumulative impact of grubbing, patches of exposed sediment coalesce into larger and larger units of exposed sediment largely devoid of vegetation. Reestablishment of vegetation is long-term and requires erosion of hypersaline, consolidated sediment and the buildup of unconsolidated soft sediment, in which plants can establish themselves. A similar loss of vegetation is occurring in coastal freshwater marshes, although the abiotic and biotic processes are different (Jefferies et al., 2003; Alisauskas et al., 2006). Erosion of peat, following loss of vegetation, can lead to exposure of underlying glacial gravels and marine clays in coastal locations and can alter the trajectory of succession (Handa et al., 2002).

For the greater snow goose (*C. caerulescens atlantica)* breeding in the northeastern Canadian Arctic, grazing pressure on graminoids during the summer is high and reduces the plant production in wetlands, although the vegetation has not been damaged past the point of recovery, as observed in areas used by lesser snow goose populations (Gauthier et al., 2006). Goose abundance on Bylot Island, one of the largest breeding colonies of the greater snow goose, was still at only half the estimated carrying capacity of the island's wetlands in 1997. Similarly, the European population of the barnacle goose is considerably lower than that of the North American snow goose (Madsen et al., 1999), and they have had relatively little impact on coastal habitats.

During autumn migration, many shorebirds and waterfowl use the coasts of Hudson and James bays as well as other locations in the eastern Canadian Arctic to build up body reserves for the flight south (Morrison and Harrington, 1979; Morrison and Gaston, 1986). Shorebird distribution in James and Hudson bays was directly related to food abundance for several species, including semipalmated sandpiper (*Calidris pusilla*), red knot, and hudsonian godwit (*Limosa haemastica*), a relationship that was evident at several geographical scales (locally across the marsh, over 15 km stretches of coast, and over several hundreds of kilometers) (Morrison, 1983, 1984; Morrison and Gaston, 1986). In northern Alaska, a number of species of shorebirds move from tundra to littoral habitats after breeding, and coastal flats are important during the autumn migration (Connors et al., 1979; Andres, 1994). In western Alaska, 17 species of shorebirds regularly use the intertidal flats of the Yukon and Kuskokwim river delta during spring and fall; peak counts reached some 300,000 birds, consisting mostly of dunlins, western sandpipers (*Calidris mauri*), and rock sandpipers (*Calidris ptilocnemis*), and an estimated total of 1–2 million shorebirds were thought to use the area each year (Gill and Handel, 1990). Many millions of shorebirds used the Copper River delta flats during spring migration (Islieb, 1979; Bishop et al., 2000) and hundreds of thousands used the Yakutat Forelands area (Andres and Browne, 1998) in Alaska. Some 20 species of shorebirds used intertidal habitats in Nelson Lagoon on the Alaska Peninsula during fall migration (Gill and Jorgensen, 1979). Such areas are of critical importance during southward migration of species such as the bar-tailed godwit (*Limosa lapponica*), which accumulates up to 55% of its body weight in fat and undergoes physiological changes involving reduction in gut sizes before a spectacular migration across the Pacific Ocean, which can involve non-stop flights of 11,000 km lasting 6 or more days to wintering areas in New Zealand and eastern Australia (Piersma and Gill, 1998; Gill et al., 2005; Gill et al., 2006). The critical importance of these coastal wetlands in the life cycles of a variety of birds is clear.

7.2.2. Mammal fauna

A variety of mammals occurs in polar coastal wetlands, including bears (polar bears, grizzly bears, and brown bears), Arctic and red foxes, wolves, wolverines, caribou, arctic hare, mink, weasels, lemmings, and voles. While less numerous than waterbirds, mammals play an important role in ecological dynamics of Arctic systems. Lemmings and other rodents undergo pronounced cyclical patterns in abundance, and the associated responses of predators such as arctic foxes (*Alopex lagopus*) in turn influences the success of other birds and animals. In years of high lemming abundance, for instance, Arctic foxes spend much of their time hunting the lemmings so that there is relatively little predation pressure on nesting birds; in contrast, in low lemming years, shorebirds and their nests may be heavily depredated by foxes. Breeding success of the birds on the breeding grounds can be affected to the extent that the lemming cycles can be detected by observing the number of shorebird young reaching migration and wintering areas (Underhill, 1987; Underhill et al., 1989; Blomqvist et al., 2002); pomarine jaegers (*Stercorarius pomarinus*), which depend on lemmings for food, may not breed at all in some areas in low lemming years (Maher, 1970). In the Canadian Arctic, lemming cycles may be less synchronized over large areas than in the Russian Arctic, although they are clearly evident in the high Arctic.

Polar bears (*Ursus maritimus*) are a top predator in marine ecosystems and are highly dependent on the presence of sea ice which provides habitat for their principal prey, ringed seals (*Phoca hispida*), in many regions of the Arctic (Stirling et al., 1999, Derocher et al., 2004). During the summer when the sea ice melts, polar bears come ashore in coastal areas. During this period when the normal diet of seals is not available, they exist on accumulated fat reserves and become fairly omnivorous predators and scavengers, feeding on berries, seaweed, and adults, young, and eggs of colonial nesting seabirds and waterfowl [including thick-billed murres (*Uria lomvia*), little auks (*Alle alle*), gulls, geese, ducks, and sometimes more terrestrial species]. Polar bears are occasionally cannibalistic and have been also known to hunt large terrestrial mammals such as caribou and muskox (*Ovibos moschatus*) (Stempniewicz, 2006). Polar bears can cause extensive damage to colonies of seabirds nesting in coastal locations; at East Bay, Southampton Island, in 1997, two bears destroyed an entire common eider (*Somateria mollisima*) colony, eating an estimated 12,000 eggs, rendering themselves temporarily immobile in the process (H.G. Gilchrist, personal communication).

The predicted thinning and reduced coverage of Arctic sea ice resulting from climate warming are likely to substantially alter sea ice ecosystems (Loeng et al., 2005) and could result in deleterious effects on availability of food sources for polar bears. These predictions reflect the strong coupling between marine and terrestrial systems in response to climate change. Such effects are likely to be most evident at the southern distribution limit of polar bears, where early melt and late freezing of sea ice extend the period when the bears are on land, during which time little feeding occurs. Recently, the condition of adult bears has declined in the southwest region of the Hudson Bay and, the number of first-year cubs as a proportion of the population has fallen associated with the early breakup of sea ice and the cubs coming ashore in poor condition (Stirling et al., 1999; Derocher et al., 2004).

Polar bears are increasingly likely to seek alternative food sources as the extent of sea ice declines and inshore time increases under climate warming (Stirling and Parkinson, 2006), although it is not clear to what extent individuals may be able to modify their feeding habits to utilize new food sources. For example, unpublished data (Ian Stirling, per.com.) indicate harbor seals (*Phoca vitulina*), which occur on rocky coasts, may be increasing in western Hudson Bay, possibly in response to climate warming and that this species is becoming more important in the diet of polar bears.

In North America, caribou (*Rangifer tarandus*) herds use coastal wetlands and plains for both calving and wintering; in the summer, coastal areas are important for avoiding predators and biting and parasitic insects. Furthermore, caribou diets shift in summer from the lichen dominated winter diets to vascular plants, including wetland sedges, grasses, and other species.

8. Environmental Hazards

Most polar coastal wetlands have been subject to few direct and indirect anthropogenic influences compared to their temperate counterparts. They are, however, environments that are easily impacted and modified by either natural disturbances or human activities.

Climate changes will affect these wetlands directly, as a result of rises in temperature and in amounts of precipitation that will affect growth of vegetation and the reproductive success of plant populations. There are also a plethora of indirect effects associated with the melting of sea ice and permafrost and changes in salinity and hydrology. For example, low-lying coasts, where wetlands occur, are vulnerable to the deleterious effects of the increased incidence of storm surges and the destructive effects of wave action in the absence of sea ice (Callaghan et al., 2005; Loeng et al., 2005; Cahoon et al., 2006). The direct effect of climate warming on melting and the changing regime of sea ice will strongly affect animal behavior, possibly leading to extinction of specialized species like polar bears in some areas of the Arctic (Derocher et al., 2004).

Human activities may impact drastically on polar coastal wetlands because of the rapidity of the imposed changes. Rapid adverse effects are associated with mega-hydrological projects, resource extraction (hydrocarbon exploration and exploitation, mineral mining for lead zinc, gold, and diamonds), ecotourism, fishing, and increased hunting and gathering by indigenous people (Anisimov et al., 2001).

Large-scale hydrocarbon exploration and production is ongoing in areas on- and offshore in the Arctic Coastal Plain of Alaska, the Mackenzie River delta, the Pechora Basin, the Lower Ob Basin, and the Western Siberian Plain. These activities adversely impact wetland ecosystems and their wildlife because of the necessary infrastructure and the disturbances created at the different locations. A more ominous impact is related to the pollution of the whole coastal and marine environment that can derive from oil spills during exploration and the marine transport of petroleum through a possible ice-free Northwest or Northeast Passage

(Anisimov et al., 2001). Both heavy metals and POPs (Persistent Organic Pollutants) are transported by water and air, and both bioaccumulate in trophic food webs and in wetland soils, thereby posing environmental risks to wildlife and human populations (AMAP, 2002).

9. Conclusions and Research Priorities

Earth is continuously changing. During the Quaternary Era, continent-wide glaciers developed and waned several times responding to alternating cold and warm periods. The biota, including human populations, adapted to these changes by migrating and recolonizing land affected by ice. However, humans are now capable of affecting rates of climatic and geochemical (pollution) changes that already are impacting polar regions, and will continue to do so. With amplification of temperature, the global warming will be more evident in the Arctic, and it can be expected to reduce the cover of both sea and land ice. As a result of changes in albedo and heat storage with the melting of ice, the redistribution of heat at the global scale can modify atmospheric properties and oceanic currents. This will probably lead to adverse consequences such as changes in atmospheric precipitation, increased frequency of storms, and a global sea-level rise. Coastal Arctic and sub-Arctic environments and the associated biota are particularly vulnerable to these climatic changes. The majority of human settlements in the Arctic are located on low-lying coasts and they will also be adversely affected by storms and tidal surges. The melting of the sea ice and the opening of Arctic sea routes present further possible hazards for low-lying coastal regions and their biota. Pollution, physical disturbance, and increased access to these remote localities are likely to result in indirect changes, many of which are unforeseen at this stage.

Research priorities include the following.

1. Monitor rates of permafrost loss, and, in particular, map the ongoing northward shift of the boundary between the continuous and discontinuous permafrost zones (Tarnocai, 2006). This change is likely to lead to the partial drying of vast peatlands and the release of greenhouse gasses (carbon dioxide and methane) to the atmosphere and, thus, an increase in the rate of global warming. In addition, shrubs and grasses are likely to replace the wetland flora of aquatic plants and sedges. Such changes will affect the existing insect fauna and the availability of suitable nesting and feeding sites for migratory waterfowl and passerines that nest in the Arctic.
2. Improve and expand the determination of rates of isostatic land uplift and sea-level rise using a network of stations, in order to predict relative sea-level changes along coasts. This is especially important where severe coastal erosion is taking place.
3. Monitor the effects of global change on coastal environments and the ability of resident wildlife populations (such as vegetation, polar bears, foxes, and lemmings) and migratory populations (most bird species, caribou) to adjust to these changes. Recording of invasive species in northern latitudes associated

with climate change is necessary. Increased attention needs to be paid to traditional knowledge and its contribution to our understanding of past and present changes in wildlife populations. More direct involvement of First Nations' people in research activities is needed.

4. Expand monitoring to understand the impact of local (oil exploration and production, mining) and distant (long-range) transport of contaminants on human activities (fishing, hunting on land and on sea ice, societal change). Migratory birds, and waterfowl in particular, constitute a means of transport of geochemical materials from the industrial, agricultural south to the northern coasts.

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