The Canadian Beaufort Sea Ecosystem: A Fisheries Perspective

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CANADA/INUVIALUIT
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The Canadian Beaufort Sea Ecosystem: A Fisheries Perspective

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Abstract

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Climate change on the Canadian Beaufort Sea continental shelves is expected to lengthen the growing season and increase the open-water area, exposing the shelves to industrial development, including commercial fishing. Primary productivity and secondary fish productivity are currently low, but both are expected to increase in coming decades.

Arctic cod, a likely target for commercial fishing, is the most abundant marine forage fish and a keystone species in Beaufort Sea food webs. Predators that depend on Arctic cod, directly or indirectly, are beluga whales, ringed seals, polar bears, and Arctic charr. Arctic cod needs to remain at its carrying capacity so that food stress is not placed upon its dependent predators at a time when they themselves are adjusting to a changing climate.

The Mackenzie Shelf near Cape Bathurst is an area of upwelling and enhanced primary and secondary productivity characterized by a distinctive benthic community. Commercial fishing could impact this habitat, important for bowhead whales and thousands of diving sea birds.

There are many effects and uncertainties associated with climate change that make predictions about species responses impossible at the present time, although various possibilities and probabilities are discussed. Specific recommendations for the monitoring of fisheries, food webs, habitats, and marine productivity are offered that, if incorporated into an integrated fisheries management plan, will help forecast how the Beaufort marine ecosystem will respond.

Preface

This report was written by Jack Mathias under contract to the Fisheries Joint Management Committee, Inuvik, NT. Funding for the contract was provided by Oceans North Canada.

Dr. Mathias worked for 31 years as a Research Scientist in Fisheries and Oceans Canada (DFO) on projects as diverse as aquaculture production, Arctic marine protection, Arctic fisheries, and ocean management. He was head of the DFO Central and Arctic Region's Arctic Ocean Management group for six years and then Senior Policy Advisor in ocean management for three years in British Columbia. Dr. Mathias retired in 2007.

The Canada/Inuvialuit Fisheries Joint Management Committee (FJMC) Report Series was initiated in 1986 and reports were published sporadically in a variety of formats until 1998. Information on the earlier publications can be obtained directly from the FJMC office. The Series was re-initiated in 2003 and a common format established with concurrent publication on the FJMC website (www.FJMC.ca).

1. Introduction

The Arctic Ocean is responding to global warming faster than other parts of the earth. Many ecological changes are happening simultaneously in the Arctic seas, but the inexorable disappearance of sea ice stands above all others, for it will expose the Arctic continental shelves to economic activity. One has to look no farther than the Grand Banks, the North Sea, or the Gulf of Mexico to see that there will be interest in oil and gas exploration, commercial fishing, and marine shipping as the Arctic continental shelves become accessible.

This paper characterizes the continental shelves of the Canadian Beaufort Sea (Fig. 1 and Section 2 *Beaufort Sea Study Area*) with respect to the potential for commercial fisheries. In doing so, it considers five main questions:

- What is known about the Canadian Beaufort shelves, their habitats, food webs, and potential productivity, including that of commercial species? (See Section 3 *Beaufort Sea Ecosystem.*)
- How do Inuvialuit people use the resources of the Beaufort Sea ecosystem? (See Section 3 *Beaufort Sea Ecosystem.*)
- What would be the possible impacts of commercial fishing on the Arctic shelves—for example, how might commercial fishing impact on Arctic marine food webs and habitats—and what might be the implications for the Inuvialuit subsistence fisheries of the Beaufort Sea? (Conclusions are given under the title "***Fisheries Implications***" at the beginning of each sub-section.)
- What information is required to guide the development of commercial fishing in view of existing fisheries policies applicable to Arctic waters? (See Section 4 *Fisheries Management*.)
- How might species and their productivity on the Beaufort shelves respond to the warming climate? (See Section 5 *Impacts of Climate Change*.)

Recommendations for further research to support an Integrated Fisheries Management Plan (IFMP[2]) are provided in Section 6 (*IFMP Recommendations*).

The study relies on information from recent Arctic research, in particular the following research programs and organizations:

- International Polar Year (IPY) projects
- Circumpolar Flaw-Lead (CFL) system study
- Mackenzie Gas Project (MGP) – Beaufort Sea Coastal Marine Program, MV Nahidik
- Beaufort Sea Strategic Regional Plan of Action (BSStRPA)
- Program of Energy Research and Development (PERD)
- Canadian Arctic Shelf Exchange Study (CASES)
- Surface Heat Budget of the Arctic Ocean (SHEBA)
- Northern Oil and Gas Action Program (NOGAP) – Beaufort Environmental Monitoring Project and Beaufort Region Environmental Assessment and Monitoring Program.

[2] See Appendix 1 for definitions of acronyms.

A significant amount of information comes from US research initiatives on the Chukchi and Alaskan Beaufort shelves, mainly from the National Marine Fisheries Service of the National Oceanographic and Atmospheric Administration (NOAA).

2. Beaufort Sea Study Area

The Beaufort Sea ecosystem is shared by Canada and the US. Of the ~1300 km length of its shelves, ~55% lies in Canada and 45% in the US. It lies north of Alaska and Canada's Yukon and Northwest Territories, approximately between longitude 160°W and longitude 115°W (Fig. 1). Its continental shelf runs approximately along latitude 70ºN, four degrees north of the Arctic Circle. It consists of a central, 3500-m-deep basin, the Canada Basin, and a continuous continental shelf that lies between the shelf of the Chuckchi Sea to the west and that of the Arctic Archipelago to the east. Between the deep floor of the Canada Basin and the shallow (80 m) shelves of the Beaufort Sea lies the continental slope. The Beaufort Sea continental shelf is divided into three parts: the Alaskan Shelf, the Mackenzie Shelf, and the Banks Island Shelf, and includes the Amundsen Gulf, which lies between the latter two shelves. The dotted white line in Fig. 1 shows the approximate seaward extent of potential commercial fishing, the 1,000-m depth contour.

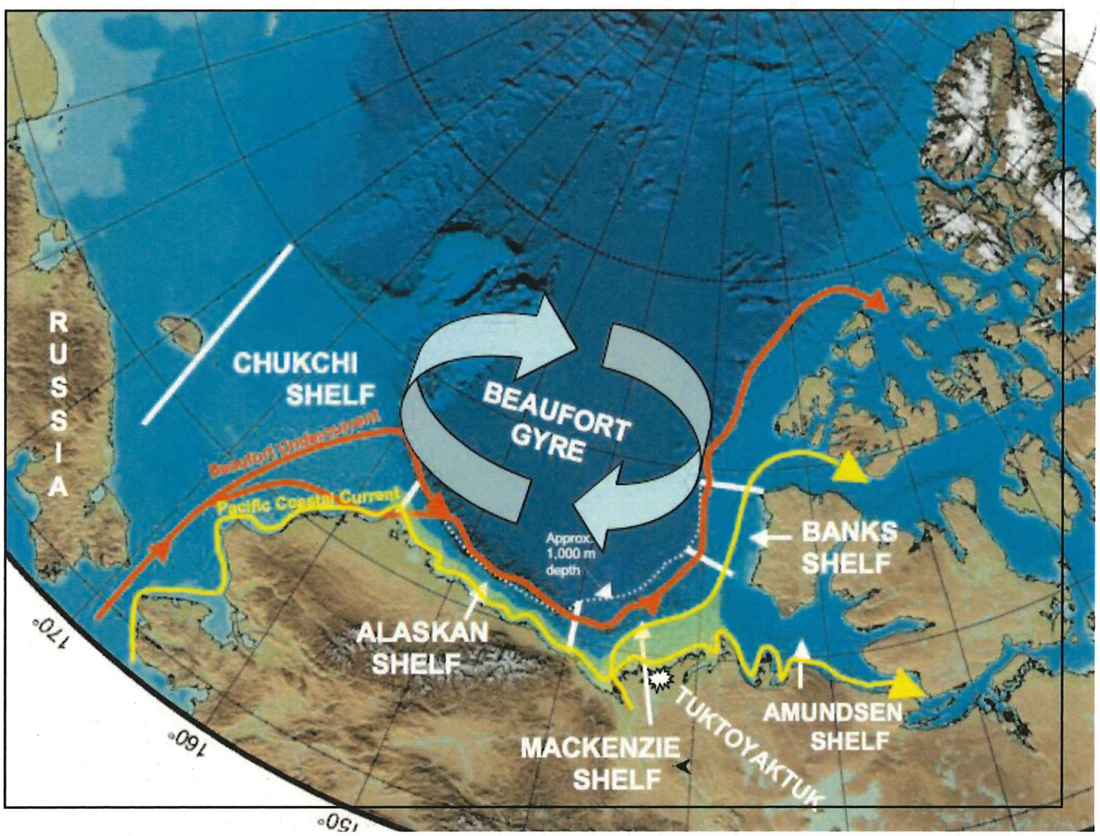

Figure 1. Oceanographic features of the Beaufort Sea continental shelves. Approximate locations of shelves are shown between white bars, and the white dotted line shows the 1000-m depth contour on the continental slope. The Pacific Coastal Current is shown in yellow and its associated estuarine habitat is indicated by the pale green band. The Beaufort Undercurrent is shown in red.

The three shelves share several important oceanographic features (Stein and Macdonald 2004): the clockwise ice drift in the Beaufort Gyre; a system of ice flaw-leads over the middle shelf; a sub-surface, counter-clockwise current along the shelf slope-break, called the Beaufort Under-current; and a weak, freshwater coastal current that creates an inshore, estuarine habitat (Fig. 1). These features are discussed in Section 3.4 *Habitats*, as they bear upon fisheries productivity and its response to changing climate in the Beaufort Sea.

Three types of continental shelf are identified in the Arctic Ocean: **inflow shelves**, which receive water from either the Pacific or Atlantic Ocean; **outflow shelves**, which export water from the Arctic Ocean to the Atlantic Ocean; and **interior shelves**, which do not exchange water directly with other oceans (Carmack and Wassmann 2006). Inflow shelves, e.g., the Chukchi (Fig. 1), are the most productive shelf type because nutrient-rich water as well as phytoplankton and zooplankton flow onto these shelves from the Pacific or Atlantic Oceans. The two major inflow shelves—the Chukchi and Barents shelves—contribute about two-thirds of the total primary productivity of the Arctic Ocean (Sakshaug 2004).

Interior shelves, like the Alaskan, the Mackenzie, and the Banks shelves of the Beaufort Sea (Fig. 1) are less productive than inflow shelves, having little direct exchange with other ocean systems. Productivity here is intermediate, driven by factors such as:

- local winds that enhance an estuarine (upwelling) circulation,
- coastal rivers that deliver terrestrial carbon to the shelves,
- upwelling areas that bring deep-water nutrients onto the shelves, and
- flaw-lead polynyas that provide consistent open water and high local productivity.

Outflow shelves have the lowest productivity because they have less access to the deeper, nutrient-rich waters adjacent to the shelf-break, generally have weaker riverine inputs, and may not be exposed to pack ice, which generates open water flaw-leads. Amundsen Gulf, considered to be part of the Canadian Arctic Archipelago, a vast outflow shelf draining into Baffin Bay and Hudson Strait (Carmack and Wassmann 2006), does receive summertime inputs from both the Hornaday and the Horton rivers, but does not experience an estuarine circulation pattern. Nor does it exhibit bathymetric peculiarities conducive to upwelling. It is exposed to pack ice, however, so that a significant polynya develops as part of the flaw-lead system of the southeastern Beaufort Sea.

The Canadian portion of the Beaufort Sea ecosystem coincides with marine areas of the Inuvialuit Settlement Region (Fig. 2; DFO 2009a), designated for the Inuvialuit people in the Inuvialuit Final Agreement (IFA) by the Government of Canada in 1984. The IFA ensures the involvement of Inuvialuit beneficiaries in the management of the region's resources.

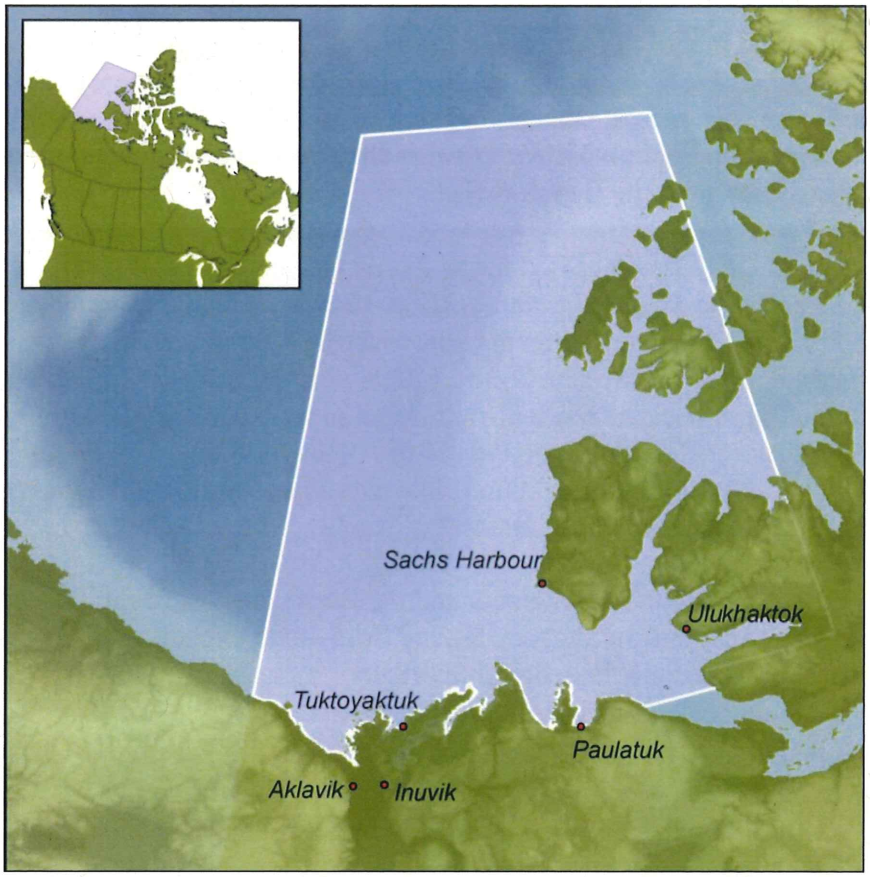

Figure 2. Marine waters of the Inuvialuit Settlement Region: the Canadian Beaufort Sea, showing the six Inuvialuit communities.

The Inuvialuit Settlement Region is described as one of the richest landscapes in the Canadian Arctic, "…centered on the great delta of the Mackenzie River … (in North America, only the Mississippi is longer)". Although the land is "well-vegetated" and "immense windrows of Mackenzie River driftwood clothe the beaches…. The sea is richer than the land and the coastline has always been the focus of human life" (Alunik et al. 2003, p. 3).

3. Beaufort Sea Ecosystem

3.1. Inuvialuit Fishing and Hunting

Fisheries Implications: *The Inuvialuit people live in six communities on the Canadian Beaufort Sea (Fig. 2). Hunting and fishing on the Sea has always been important. Of >100 species of fish, mammals, and birds harvested by Inuvialuit, ~40 species make up the bulk of the harvest and, of these, 18 are marine species. It is clear that Inuvialuit utilize a broad range of marine species of high value. As evidence accumulates that marine food webs are re-structuring in response to climatic change, it becomes imperative that industrial fishing does not remove biological productivity that supports the subsistence fisheries on which the Inuvialuit depend. The habitats, food webs, and keystone species that may be potentially impacted by industrial fishing are* *discussed in the following sections: 3.5 Hotspots, 3.6 Food Webs, and 3.7 Keystone Species. Information needs for designing an IFMP to protect food webs and habitats are discussed in Section 4 Fisheries Management.*

The following quotation from Alunik et al. (2003, p. 3) provides a sense of the importance of the marine environment in providing food for the Inuvialuit: "The Western Arctic supports four important sea mammal species. The ringed seal and bearded seal are both able to make breathing holes through the thick winter ice, and are found in the area all year round. Both are widespread, and for many Inuvialuit the ringed seal, in particular, was a mainstay of winter life in ancient times. ... [The polar bear, also widespread, is the main predator of the ringed seal, and is hunted commercially, and for food and skin.] Two important whale species spend the summer in the area: the 15-metre-long (50 foot) bowhead and the four-meter (13 foot) beluga. Less able than the seals to deal with thick winter ice, both are migratory. They winter in the warmer waters of the north Pacific, then move north and east around Alaska with the summer melt, entering the eastern Beaufort Sea and Amundsen Gulf in late spring or early summer and leaving before freeze-up. Belugas are found as far east as Banks and Victoria islands, but congregate in large numbers off the mouth of the Mackenzie River, where they feed on the abundant herring [cisco[3]] crop. By contrast, bowheads are deep-sea feeders best hunted from large promontories such as Point Atkinson and Cape Bathurst. Killer whales are sometimes seen off the Northern Yukon coast. ... In times past, sea mammals were a crucial source of meat and fat and an important basis for much of the prosperity enjoyed by the Inuvialuit. ... Today the beluga hunt in particular is still of great cultural and social importance. ... Fish resources in the Inuvialuit homeland are by far the richest in Arctic Canada, with at least 20 economically significant species. Major fresh-water and anadromous species include Arctic char, burbot, inconnu, lake trout, and five species of cisco and whitefish. Marine species include Arctic cod and herring. With so diverse a resource, the Inuvialuit fishery was–and is–productive nearly all year round, and fish may have been the single most important element in the traditional diet." The IFA is designed to "protect and preserve this Arctic wildlife, environment and biological productivity" (Principle #3; IRC 1987).

Hunting and fishing for food has always been important to the Inuvialuit people in the six communities along the Canadian Beaufort Sea. Eighty percent of Inuit men hunted or fished for food in 2000 (Statistics Canada 2001). Marine food made up the overwhelming bulk of country food for the Inuvialuit, both in the 1960s and in the 1990s (Table 1; ICC et al. 2006). The decline in harvest of ringed seal and fish between these periods is related to the replacement of sled dogs by snowmobiles because in earlier days these species were used to feed dogs as well as people (Usher 2002). Foxes and muskrats were hunted for pelts. Usher (2002, p. 25) speculated: "The availability of food intended specifically for human consumption may well have remained more or less constant over the period, and indeed the mix of terrestrial and marine sources of human food may also not have changed much".

The contribution that country food makes to Inuvialuit communities is shown in Table 2. Of the top 10 species harvested, seven are marine or estuarine species, and these contributed 145 tonnes per year of country food to the Inuvialuit communities during the past decade. The species are

[3] Arctic cisco are often called "herring" by Inuvialuit.

beluga whale, broad whitefish, Arctic charr, ringed seal, inconnu, humpback whitefish, and Arctic cisco. Marine-related species, therefore, contributed about half of all country food.

Table 1. Mean annual Inuvialuit harvest of selected species, 1960–1965 and 1988–1997. (Adapted from Usher 2002.)

	Number of Animals and Weight of Fish	
Years	**1960–1965**	**1988–1997**
Marine Species		
Bowhead whale	0	2 [1]
Beluga whale	83	117
Ringed seal	4900	1085
Polar bear	68	56
Marine and anadromous fish (kg)	400,000	92,034
Terrestrial Species		
Caribou	1300	3114
Muskox	0	327
Moose	60	28
Muskrat	98,000	10,019
Arctic fox	5300	1384
Freshwater fish (kg)	40,000	17,450

[1] Total number taken, not annual harvest.

Table 2. Top 10 species harvested as country food between 1988–1997. (After Usher 2002.) Data do not include the two bowhead whales captured during the 1990s.

Rank	Species	Production (edible weight, kg)
1	Caribou	110,730
2	*Beluga whale	43,215
3	*Broad whitefish	38,254
4	Muskox	22,563
5	*Arctic charr/Dolly Varden	17,553
6	*Ringed seal	14,105
7	*Inconnu (fish)	13,602
8	*Humpback whitefish	10,161
9	Snow goose	9981
10	*Cisco (fish)	7897

* Indicates marine/estuarine species.

"About 40–60% of NWT [Northwest Territories] people living in small communities…rely on country food for most (at least 75%) of their meat and fish. This percentage has not changed greatly for the past 10 years" (NWT 2011). Usher (2002) estimated that the value of country food to the Inuvialuit is ~\$3.35 million annually, or \$1150 per person, assuming an average value of \$10/kg for meat, fish, or fowl, if the food were bought at the local store. The marine environment provides a healthy and preferred diet for many Inuvialuit, and the hunting, fishing, processing, and sharing of country food provide a means for maintaining Inuvialuit social and cultural continuity.

Inuvialuit harvesting produces more than food. Hides, pelts, down, and bone are used to make country clothing and to support the tourist art market. Polar bear and ringed seal hides are used in traditional clothing. Recently, guided hunting for polar bear has been an important source of community income. For example, the regulated hunt for polar bear accounts for about half of the bear harvest, and contributed ~\$700,000 CAD a year to hunters in Sachs Harbour, Paulatuk, Holman, and Tuktoyaktuk (Waters et al. 2009, table 2, p. 17). To Inuit hunters working outside the wage sector of the economy, the income provided by guiding visitor-hunters is an important subsistence resource. Regardless of whether the polar bear hunt is for subsistence or is a business, polar bear remain a cultural resource for all Inuit (Wenzel 2004).

In a similar way, the hunting of bowhead whales in recent times has restored an ancient tradition of large cetacean harvesting for subsistence purposes by the Inuvialuit. The value of the hunt to reaffirming cultural values and building social strength in the communities cannot be underestimated. It also reaffirms the strength of the IFA in protecting the wildlife harvesting rights of the Inuvialuit in the face of national and international sentiment (Zellen 1992).

3.2. Diminishing Ice

Fisheries Implications: *Ice, its extent, its duration, and its thickness are decreasing in the Arctic. However, some parts of the Arctic are changing more rapidly than others. Ice on the Chukchi Shelf seems to be changing most rapidly, that on the Alaskan Beaufort Shelf moderately, and that on the Canadian shelves more slowly. The Mackenzie Shelf, because of the Bathurst polynya, has always had about half the percent ice coverage of the Alaskan Shelf over 40 years of observation. Nevertheless, during that time, ice coverage has declined much faster on the Alaskan Shelf than on the Mackenzie Shelf, so in the last decade the ice coverage has become similar on the two shelves. Although ice coverage on the Mackenzie Shelf has not declined markedly, it is expected to decrease as the seas around it respond to a warmer climate. This decrease will expose the Canadian shelves to industrial activity such as the possibility of commercial fishing.*

3.2.1. Ice Loss from the Arctic Basin

The Arctic is warming at a much faster rate than the earth as a whole (Comiso 2006), and the most dramatic signal of Arctic warming is the continued reduction in the extent of summer sea ice cover and a decrease in the amount of multi-year, thicker ice over the Arctic basins (Barber et al. 2008b). Summer ice cover has decreased at a rate of 8.9% per decade over the past 30 years (Perovich et al. 2010, Comiso 2008), and the average thickness of sea ice has declined by ~50% between 1980 and 2009 (Fig. 3; Richter-Menge and Overland 2009). Since ~1976, Arctic sea ice has been disappearing at much higher rates that those predicted by the models employed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Fig. 3; Stroeve et al. 2007). The decline has been particularly rapid during this decade, with record lows in 2007. The implication for the Canadian Beaufort Sea is that eventually the continental shelves and shelf-slopes will become ice-free in summer, opening the possibility of commercial fishing, oil and gas exploration, and marine transport over the shelves. The next section describes the shelves from a fisheries perspective.

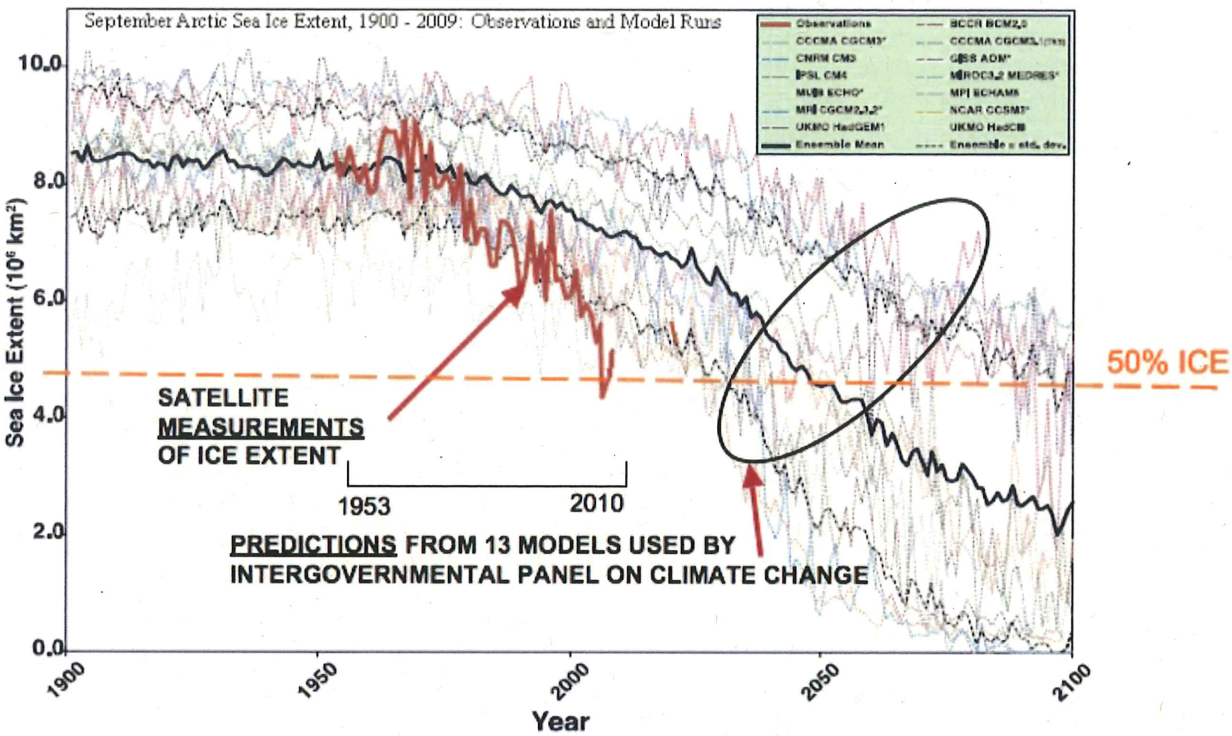

Figure 3. Arctic sea-ice extent from observations (thick red line) and 13 model forecasts used to formulate the 2007 IPCC report (light lines). The thick black line is the mean of the 13 models, with the standard deviation plotted as a dashed black line. Image has been updated to include the observed 2008 and 2009 measurements. Sea-ice extent in 2010 was 4.6 x 10^6 km^2. None of the models predicted the record 2007 sea-ice loss. (From Stroeve et al. 2007.)

3.2.2. Ice Loss from the Canadian Beaufort Shelves

Although the *extent* of ice over the Canadian Beaufort shelves appears to be decreasing, its *rate of decline* is uncertain. Certainly the extent of summer ice coverage over the deepest part of the Beaufort Sea, the Canada Basin, has decreased by 7.2% per decade (Fissel et al. 2009). However, over the Mackenzie Shelf the trends have been much smaller and there is so much year-to-year variation that some of the measurements are statistically uncertain. For example, Fissel et al. (2009), using ice charts from the Canadian Ice Service, found that ice coverage on the Mackenzie Shelf declined by 2.9% per decade in the 28 years from 1968–2005, but the trend was statistically overwhelmed by the high variation from year to year. Similarly, Melling et al. (2005), measuring the draft of winter ice from upwards-looking sonar on the middle of the Mackenzie Shelf found a slight decline in winter ice thickness (7 cm per decade) in the 12 years from 1992–2003, but the trend was overwhelmed statistically by the large year-to-year variation. On the other hand, Barber et al. (2008a) were able to demonstrate clear evidence of a slow decrease of the ice cover in Amundsen Gulf and north of the Alaskan Shelf. Considerable uncertainty about ice thickness has arisen from the observation that ice thickness measured by traditional satellite imagery (i.e., Canadian Ice Service) was vastly over-estimated when compared with actual conditions on the sea surface of the Mackenzie Shelf (Barber et al. 2009), suggesting that ice thickness has decreased substantially.

In parts of the Beaufort Sea, ice concentration has increased, and in other parts it has decreased. For example, to the west of Banks Island, Barber et al. (2008b) noted an increase in sea ice concentration between 1979–2002, and attributed it to compaction associated with motion of the central Arctic ice pack up against the Queen Elizabeth Islands. On the other hand, Fissel et al. (2009) found that the season for shipping between Pt. Barrow and Prudhoe Bay on the Alaskan Beaufort Shelf had increased by 24 days between 1953–2006. Similarly, Barber et al. (2008a) showed that the mean start date of ice break-up in Amundsen Gulf was earlier in the period 1980–2004 compared to the period 1964–1974.

There has been a significant decline of 11% per decade in ice coverage over the Alaskan Beaufort Shelf (Fissel et al. 2009). Drobot and Maslanik (2003) have noted that ice coverage during the shipping season on the Alaskan Shelf differed little between 1968–1996, but decreased greatly after that. They attributed light ice summers over the Beaufort Sea to a strongly defined high pressure system over the Canadian Arctic Archipelago, which enhances easterly and northerly winds that advect sea ice out of the Beaufort Sea. The Beaufort High is correlated with oscillations in northern atmospheric patterns.

3.3. The Continental Shelves

Fisheries Implications: *The ice-free area in the Canadian Beaufort Sea open to industrial fishing in the summer is limited presently to the Mackenzie Shelf and Amundsen Gulf. The maximum open-water period is limited to less than three months. Underwater hazards are known and many are mapped by Natural Resources Canada. The Mackenzie Shelf is highly estuarine, whereas Amundsen Gulf is oceanic in nature. The inshore region of the Mackenzie Shelf supports a number of estuarine fish species that are important for the Inuvialuit subsistence fishery, whereas an Arctic cod fishery would be more likely found in offshore, more marine waters of the Mackenzie Shelf, as well as in Amundsen Gulf. The Banks Shelf is mostly ice-covered. Flaw-leads from the Bathurst polyna on the Mackenzie and Banks shelves open early in the season and are important areas of productivity for whales, seals, polar bears, eiders, and long-tailed ducks. They are presumably also important for fish such as Arctic cod, but no systematic fishery surveys have been carried out in this habitat.*

3.3.1. Mackenzie Shelf

The Mackenzie Shelf is a flat, shallow plain (64,000 km^2) running ~530 km from the Canadian border in the west, to Amundsen Gulf in the east. Its average depth is 35 m, and its average bottom slope is 0.04% The shelf-break occurs between the 80- and 120-m isobaths, ~120 km offshore (Carmack et al. 1989). Generally, the shelf slopes to >1000 m in <50 km distance from the shelf-break (Dome Petroleum et al. 1982). The Mackenzie is the largest Canadian shelf on the North American side of the Arctic Ocean.

The two main features of Shelf topography are a deep, V-shaped canyon, the Mackenzie Trough, at its western edge and, parallel to it, a smaller canyon, the Kugmallit Trough, near mid-shelf. Shelf sediments consist of clays and silts originating from the Mackenzie River (Dome Petroleum et al. 1982). The bottom is flat and regular. There are several geological features on the Mackenzie Shelf that may be hazards to commercial fishing. These are underwater pingos, mud volcanoes, gas vents, ice scours, and artificial islands. Underwater pingos and mud volcanoes are substantial mounds rising from the sea floor associated with the gassing of methane gas hydrates beneath the sea bed (Paull et al. 2007). These formations occur as single features or as several hundred in long corridors. A recently discovered corridor is the "Garry Knolls" area, located west of Richards Island and extending northwest to the shelf-break. Gas vents are depressions in the sea floor also arising from the venting of methane gas (Cobb et al. 2008). These features may be a geohazard for drilling, shipping, and commercial fishing. Ice scours are caused by keels of ice moving along the sea bed. Scouring is most active in the 5–25-m depth zone. Thirty-six artificial islands, built to support hydrocarbon drilling activity in the 1970s, rise to a few metres below the sea surface of the Mackenzie Shelf. Many of these geohazards have been mapped by Natural Resources Canada and the Pacific Geoscience Centre at Sidney, BC, and maps have been compiled by Quadra Planning Consultants (2002).

The average extent of open water on the Mackenzie Shelf in the summer is shown in Fig. 4. The open-water season usually lasts for about three months, from mid-July to mid-October. However, during the open-water season, heavy pack ice can move into the nearshore waters of the Shelf under the influence of strong winds from the north. These ice intrusions result in the high degree of variability in the length of the open-water season that is observed from year to year (Devon Canada 2004).

The Mackenzie Shelf is the most estuarine of all Arctic Ocean shelves because it is small relative to the amount of fresh water it receives from the Mackenzie River— ~330 km^3 annually, mostly between May and September (Ayles and Snow 2002). The River's annual outflow, if not mixed, would constitute a layer of fresh water 5 m deep covering the entire Shelf. In contrast, freshwater layers on Eurasian, interior continental shelves would amount to only 0.8 m for the Laptev Sea and 1.3 m for the Kara Sea (Macdonald et al. 1987). The Mackenzie Shelf has a 2–3 month flushing time (time to renew the fresh water on the Shelf), much lower than that for the Eurasian shelves because the Mackenzie Shelf is relatively small in relation to the Mackenzie River flow rate. The concept of a single "plume" issuing from the incoming river and forming a strictly two-layered structure over uniform shelf water is misleading because a variety of temperature, salinity, and turbidity fronts co-exist on the Shelf at any given time (Carmack et al. 1989). Thus, the food web of the inner Shelf is estuarine in nature, characterized predominantly by river-based production. The outer Shelf beyond 20 m depth and Cape Bathurst are characterized by both river-based and marine production (Fortier et al. 2008). See Section 3.4.4 *Dominance of Mackenzie River* for a discussion of the Mackenzie River influence on the Shelf.

Currents on the Mackenzie Shelf are generally weak easterly, driven by the Coriolis force acting on the Mackenzie River outflow, but surface water can be driven to the west by easterly winds. On the outer Shelf, the surface waters move in a westerly direction, driven by the Beaufort Gyre. However, beneath the surface layer, the Beaufort Countercurrent, 75–250 m deep, moves eastwards, carrying Pacific water along the edge of the Shelf slope-break (Lavoie et al. 2009).

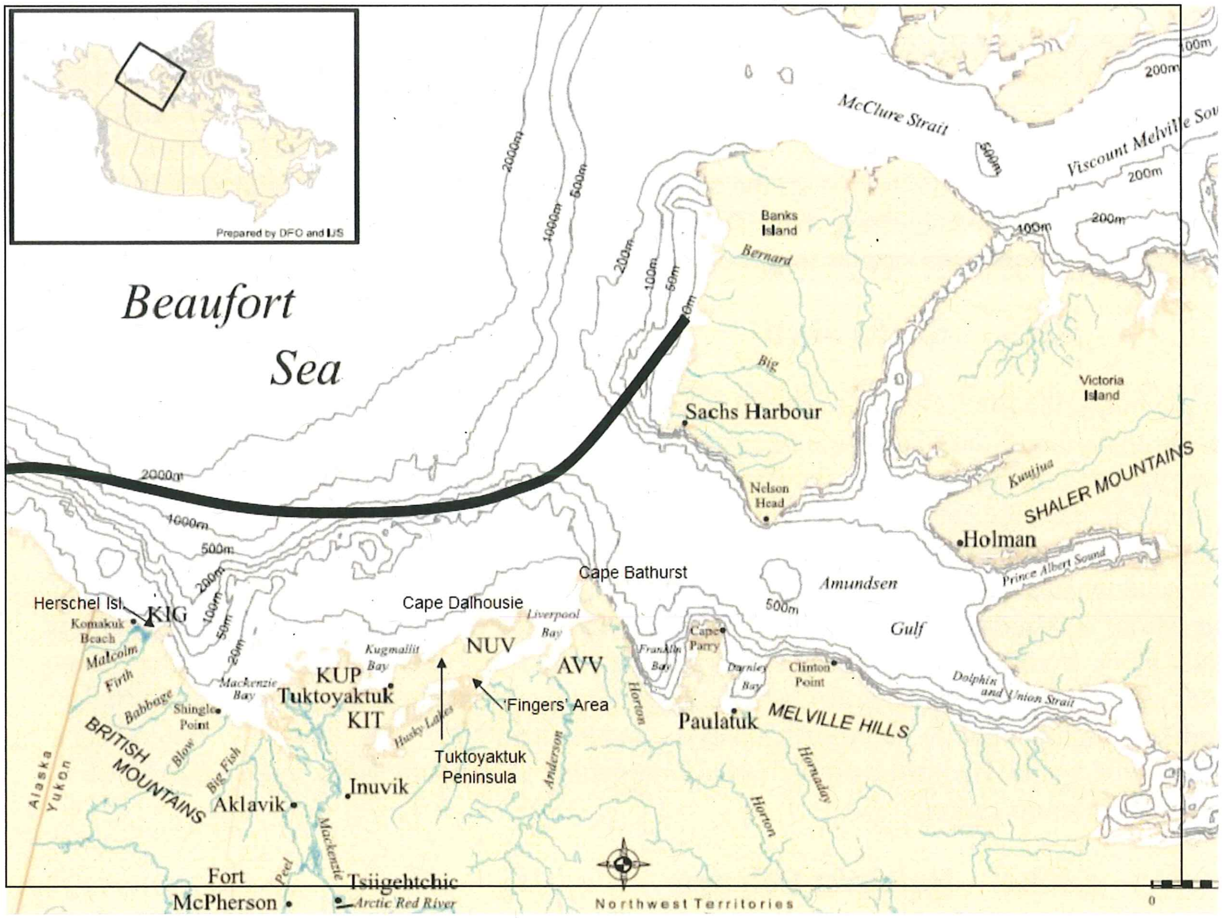

Figure 4. Canadian Beaufort Sea area, showing ocean depth contours, settlements, major rivers, and geographical features mentioned in the text. Abbreviations indicate geographical centres of Inuvialuit groups at the time of first European contact. Black line indicates southern extent of ice cover in late summer. (From Ayles and Snow 2002 and Ingram et al. 2008.)

3.3.2. Amundsen Gulf

The Amundsen Gulf (Fig. 1) is a large, undersea valley (~400 km in length and 130 km in width) that extends, at a depth of 300–400 m, from the shelf slope-break at the southeastern corner of the Beaufort Sea to the entrance of Dolphin and Union Strait (Fig. 4). The mouth of the Gulf is bordered by the Banks Island Shelf to the north and by the Mackenzie Shelf to the southwest. Most of the Mackenzie River sediments (97%) are deposited inshore on the Mackenzie Shelf (O'Brien et al. 2005), so very little of the material in the river plume reaches the Amundsen Gulf. Food webs in Amundsen Gulf are characterized by marine production (Fortier et al. 2008).

Amundsen Gulf is classified as an outflow shelf, so its water takes on the strongly stratified nature of water in the Canada Basin. The water column is typically formed by the "Polar Mixed Layer" from 0–50 m, overlying a cold, halocline layer from 50–200 m, which is derived from waters of Pacific origin, and under that, an "Atlantic Water Layer" at depths >200 m (McLaughlin et al. 1996). Nutrients are brought slowly into the upper mixed water layer during the winter, and as soon as there is enough light for photosynthesis in May, the ice-algae quickly exhaust the nutrients by the time the ice has melted. Primary production then shifts to the bottom of the mixed water layer, between 30–60 m, where nutrients are higher, but where light is lower (Tremblay et al. 2008). Productivity in Amundsen Gulf was similar to that on the Mackenzie Shelf (Brugel et al. 2009). This fact is consistent with the finding that the benthic community in Amundsen Gulf is similar to that on the Mackenzie Shelf and slope to the west at similar depth (Conlan et al. 2008), suggesting that processes within the Bathurst polynya that influence carbon export to the benthos are similar to those on the Mackenzie Shelf.

3.3.3. Banks Shelf

To the north, the Banks Shelf is roughly 230 km long and ~100 km wide. Its slope-break is deeper than that of the Mackenzie Shelf, at ~250–300 m (Ayles and Snow 2002). There is not a great deal of information about the Banks Shelf, probably because up to the present, it has been covered by pack ice continuously throughout the year, except for a large open-water flaw-lead that parallels the shore at ~20 m depth. This flaw-lead is known to be a productive area where bowhead whales feed at certain times (Harwood et al. 2008a, b) and where, during the spring migration, hundreds of thousands of eiders and long-tailed ducks dive and feed in the shallow water along Banks Island and near Cape Bathurst (Dickson and Gilchrist 2002). The ice flaw-leads on the Banks Shelf and off Cape Bathurst are two areas where theoretical models have predicted high benthic productivity (Kostylev and Hannah 2007, V.E. Kostylev, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, NS, Canada, B2Y 4A2 personal communication).

3.3.4. Bathurst Polynya

An area of open water known as the Cape Bathurst polynya forms almost every year, sometimes as early as mid-March, between Baillie Island and Banks Island in Amundsen Gulf. Its associated ice flaw-lead system runs east–west along the southern Beaufort Sea over the Mackenzie Shelf, swings north parallel to the western coast of Banks Island, past the entrance to M'Clure Strait, and along the western coast of Prince Patrick Island. It is caused by the shearing action of multi-year ice rotating in the Beaufort Gyre in the Canada Basin, against the stationary land-fast ice of Amundsen Gulf. The polynya and flaw-leads are important because they expose the sea surface to sunlight, which stimulates an early plankton bloom at the ice edges. These areas of higher productivity are significant because they attract concentrations of sea birds, seals, and polar bears, particularly in the early spring.

3.4. Habitats

Fisheries Implications: *Major food webs on the Canadian Beaufort shelves depend on the integrity and stability of the habitats in which they are found. Three generalized habitats are identified. The open-water marine habitat is considered the likely venue for a potential commercial fishery. The estuarine habitat is the site of most of the subsistence fishery. The ice-edge habitat is critical for ice-adapted marine mammals and for migrant birds.*

The offshore marine habitat of the Canadian Beaufort Sea is nutrient poor because nutrient-rich water lying at depth is overlain by a low-salinity water layer and a strong halocline, which prevent upward mixing. Nutrients are brought into the Beaufort Sea from the Bering Sea via a *deep current that runs eastward, along and just below the edge of the continental shelf. However, these nutrients only fertilize surface waters when deep water is brought to the surface by upwelling events. Upwelling is expected to increase with further loss of ice, so productivity is expected to rise in the coming decades.*

The inshore estuarine habitat supports a wide variety of anadromous fish, which form the basis of the Inuvialuit subsistence fishery. It is also a potential migration route for immigrant species from the Pacific Ocean.

The ice-edge habitat is an area of high but transient and short-lived productivity that modulates carbon flux to the sea floor. In years of early ice melt, less primary production reaches the sea floor, suggesting that climate change will favour the pelagic community over the benthic community. The ice-edge habitat of flaw leads is an important migration and feeding area for early marine mammal and bird migrants.

The benthic habitat of the Mackenzie Shelf is flat and muddy with little evidence of soft corals or macrophytes. The shelf area around Cape Bathurst is recognized as an Ecologically Significant Area that has a distinctive benthic community and high productivity.

3.4.1. Marine Habitat

The marine environment is dominant over the Banks Shelf, in Amundsen Gulf, and over the outer Mackenzie Shelf (Fig. 5). On the inner Mackenzie Shelf, an estuarine habitat of low salinity can extend for 20–60 km offshore in a thin, floating band 12 m thick, and the marine habitat lies below it, starting at about the 12-m depth contour at ~20 km offshore. There, the sea water rises to ~80% full strength (salinity ~28 ‰) and increases in salinity in a seaward direction to ~31‰ at the edge of the shelf-break (Fig. 5). Carmack et al. (1989) cautioned, however, that a variety of temperature, salinity, and turbidity fronts co-exist on the Mackenzie Shelf at any given time, so the concept of a discrete, low-salinity plume overlaying a full marine habitat is an over-simplification. For example, on shelves with less riverine input, like the Banks Island Shelf, the marine habitat may extend completely into the shore.

3.4.1.1. Polar-Mixed Layer

The marine habitat over the Beaufort shelves and shelf-slopes consists of three water layers. First is the Polar-Mixed Layer (Fig. 5). It is a thin (50 m) surface layer of oceanic water extending over the entire Arctic Ocean. It is buoyant because of its low salinity and is well mixed by summer winds. The fresh water causing its low salinity comes from two sources:

- Major river systems draining into the Arctic Ocean supply ~4270 km^3 of fresh water annually and another 900 km^3 comes from precipitation. Together, these sources would add the equivalent of 37 cm of fresh water to the entire surface of the Arctic Ocean. The low salinity of the Arctic surface layer is ultimately responsible for its ice cover (Carmack et al. 1989).

- The distillation of sea water—when sea water freezes, salt is removed from the ice as heavy brine, which sinks below the surface; when the ice melts, it forms a freshwater layer, minus the salt. The fresh water mixes with sea water, forming a floating, well-mixed layer from the surface down to ~50 m deep. This Polar-Mixed Layer is relatively poor in nutrients.

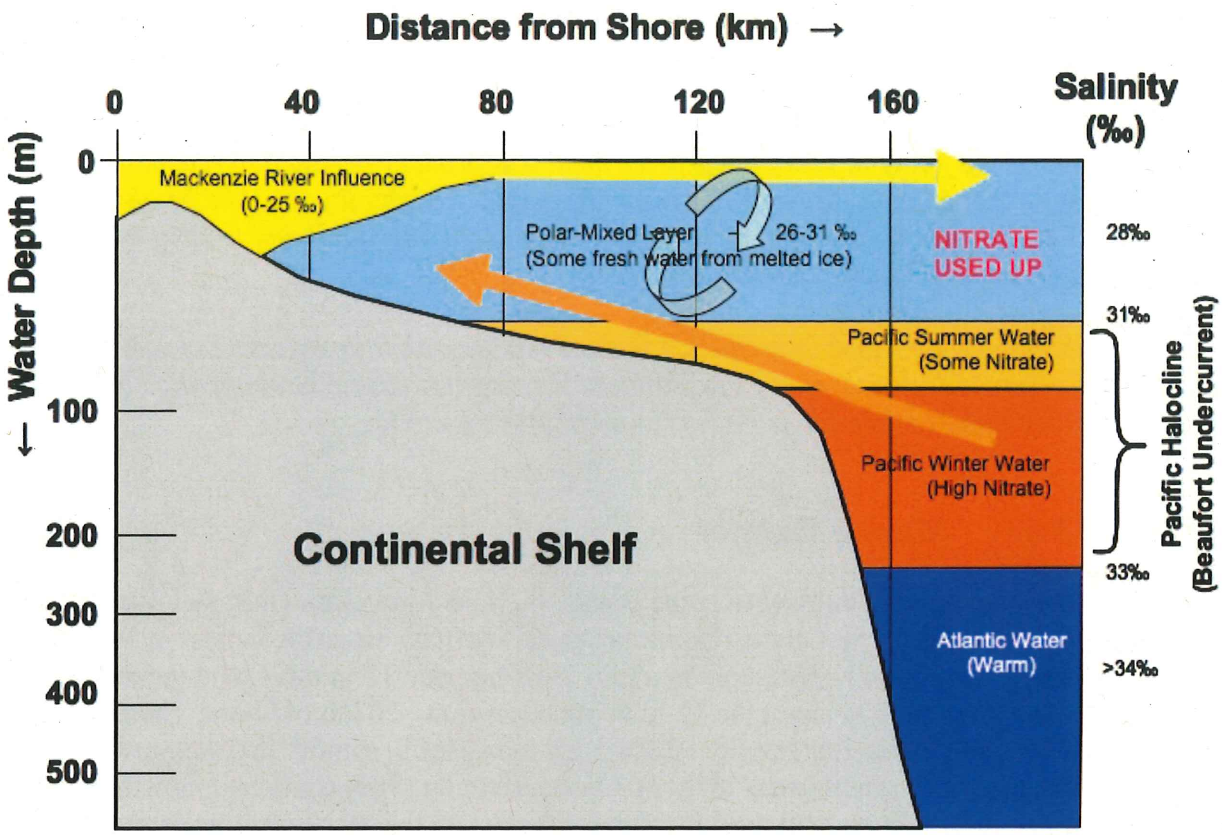

Figure 5. Cross-section of the Mackenzie Shelf showing different water layers in relation to water depth and distance from the shore. The salinity of each layer is shown in units of parts per thousand. Water layers consist of the brackish surface layer (yellow) influenced by the Mackenzie River, the Polar-Mixed Layer (light blue) that is mixed by the wind, the Pacific Halocline (orange) made up of Pacific Summer Water and Pacific Winter Water, and the Atlantic Water Layer (dark blue). The orange arrow indicates the upwelling of Pacific water to replace surface water blown offshore (yellow arrow) by wind.

3.4.1.2. Pacific Halocline or Beaufort Undercurrent

The second layer making up the marine habitat is the Pacific Halocline (Fig. 5). The term "halocline" refers to the fact that, within this layer, the water becomes more salty from top to bottom. The water in the Pacific Halocline, under the influence of the Coriolis force, moves from west to east along the edge of the Beaufort Sea shelves in a counter-clockwise direction as a current called the "Beaufort Undercurrent". It exists in a narrow band (~20 km wide) with an average core speed of 8 cm s^{-1} centred at ~170 m depth (Hopcroft et al. 2008). Water in the

Beaufort Undercurrent originates in the Bering Sea, enters the Arctic Ocean through the Bering Strait, and crosses the Chuckchi Shelf at a rate of ~25,300 $km^3 y^{-1}$. It is drawn from the top 60 m of the Bering Sea, the depth of the Bering Strait. Heavier than the Polar-Mixed Layer, it flows over the edge of the Chukchi Shelf to form a layer below the Polar-Mixed Layer, but above the Atlantic Water Layer that fills the basins of the Arctic Ocean. The Beaufort Undercurrent transfers nutrients, heat, and plankton to the Beaufort shelves from the Pacific Ocean (Fig. 1). It is an important route for Pacific marine species to move into the Beaufort Sea as the climate warms.

The Beaufort Undercurrent is the source of nitrate that the Beaufort Sea marine ecosystem requires for increased productivity. However, it is composed of two layers: Pacific Summer and Winter Water. Water that flows over the Chukchi Shelf in summer is heated and partially stripped of nutrients by the phytoplankton on the Shelf. Therefore, the Pacific Summer Water is lighter and poorer in nutrients than water that flows over the Chukchi Shelf in winter. The Pacific water in the Beaufort Undercurrent is important to the productivity of the Canadian Beaufort shelves for three reasons:

- Its nutrient-rich waters can be carried onto the shelves when easterly winds blow the surface water away from the shelves. When this happens, surface water is replaced by deeper water from the Beaufort Undercurrent, which flows up onto the shelves as shown in Fig. 5, or up through canyons on the Mackenzie Shelf (after Dunton et al. 2006).
- Second, Carmack and Chapman (2003) predicted that if seasonal ice melts seaward beyond the slope-break of the continental shelves, then the Beaufort Undercurrent will be exposed directly to wind mixing, with the result that its nitrate will be brought into the surface Polar-Mixed Layer where it will fertilize increased productivity (see Section 5.1.2 *Enhanced Upwelling*).
- The Bering/Chukchi shelves are shallow, so that Pacific Ocean water is heated as it flows over ice-free areas during the summer, which creates a reservoir of heat at shallow depths within the Pacific Halocline. This heat could potentially retard the growth of ice in the subsequent winter, an effect that could spread eastward to the Beaufort shelves (Leong 2005.

3.4.1.3. Atlantic Water Layer

Below the Pacific water, at ~200 m depth, lies water that has come from the Atlantic Ocean (Fig. 5). The Atlantic supplies about 5–7 times more water annually to the Arctic Ocean than does the Pacific (Roach et al. 1995). This water is less important to a discussion of primary productivity on the Beaufort Sea shelves because it is too deep to exchange with shelf water and bring nutrients onto the shelves. However, it is important to the marine food web because it brings with it Atlantic species, which can populate the Arctic Ocean under the right conditions. An example is the Greenland halibut, which is fished commercially throughout Davis Strait in the eastern Arctic and has recently been found on the Banks Shelf within the Atlantic Water Layer (Chiperzak et al. 1995). Below the Atlantic Water Layer at ~850 m is a cold, more saline, deep layer, which extends to the bottom of the Canada Basin, at ~3800 m.

3.4.2. Ice-Edge Habitat, Polynyas, and Flaw-Leads

The ice edge is a unique marine habitat associated with the edge of melting ice during the Arctic spring and summer. It is a highly productive zone for a short period, and the productive band of the ice edge moves over the sea bottom as the ice melts back. Its productivity acts to concentrate fish, birds, and marine mammals. Its open water encourages the migration of beluga and bowhead whales and tens of thousands of sea birds into the Canadian Beaufort Sea.

The Bathurst polynya is a special type of ice-edge habitat because it recurs each year in the southeast corner of the Beaufort Sea in the early spring while the rest of the Sea is ice-covered (Fig. 6). Its shore-leads extend north, parallel to the shore of Banks Island, and west, parallel to the Tuktoyaktuk Peninsula. This polynya/shore-lead system is of enormous biological importance because it is predictable in location, recurrent, and among the most constant of areas where open water occurs in the Beaufort Sea in the spring.

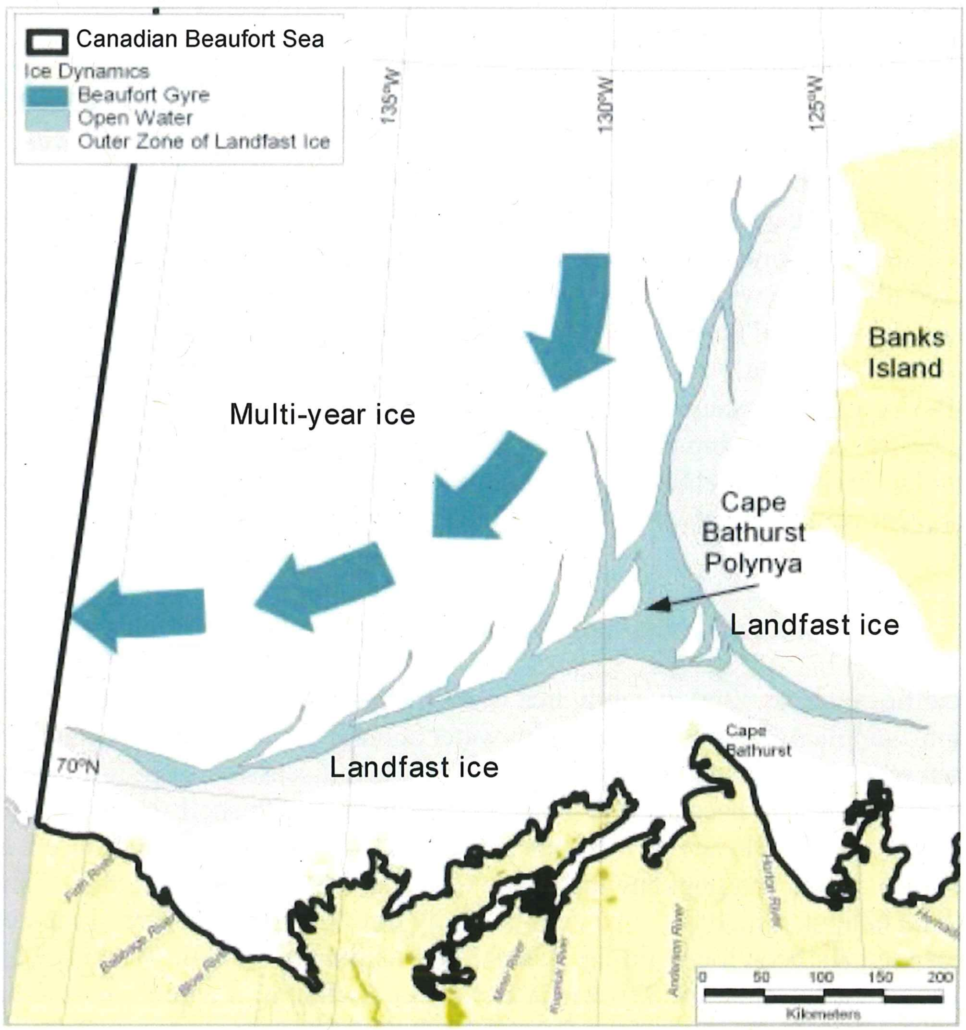

Figure 6. Movement of multi-year ice in the Canadian Beaufort Sea interacting with landfast ice to create the Bathurst polynya and its associated flaw-leads at the shear zones during winter. In summer, the sea is ice-free from shore to the multi-year ice (Cobb et al. 2008, adapted from Percy et al. 1985.)

The following idealized description of ice dynamics, taken from Carmack et al. (2004) and Carmack and Wassmann (2006), provides an understanding of how the ice-edge habitat behaves. At the end of September, the sea is free of ice between the shore and the multi-year pack ice lying offshore (Fig. 6). Generally, in the Canadian Beaufort Sea the multi-year pack ice in summer arcs in a band from the north end of Banks Island to several tens of kilometres offshore of Herschel Island. As ice begins to form in October, the ice growing seaward from the shore—and shoreward from the multi-year pack ice—comes together. Where the moving pack ice grinds against the landfast ice, a series of compression ridges, called "Stamukhis", form above and below the sea surface. They anchor the outer edge of the landfast ice to the sea bottom in ~20 m of water, ~20 km offshore.

Along this shear zone, a system of recurrent, open-water cracks in the ice, called "flaw-leads", collectively engirdles much of the entire Arctic Ocean. In the Canadian Beaufort Sea, the flaw-leads generally run from Herschel Island, along the Tuktoyaktuk Peninsula, past Cape Bathurst, and into Amundsen Gulf where they turn north along the west coast of Banks Island (Fig. 6). This open water is the Bathurst polynya and flaw-lead system. In the spring (mid-May), the flaw-leads begin to open as the first-year ice melts south towards the shore and north towards the multi-year pack ice. The area between the maximum (winter) and minimum (summer) ice cover that freezes and melts annually is called the "seasonal ice zone". As the ice edge melts, it moves across the seasonal ice zone. Thus, the seasonal ice zone is where the ice-edge habitat is to be found.

The ice-edge habitat is important for the following three reasons:

1. Productivity: Ice edges of the Bathurst polynya produce carbon early in the spring as the ice just begins to break up. The ice edges in the Bathurst polynya and the flaw-leads extending north along Banks Island (Fig. 7) are areas of higher food availability than the surrounding areas. They have been identified as Ecologically Significant Areas by hunters and elders from the six Inuvialuit Communities, marine scientists (Paulic et al. 2009), and by early explorers impressed with the increase in abundance of plankton, birds, seals, and whales near the ice edge in comparison with the open sea (e.g., Ross 1847, Fraser and Ainley 1986; after Stirling 1997). For example, each spring from mid-May to mid-June, hundreds of thousands of birds stop temporarily in leads of open water in the southeastern Beaufort Sea to rest and feed (Alexander et al. 1997). The most abundant species are the common eider, king eider, long-tailed duck, glaucous gull, and three species of loon.

2. Benthic/Pelagic Coupling: The ice edges in flaw-leads and polynyas are thought to shunt a significant fraction of the early productivity of ice-algae to the benthos on the sea floor, particularly in the early spring when phytoplankton can reproduce so quickly that they escape grazing and sink to the bottom. Also, ice-associated diatoms aggregated with the viscous exopolymers they produce are released from the ice when it melts and sink towards the sea floor (Forest et al. 2010). This sinking gives rise to a greater flux of carbon to the sea floor than in summer-stratified waters, when carbon production would be intercepted by zooplankton (Arrigo and van Dijken 2004). Another potential effect of the Bathurst polynya on the benthos is increased vertical mixing due to wind effects and brine release by newly forming sea ice. Grebmeier and Cooper (1995) documented this effect in the central Bering Sea polynya.

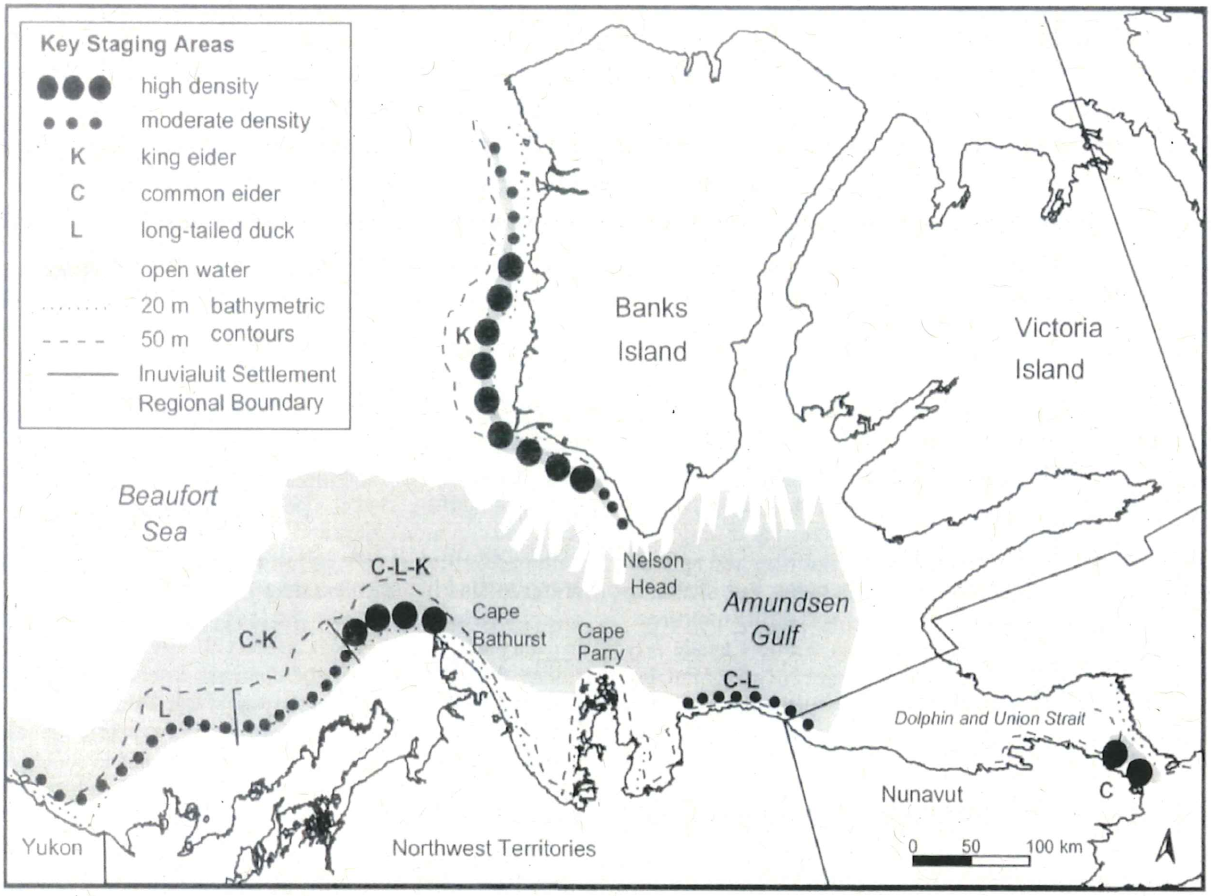

Figure 7. Location of major staging areas for king eiders, common eiders, and long-tailed ducks in western Arctic Canada during spring migration. (From Dickson and Gilchrist 2002.)

Benthic/pelagic coupling was detected in western Franklin Bay, where the benthos 230 m deep responded to the overlying ice-algae bloom with a 10-fold increase in respiration rate (Renaud et al. 2007). Interestingly, the abundance and species composition of benthos in the Bathurst polynya were similar to that on the Mackenzie Shelf-slope at the same depth (Conlan et al. 2008), suggesting that the polynya itself may be no more productive than surrounding areas of similar depth. This conclusion should be tested with measures of benthic biomass, a better indicator of productivity than benthic abundance.

In Amundsen Gulf, when ice melted late in the season, surface water temperatures were lower, zooplanton less abundant, and more of the primary production carbon from ice-algae (up to 30%) reached the 100 m depth (Forest et al. 2010). When ice melted early, surface water temperature was higher, zooplanton were more abundant, and most of the production was consumed in the water column by the pelagic herbivore community, only 10% reaching the 100 m depth. Forest et al. (2010) concluded, therefore, that as the Arctic Ocean warms up, earlier ice melt will promote energy pathways that benefit pelagic rather than benthic food webs.

3. Marine Mammal Migration: Coastal flaw-leads and polynyas provide the earliest zone of open water in the spring, and are used extensively by animals migrating into the Beaufort Sea ecosystem (e.g., beluga and bowhead whales coming from their wintering grounds in the Bering Sea). Beluga and bowhead whales enter the shore-lead systems off western Alaska in March and April and begin to migrate east, arriving in the Cape Bathurst polynya by about late May (Fraker et al. 1978). After feeding there for about six weeks, belugas move westward to the Mackenzie River estuary to have their calves and feed in the estuary. Bowhead whales also appear to feed in the vicinity of the Cape Bathurst polynya, and many remain to feed in Amundsen Gulf after the ice breaks up (Stirling 1997). The ice edge attracts a higher density of ringed seals and polar bear than other areas.

3.4.3. Estuarine Habitat

The Beaufort Sea estuarine habitat (Fig. 1) is a local reflection of what Carmack and Wassmann (2006) call the "Riverine Coastal Domain"—the transport of fresh water that pulses slowly, counter-clockwise around the perimeter of the Arctic Ocean as a floating coastal current, derived from inflowing rivers. The estuarine habitat is an inshore, continuous band of relatively warm and brackish water (temperature: 5–10°C; salinity: 10–25‰) that lies adjacent to the shoreline in summer. It is held against the coastline by Coriolis forces. It extends >750 km along the Beaufort Shelf coast from Pt. Barrow, Alaska, to the Amundsen Gulf, and is found in Liverpool Bay, Franklin Bay, Darnley Bay, and the inner reaches of Prince Albert Sound (Fig. 4). This estuarine band is generally narrow (usually 2–10 km wide) and is often distinctly different from adjacent marine waters, which characteristically have a temperature of 1–3°C and a salinity of 27–32‰. The estuarine habitat on the Mackenzie Shelf is wider, warmer, and fresher than elsewhere because of the influence of the Mackenzie River (Craig 1984, Carmack and Macdonald 2002). The estuarine habitat provides a summer feeding ground for ~20 anadromous fish species that spawn and overwinter in coastal rivers, thereby giving rise to a distinct estuarine food web that supports the bulk of the Inuvialuit subsistence fishery. A number of localities within the estuarine habitat have been identified as ecologically significant (Appendix 2) by the Inuvialuit (Paulic et al. 2009).

The estuarine habitat is created by the Pacific Coastal Current, reinforced by local Arctic rivers, as it flows east along the Alaskan Shelf, and is massively enhanced by the Mackenzie River as it reaches the Mackenzie Shelf. The Pacific Coastal Current is an intermittent but contiguous band of fresh water slowly moving along the coast, north from the Bering Sea where it is fed by the Yukon River, then eastward along the coast of the Chuckchi Sea and the Beaufort coasts. As it moves eastward it is swollen by numerous rivers that drain onto the Beaufort shelves, and is protected from the sea along many parts of the Alaskan Shelf by numerous barrier islands. The inflowing rivers are true Arctic rivers in that they freeze during the winter and flow ceases. In the spring, they discharge ~90% of their total flow in a three-week freshet while the coast is still covered by ice. These rivers export terrestrial organic material to the estuarine habitat that substantially supports the estuarine food web. The estuarine habitat created by the Pacific Coastal Current provides a continuous migration corridor along the shore for anadromous fish and, therefore, provides a migration route for southern species to extend their range into the Beaufort Sea as the climate warms.

Four major rivers drain into the Canadian Beaufort Sea from the British Mountains and across the Yukon Coastal Plain: the Malcolm, Firth, Babbage, and Blow (Fig. 4). In addition, the Big Fish River flows into the Mackenzie River at its western mouth. The rivers arise from springs and surface runoff, and as there are no large lakes on any of the systems, flow is highly variable. The springs and associated pools are critical for overwintering and spawning of Dolly Varden charr, which is an important fish in the subsistence fishery and is considered a keystone species in the estuarine habitat (see Section 3.7 *Keystone Species*).

East of the Mackenzie River Delta, the Anderson Plain ecoregion is drained by the Anderson, Horton, and Hornaday rivers (Fig. 4). All three have large drainage basins compared to the streams to the west of the Mackenzie River, and there are generally small lakes in their headwaters. The Anderson River drains into Liverpool Bay, the Horton River drains into Franklin Bay, and the Hornaday River drains into Darnley Bay (Ayles and Snow 2002). All rivers contain Arctic charr populations important for the subsistence fishery and considered a keystone species in the estuarine habitat (see Section 3.7 *Keystone Species*).

3.4.4. Dominance of Mackenzie River

The estuarine habitat of the Mackenzie Shelf is quite different from that of the Alaskan Shelf because of the massive impact of the Mackenzie River. Its discharge, 330 km^3 annually, supplies ~9% of the annual runoff to the entire Arctic Ocean (Serreze et al. 2006). Draining ~20% of the land area of Canada (Ayles and Snow 2002), much of its drainage basin lies in the temperate zone, so it flows all year long. Even in winter, it delivers ~70 km^3 of fresh water to the coast. This fresh water floats on the sea water, but is held under the ice as a "floating freshwater lake" ~5 m deep with an area of 12,000 km^2 that can extend 60 km offshore (Macdonald et al. 1995). During the spring and summer, the Mackenzie River delivers a further ~260 km^3 of fresh water to the Beaufort Shelf (Stein and Macdonald 2004).

Fresh water from the Mackenzie River is mixed downwards by the wind to form a shallow, relatively fresh (0–20 ‰ salinity) mixed layer at a depth of 10–15 m, which stratifies the upper ocean and extends across the full width of the Mackenzie Shelf (Carmack et al. 1989). Underneath it, the cold, saltier water of the Polar-Mixed Layer overlies the whole of the Canada Basin. In the absence of winds, the incoming river water will tend to bend eastwards under the influence of the Coriolis force and flow along the Tuktoyaktuk Peninsula toward Amundsen Gulf (Carmack and Macdonald 2002), but it frequently spreads offshore and westward under the influence of southeasterly winds.

The Mackenzie River has the highest annual sediment load of all Arctic Rivers, transporting 125 million tonnes of sediment to the Mackenzie Shelf each year. Discharge and sediment supply from the Mackenzie are highest in late April and May prior to break-up. Clay, silt, and fine sand are carried northward onto the continental shelf and then eastward. During the open-water summer months, a surface plume of brackish water with relatively high concentrations of suspended sediment extends over much of the Shelf east of the Delta. Sedimentation rates off the Mackenzie Delta are 4–5 cm per decade, whereas areas to the east and in other locations more exposed to bottom currents or farther from the Mackenzie receive only 0.25 cm per decade (from Ayles and Snow 2002). The high sedimentation rate may be the reason that soft corals and sponges were not found in benthic sampling by Conlan et al. (2008), whereas they were noted by Moulton and Tarbox (1987) in the shallow water off Prudhoe Bay on the Alaskan Shelf.

3.4.5. Benthic Habitat

The benthic habitat of the Mackenzie Shelf is the most studied of the three Canadian shelves, although the recent CASES study has extended information about biodiversity into the Amundsen Gulf. (A discussion of information needs for a fisheries management plan is found in Section 4.1 *Policy Framework*. The state of knowledge about benthic habitats is discussed in Section 4.2.4 *Habitat–Benthos.*)

The benthic habitat on the Mackenzie Shelf is dominated by estuarine conditions, the dynamics of sea ice, and a high sedimentation rate. Gravel is found at the River mouth, but the Shelf is covered by fine silt, sand, and clay. Sedimentation rates vary from 4–5 mm y^{-1} inshore to 0.25 mm y^{-1} near the edge of the Shelf (Ayles and Snow 2002). Soft muddy sediments covering most of the Canadian Beaufort shelves are most suitable for benthic infauna, living within soft-bottom substrata, i.e., organisms such as bivalves and polychaetes. A general lack of hard substrate and the high turbidity of shallow areas do not favour the growth of sessile epifauna such as soft corals or macrophytes. In the area of Stamukhis (see Section 3.4.2 *Ice-Edge Habitat, Polynyas, and Flaw-Leads*), ~20 km offshore in ~20 m water depth, ice-keels mechanically gouge the sea bed, continually disrupting benthic communities. Scouring rates in shallower areas are limited by the presence of landfast ice, whereas they are limited by water depth in deeper areas. The two major gradients in the distribution of benthic communities on the Beaufort Shelf are onshore–offshore and west–east. The onshore–offshore gradient is driven largely by ice scouring, salinity, and water depth, whereas the west–east gradient is a result of productivity and substrate. The west–east gradient in benthic biomass is discussed in Section 3.9.1 *Benthic Biomass.*

Wacasey (1975) described four depth zones for the southern Beaufort Sea, based on water depth, temperature, and salinity (Table 3). The estuarine zone, extending from the shore to water depths of 15 m, is strongly influenced by freshwater input from the Mackenzie River. Salinities are typically <20‰. Diversity is low in this zone, with stations bordering the transitional zone having a higher number of species. Wacasey (1975) attributed the low species diversity (<20 species per station) and low biomass (2 g m^{-2}) in the estuarine zone primarily to the reduced tolerance of many species (e.g., echinoderms) to low salinities over extended periods of time. Characteristic invertebrates of this zone included polychaetes, amphipods, bivalves, mysids, and isopods. Echinoderms were absent from this zone.

A transitional zone between 15–30 m depth is characterized by fluctuations in temperature and salinity (20–30‰) of the bottom waters. A high proportion of this zone is located within an area that experiences the highest rates of ice scouring. Biodiversity is higher (20–40 species m^{-2}) than in the estuarine zone, including species from both the estuarine and further-offshore marine zone, but biomass is low (5 g m^{-2}), in part because of ice scouring in this zone. Review of archived data (S. Blasco and V. Kostylev, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, NS, Canada, B2Y 4A2, personal communication) suggests that diversity is highest just offshore of the peak scouring depth. Echinoderms are present here.

Table 3. Summary of depth zones and benthic invertebrate biomass in the southern Beaufort Sea. (After Wacasey 1975.)

Zone	Depth (m)	Temp. (°C)	Salinity (‰)	Biomass Range ($g\ m^{-2}$)	Biomass Average ($g\ m^{-2}$)	Species per Site
Estuarine	0–15	–1.2 (May) 16.6 (July)	0.1–>40	0.1–20	2	1–32
Transitional	15–30	–1.8 (May) 6.3 (July)	11.6–31.3	1–20	5	20–40
Marine	30–200	–1.6 (Sept) –0.1 (July)	30.1–32.8	1–72	14	3–81
Continental Slope	>200–900	–0.3 (Sept) 0.4 (July)	34.3–34.8	1–8	4	31–53

A marine zone extends from water depths of ~30 m up to 200 m, with salinities ranging from ~30–33‰ (Wacasey 1975). The eastern portion of this zone produced the greatest number of species (3–81 taxa m^{-2}) and the highest biomass of all areas investigated. Average biomass for the entire zone was 14 g m^{-2} (range 1–72 g m^{-2}) with the greatest value north of Liverpool Bay (Wacasey 1975). Conlan et al. (2008) confirmed the high biodiversity at the eastern end of the Mackenzie Shelf north of Cape Bathurst.

A continental slope zone lies in water depths beyond 200 m (Wacasey 1975). Average biomass here was 4 g m^{-2}, lower than for the marine zone, and biodiversity was comparable to that measured in the transitional zone. Biodiversity typically decreased with increasing water depth. As in the marine zone, Wacasey (1975) regarded nutrient availability as the primary variable governing benthic invertebrate biomass and diversity.

Conlan et al. (2008) compared benthic abundance among areas known to be hotspots for bird and marine mammal feeding, i.e., Mackenzie Trough, Amundsen Gulf beneath the polynya, the Cape Bathurst area, and the Mackenzie Shelf-slope and flaw-leads. All areas were similar in abundance except for the Cape Bathurst area, which was higher. Mackenzie Trough and the Cape Bathurst area were distinctively different from the other areas in species composition. Taxonomic diversity was lower and density was higher in the flaw-leads than in other areas.

3.5. Hotspots

Fisheries Implications: *A number of areas in the Canadian Beaufort Sea are identified as "hotspots" where organisms are concentrated or primary productivity is high. Although there is virtually no information about the density of fish in these hotspots, their presence may be suspected owing to the enhanced density of forage organisms there. Some hotspots, such as the Mackenzie Trough, the Mackenzie Shelf-break north of Cape Dalhousie, Cape Bathurst, and the Fingers Area of Liverpool Bay, would be of interest to commercial fishers as places where harvest rates might be maximized. Other areas, such as the ice edge at the Mackenzie and Banks Island flaw-leads of the Bathurst polynya and Franklin Bay in winter, are of less interest because high ice concentration limits fishing. Concentrations of organisms at most of the identified hotspots appear to result from oceanographic fronts, upwellings, or currents. The Cape Bathurst* *area warrants more detailed examination because its high primary productivity, and the community structure and remarkable density of its benthos, suggest it is a unique habitat.*

Certain places in the Canadian Beaufort Sea have been defined as "Ecologically and Biologically Significant Areas" (EBSA) (Paulic et al. 2009, DFO 2004b, DFO 2006, DFO 2011b) because they are important as feeding or spawning locations for keystone species and other species important in food webs supporting the Inuvialuit subsistence fishery (see Section 3.7 *Keystone Species*). EBSAs (Fig. 8; Appendix 2) can be grouped into five categories as follows:

1. Upwelling areas that are high in productivity, biomass, or diversity of species
   - Mackenzie Trough, including Herschel Island
   - Cape Bathurst
   - Beaufort Sea Shelf-break
   - Liverpool Bay
2. Beluga whale habitats, which correspond mostly to beluga protection zones* identified in the proposed Tarium Niryutait Marine Protected Area (MPA) in the Canadian Beaufort Sea
   - Shallow Bay*
   - Beluga Bay*
   - Kugmallit Corridor*
   - Viscount Melville Sound
3. Feeding areas important for seals, polar bears, and sea birds
   - De Salis Bay
   - Cape Bathurst polynya, including Banks Island flaw-lead and Mackenzie flaw-lead
   - Albert Islands/Safety Channel
4. Feeding/spawning areas important for marine fish
   - Husky Lakes
   - Walker Bay and Minto Inlet
   - Thesiger Bay
5. Feeding areas important for estuarine fish
   - Horton River
   - Hornaday River and Pearce Point.

Of these EBSAs, five locations can be identified as hotspots. Inshore hotspots were identified from the traditional knowledge of hunters, whereas offshore areas were identified by aerial or ship-based observations of whales, seals, and sea birds. Hotspots that are likely to be of interest to a commercial fishery are:

- the ice edge at the Mackenzie and Banks Island flaw-leads of the Bathurst polynya
- the Mackenzie Trough
- the Mackenzie Shelf-break north of Cape Dalhousie
- the Cape Bathurst area
- the Fingers Area of Liverpool Bay.

Two other areas where organisms are concentrated are **not** likely to be of interest to commercial fishery management:

- shallow areas of the Mackenzie estuary, such as Beluga Bay and Shallow Bay, where beluga whales congregate. These places are part of the Tarium Niryutait MPA and are, thus, protected from impacts of fishery activity
- a known concentration area for Arctic cod in Franklin Bay, which is ice-covered when cod are most concentrated and, therefore, not available to fishing.

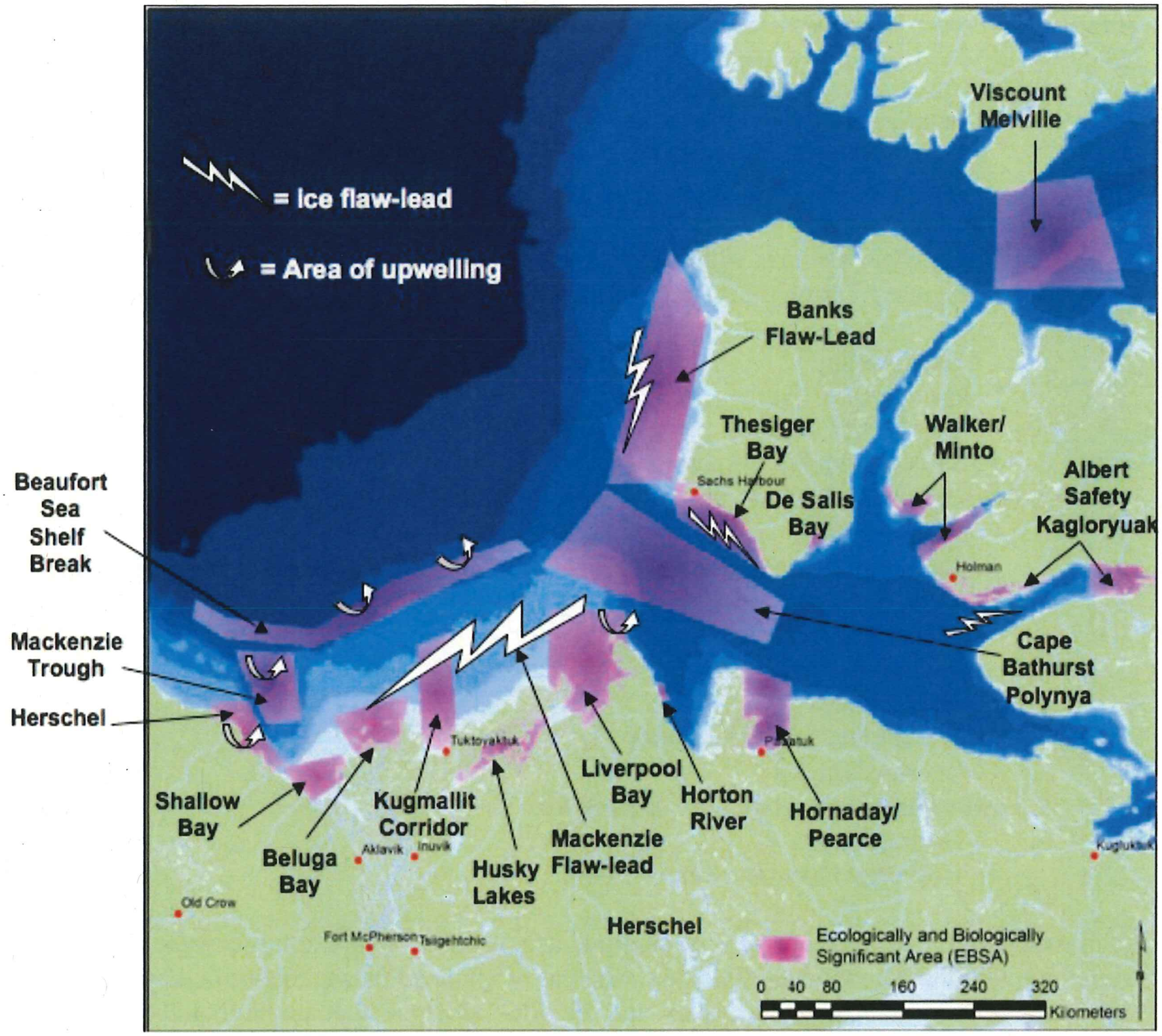

Figure 8. EBSAs in the Beaufort Sea Large Ocean Management Area (LOMA). (After Paulic et al. 2009.)

Hotspots are important for two reasons. From the perspective of fishers, they may be places where fish are concentrated, and from the point of view of Canadian Fisheries Policy they may be places where sensitive habitat could be potentially compromised by fishing practices. Section 4 *Fisheries Management* provides information required to assess the sensitivity of hotspots to commercial fishing. The nature of the hotspots is described below.

3.5.1. Mackenzie and Banks Flaw-Leads: Bathurst Polynya

The ice edge in flaw-leads is a locally productive hotspot, but it moves across the seasonal ice zone as the ice melts, and the productive zone at the ice edge moves with it. Although a pulse of production from the ice edge settles to the sea floor, the pulse is transitory as the ice edge moves away. Thus, the ice edge has a low to moderate level of productivity if integrated over time at any one location (Carmack and Wassman 2006). (See Section 3.4.2 *Ice-Edge Habitat, Polynyas, and Flaw-Leads* for a description of these hotspots and Section *3.6.2 Ice-Edge Food Webs* for a description of the associated food web.) These ice edges are likely to be difficult to fish commercially because of the high concentration of floating ice in the area.

3.5.2. Mackenzie Trough

The Mackenzie Trough cuts into the Shelf northwest of the Mackenzie Delta to a depth of ~400 m. The Trough is 60 km wide and 100 km long. Deposition rates of particulate matter in the Trough are >500% greater than on the upper slope edge to the east (Byers et al. 2010). Mackenzie Trough is an area of enhanced primary and secondary production where bowhead whales, high densities of foraging birds, and ringed seals are frequently observed during the open-water season (Harwood and Stirling 1992, Harwood et al. 2008a,b). The interaction of the Mackenzie River plume with oceanographic turbulence associated with the Mackenzie Trough creates fronts where plankton are concentrated (Dunton et al. 2006).

The upwelling of nutrient-rich waters is also important at this hotspot in determining high zooplankton concentrations (Harwood and Borstad 1985), which in turn appear to influence the distribution of bowhead whales (Fig. 9; Harwood et al. 2008a,b). Strong northeast offshore winds can create upwelling into the Trough. Williams et al. (2006) observed that near the head of the Trough, water from >180 m deep was brought up to the 90-m depth, bringing nutrients from the lower part of the Beaufort Undercurrent (Fig. 5) to where it stimulates phytoplankton growth. The longest upwellings can last over a month. Carmack and Macdonald (2002, p. 35) stated: “It has been hypothesized that primary production initiated here is followed by production at secondary and higher levels as the water moves eastward across the shelf”.

It is not clear whether the benthic habitat in the Trough is critical to bowhead feeding. Conlan et al. (2008) did not find the diversity or abundance of the Trough benthos to be distinct. The evidence suggested that most of the productivity is in the pelagic habitat (copepods), but epi-benthic organisms like mysids, gammarid amphipods, and isopods also concentrate in these places. For example, sampling of plankton in close proximity to feeding bowhead whales revealed predominantly (76–92%) copepods (*Limnocalanus macrurus*, *Calanus hyperboreus*, *Calanus glacialis*), along with gammarid and hyperiid amphipods, euphausiids, and isopods (Bradstreet et al. 1987). Traditional ecological knowledge of the Inuvialuit has identified this area as having high ecological significance (Hartwig 2009; Fig. 8, Appendix 2).

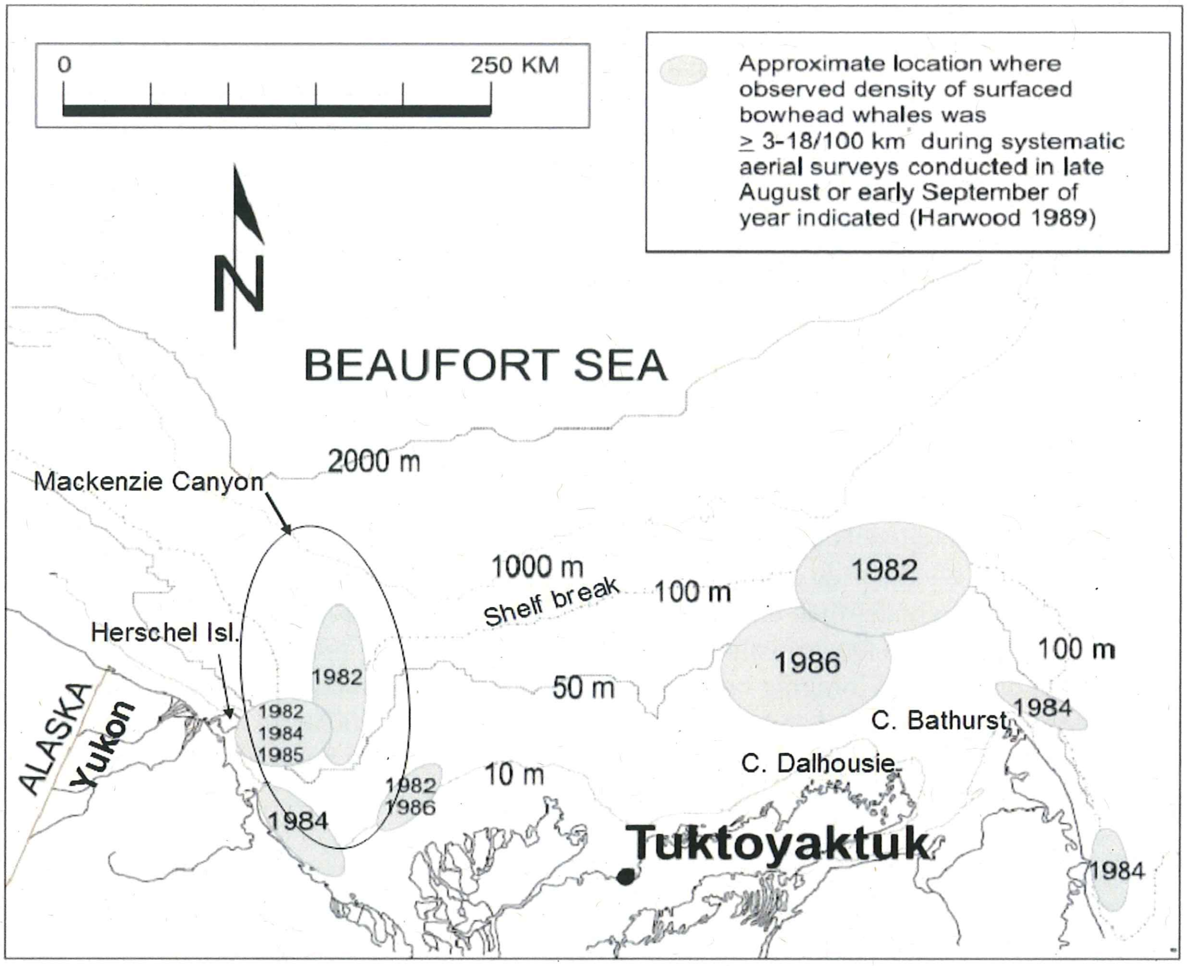

Figure 9. Areas important for bowhead whale feeding. (Adapted from Harwood and Smith 2002.)

3.5.3. Mackenzie Shelf-Break North of Cape Dalhousie

Aitken et al. (2008) mapped potential benthic secondary production estimated from 1970s literature and CASES 2002 studies. The greatest potential secondary benthic production was on the Mackenzie Shelf out to the Shelf-break, at sites north of the Tuktoyaktuk Peninsula and west of the Cape Bathurst polynya, between the flaw-lead and the 400-m isobath. Harwood and Smith (2002) found bowhead whales feeding in this area in 1982 and 1986 (Fig. 9). The Tuktoyaktuk Peninsula inner and outer shelves are considered sensitive habitat areas for bowhead whale in the southeastern Beaufort Sea (from Indian and Northern Affairs Canada "valued component features"; http://www.ainc-inac.gc.ca/nth/og/pemt/bow-eng.asp).

The shelf-break north of Cape Dalhousie is also an area where other marine mammals and sea birds are known to congregate. Ringed seal aggregations were most often located here and north of the Yukon coast (Harwood and Stirling 1992). These authors hypothesized that the ringed seals feed in these aggregations because the areas are known to have oceanographic conditions favourable to zooplankton production. In addition (Mackenzie Gas Project 2005, p. 4), sea birds have been observed feeding in the same areas; in some years, bowhead whales have gathered in these locations, probably to feed; and the stomach contents of four seals from an aggregation area were discovered to be full of mysids.

3.5.4. Cape Bathurst

Cape Bathurst is a unique feature of the Mackenzie Shelf, forming its eastern boundary with Amundsen Gulf, and projecting about one-third of the width of the Shelf. On the eastern side of Cape Bathurst, the sea floor slopes steeply down into Amundsen Gulf to a depth of 60 m in only 8 km. As ocean water passes westward around the Cape driven by easterly winds, it is forced up onto the Shelf at a depth of ~20 m. This sudden change in depth produces significant upwelling to the west of Cape Bathurst. Cold (1–3°C), deep water (pink and blue in Fig. 10) is brought up to the surface, which is generally ~7°C (green in Fig. 10) (Williams and Carmack 2008).

The upwelling at Cape Bathurst brings nutrient-rich Pacific-origin water from ~110 m deep in Amundsen Gulf to the surface. This water fertilizes the phytoplankton over the Mackenzie Shelf and gives rise to a rich benthos to the west of Cape Bathurst. The density of benthic organisms found here is 17,000 individuals m^{-2}. This density is the highest measured in the Arctic, with the exception of some parts of the Bering and Chukchi seas (Conlan et al. 2008), and is 10 times greater than in surrounding areas of the Mackenzie Shelf. The tube-dwelling amphipod *Ampelisca macrocephala* and the polychaete *Barantolla americana*, species that were not abundant elsewhere, made up most of the density. The density of amphipods alone was >8000 individuals m^{-2}.

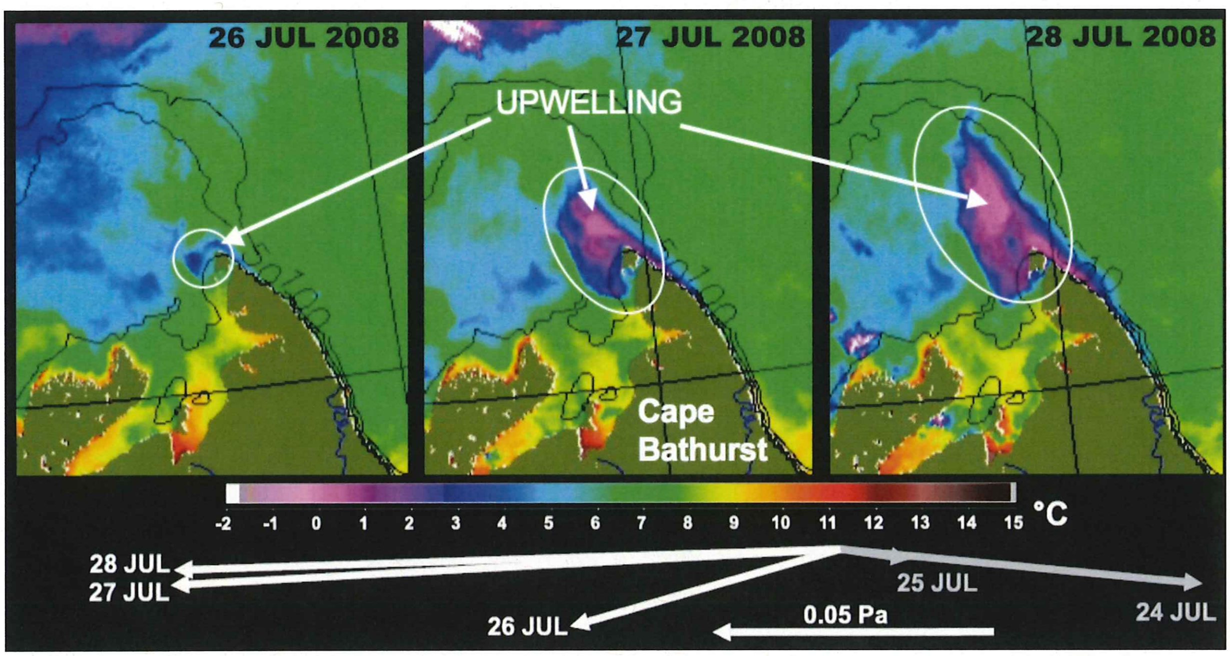

Figure 10. A sequence of sea-surface temperature images of Cape Bathurst taken starting at the onset of upwelling-favourable wind stress. The evolution of the daily averaged wind stress is shown below, beginning two days before the first satellite image. Dark blue and pink areas denote upwelling, colder water being drawn up from depth. Green areas are surface water. (From Williams and Carmack 2008.)

Cape Bathurst is known to be a productive area where bowhead whales feed at certain times (Harwood et al. 2008a,b) and where, during the spring migration, hundreds of thousands of eiders and long-tailed ducks feed in the early open water (Fig. 7; Dickson and Gilchrist 2002). Traditional ecological knowledge of the Inuvialuit has identified this area as having high ecological significance (Fig. 8; Hartwig 2009). The abundant tube-dwelling amphipod *Ampelisca macrocephala* is a prime food resource for California grey whales in the Bering and Chukchi seas (Conlan et al. 2008, after Oliver et al. 1983). Grey whales forage on the Mackenzie Shelf occasionally, and bowhead whales are sometimes known to feed benthically (Frost and Lowry 1984). Therefore, it is possible that grey and bowhead whales feed on the rich benthos at Cape Bathurst. Where it extends into shallower water, this rich benthic resource is important for diving sea birds such as the common and king eiders and long-tailed ducks (Dickson and Gilchrist 2002).

3.5.5. Fingers Area of Liverpool Bay

Pacific herring are most abundant east of the Mackenzie Delta, particularly in Tuktoyaktuk Harbour and areas of the Tuktoyaktuk Peninsula, Liverpool Bay, Husky Lakes, and Cape Bathurst (Stewart et al. 1993). The Fingers Area of Liverpool Bay is known to be where herring congregate to spawn and where other fish species are abundant. Shields (1985) estimated a spawning biomass of 8.2 metric tonnes (mt) of herring based on a diver survey in 1985. Tidal currents in this area are known to be among the highest measured in the Beaufort Sea, exceeding 50 cm s^{-1} (Carmack and Macdonald 2008), and it is thought that the high degree of water mixing contributes to high productivity in the area. This area is known to of high ecological significance by Inuvialuit traditional knowledge (Fig. 8; Hartwig 2009, Paulic et al. 2009).

3.6. Food Webs

Fisheries Implications: *In the marine food web, relatively few forage fish species support a wide variety of predators, and the ice-adapted Arctic cod emerges above all other forage fish as a singular keystone species in all food webs. Major predators that depend directly or indirectly on Arctic cod are beluga whales, polar bears, ringed seals, Arctic charr, and sea birds. Food webs that support these top predators—many important for Inuvialuit subsistence—are sensitive to climate change and altered ice conditions that would affect Arctic cod. Removal of Arctic cod by commercial fishing would further weaken Arctic food webs that are already beginning to re-structure in response to climate warming.*

The estuarine food web, dominated by the Mackenzie River, is characterized by a wider diversity of forage fish—mostly anadromous—than the marine food web. In the estuarine food web, Arctic cisco plays a keystone role as prey for beluga whales—particularly juveniles—as does Arctic cod. The Inuvialuit subsistence fishery is more strongly linked to the estuarine food web than the marine food web, so the impacts of a fishery would be more strongly perceived if it targeted components of the estuarine food web. Energy for the estuarine food web comes from two sources, one from marine phytoplankton, and the other from terrestrial inputs (Dunton et al. 2006). Food webs based on these different energy sources are likely to respond to climate change in different ways because of the way that the marine and estuarine environments are controlled.

The ice-edge food web represents a zone of high food concentration, particularly in the major ice flaw-leads that form over the Mackenzie and Banks shelves. This food web is important for thousands of diving birds that migrate to the area in the early spring. It is also important for Arctic cod, seals, and polar bears that follow the ice margin as it recedes in summer. However, the presence of high concentrations of floating ice at the ice edge makes this habitat unsuitable for fisheries activities.

Benthic food webs in the Arctic are poorly understood (e.g., Iken et al. 2010). The basic biology of the benthic communities of the Beaufort Sea, such as life cycles, larval stages, development, growth rates, and food habits, is unknown for even the common taxa such as polychaetes, bivalves, amphipods, ophiuroids, and sea stars (Hopcroft et al. 2008). It is unknown what role the benthos plays in terms of energy flow, mineral cycling, and nutrient regeneration for overlying waters. However, the few studies on Arctic invertebrate population dynamics suggest low growth rates and high longevity (e.g., Bluhm et al. 1998). These characteristics are typical of species that are most vulnerable to trawling, dredging, and mineral extraction (Kostylev and Hannah 2007).

Food webs of the marine, ice-edge, and estuarine habitats are shown in Fig. 11, Fig. 12, and Fig. 13, respectively. These figures indicate the main predator–prey relationships documented in the literature. In each food web, species considered important to the integrity and sustainability of the food web are marked as keystone species (see Section 3.7 *Keystone Species*). Keystone species important for Inuvialuit subsistence are further indicated. Inuvialuit traditional knowledge and scientists associated with the Beaufort Sea Partnership have identified these species and their habitats (Hartwig 2009). Removal of keystone species from the ecosystem may be expected to cause a disproportional impact on food-web structure.

3.6.1. Marine Food Web

Marine food webs in the Arctic contain significantly fewer species than more southern continental shelves. The 66–70 fish species that use the continental shelves of the Canadian Beaufort Sea and Amundsen Gulf (Coad and Reist 2004) are considerably fewer than the >400 species of the Bering Sea, and the 140 species on the Scotian Shelf (Shackell and Frank 2003). The marine food web in the Beaufort Sea has four main trophic levels, not including polar bears: 1. phytoplankton, 2. copepods, 3. Arctic cod and other forage fish, and 4. main predators—beluga whale, Arctic charr, ringed seal, and sea birds. Hyperiid amphipods are an important extra trophic level between 2 and 3 because, although they prey on copepods, they are still small enough to be eaten by Arctic cod. Bowhead whales feed on copepods at trophic level 3. The average food-chain length is calculated as 3.97–4.34 trophic levels, not including polar bears (Hoekstra et al. 2002, 2003), close to the average of 3.97 for the 47 marine ecosystems examined by Vanderzanden and Fetzer (2007), and similar to the trophic structure found by Hobson and Welch (1992) in Barrow Strait. The marine food web is characterized by several keystone groups: herbivorous zooplankton, represented by copepods (Section 3.7.8); pelagic, hyperiid amphipods (Section 3.7.7); and Arctic cod (Section 3.7.1), Arctic charr (Section 3.7.6), ringed seal (Section 3.7.3), beluga whale (Section 3.7.5), and polar bear (Section 3.7.2). Benthic amphipods play an important role in the benthos, passing energy from phytoplankton detritus to demersal fish and to a number of sea birds, including eider ducks, during their staging for migration and when they moult. Bowhead whale (Section 3.7.4) are shown in Fig. 11 as important for Inuvialuit subsistence. Although this status has been so in the past, they are now harvested only infrequently as an expression of cultural heritage.

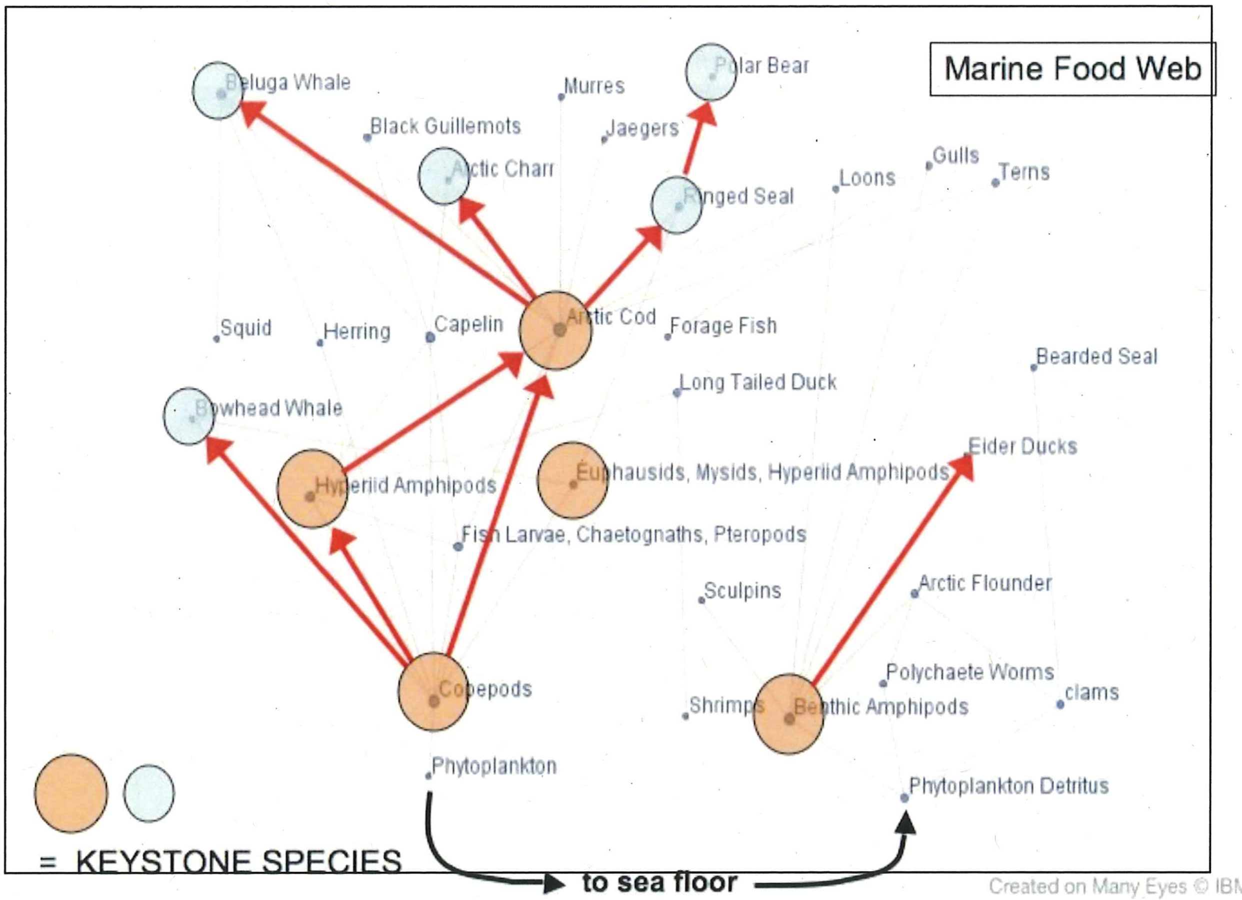

Figure 11. Food web of the marine habitat. Orange circles are keystone species important for food-web integrity. Blue circles are also keystone species that, in addition, are important for Inuvialuit subsistence. Predator–prey relationships are based on published reports. Red arrows indicate predominant energy pathways.

Three forage groups in Fig. 11 are important because they transfer energy from the phytoplankton to marine mammals. The body size of each group is roughly 10 times larger than the next smaller group, to span the complete size range from phytoplankton (~5–20 μm; Sakshaug 2004) up to seals and beluga whales (~1–2 m). Body sizes are:

• copepods	0.1–0.5 cm
• pelagic (hyperiid) amphipods (also mysids and euphausids)	1.0–3.0 cm
• Arctic cod, together with alternate forage species, Pacific herring and capelin	10.0–30.0 cm

Figure 11 shows that Arctic cod, the most ubiquitous and abundant of the forage fish, plays a central role in the marine food web throughout the Canadian Beaufort Sea. Removal of Arctic cod from this food web could impact the food supply of beluga whales, Arctic charr, ringed seals (by association, polar bears), and sea birds, including the gulls, of which two species are endangered or threatened.

3.6.2. Ice-Edge Food Webs

The ice-edge habitat (Section 3.4.2 *Ice-Edge Habitats, Polynyas, and Flaw-Leads*) is a productive interface between ice and sea that provides food for seals, fish, birds, and beluga whales. The ice-edge habitat is characterized by two food webs: 1. a sea-ice (sympagic) food web on the underside of sea ice, and 2. a marine food web in between melting ice and in open water off the ice edge.

The sea-ice food web is characterized by the production of ice-algae that inhabit the lower few centimetres of the ice, an ice-algae community of specialized grazers, and predators like pelagic amphipods (e.g., *Themisto libellula*) that provide food for forage fish like Arctic cod. Ice-algae live on the underside of sea ice in pockets and brine channels within the ice (Bluhm and Gradinger 2008). They bloom early in the spring (April and May) before the pelagic phytoplankton start to bloom (usually in June) (Horner and Schrader 1982). Organic matter produced within the sea ice serves as the base for the ice-associated food web shown in Fig. 12. Ice-algae, ice-associated zooplankton, and pelagic amphipods (see Section 3.7.7 *Mysids, Pelagic Amphipods, and Ice-Algae*) are all considered keystone groups because of their unique roles in producing and transferring energy from the under-ice habitat to the forage fish of marine and estuarine habitats.

Zooplankton associated with the ice include protozoans and metazoans, e.g., ciliates, rotifers, copepods, nematodes, and turbellarians (Bluhm and Gradinger 2008). Feeding on them at the underside of the ice are ice-associated amphipods that may reach abundances of 1–1000 individuals m^{-2} (Gradinger and Bluhm 2004). In the Beaufort Sea ecosystem, ice-associated amphipods are considered a keystone group (Table 4)—an important food source for Arctic cod and diving birds (Bradstreet and Cross 1982), linking the sea-ice food web to the pelagic marine habitat.

Arctic cod, feeding on ice-associated amphipods, link the sea-ice food web to marine mammals, in particular ringed seals and beluga. They ''concentrate mg-sized particles into energy packets large enough to be eaten efficiently by other fish, seals, whales and birds'' (Welch et al. 1992, p. 351). Arctic cod is the only fish species regularly associated with Arctic sea ice, occurring in small groups in protected seawater wedges within the offshore pack ice (Gradinger and Bluhm 2004).

Marine Food Web at the Ice-Edge: The ice-edge habitat also has an open-water, marine component that is characterized by local, but intense, productivity. In areas with first-year ice, the growth season begins with a plankton bloom that forms in a 20–50-km wide belt of open water off the ice edge (Sakshaug and Skjòldal 1989). As the ice melts, its fresh water lowers the salinity of an ocean surface layer that may be 10–50 m deep, and acts as a barrier to mixing from below. The upper layer, however, contains nitrate, mixed to the surface during the preceding winter. As the ice disappears, the combination of high light and nitrate triggers an intense phytoplankton bloom. The bloom is short-lived, however, because nitrate is used up within 2–3 weeks, and is not replenished because of the strong water stratification (Carmack and Wassmann 2006). Nevertheless, during the bloom, phytoplankton are grazed by herbivorous zooplankton that have over-wintered in deep water and move up to the food source. The zooplankton attract predators such as Arctic cod and herring if the ice edge lies over the marine habitat, and predators like Arctic cisco, least cisco, and rainbow smelt if it lies over the estuarine habitat. For seals and sea birds, the ice edge represents an area of high food concentration. In addition, the ice provides a resting platform for seals and a refuge for both seals and whales from marine predators such as killer whales. Carmack and Wassmann (2006) pointed out that the ice edge has a low to moderate level of productivity if integrated over area or time because the ice edge moves across the sea as it melts. High productivity is only local in time and place, and is transitory. It does concentrate animals that follow it, however, and so gives the appearance of a highly productive zone.

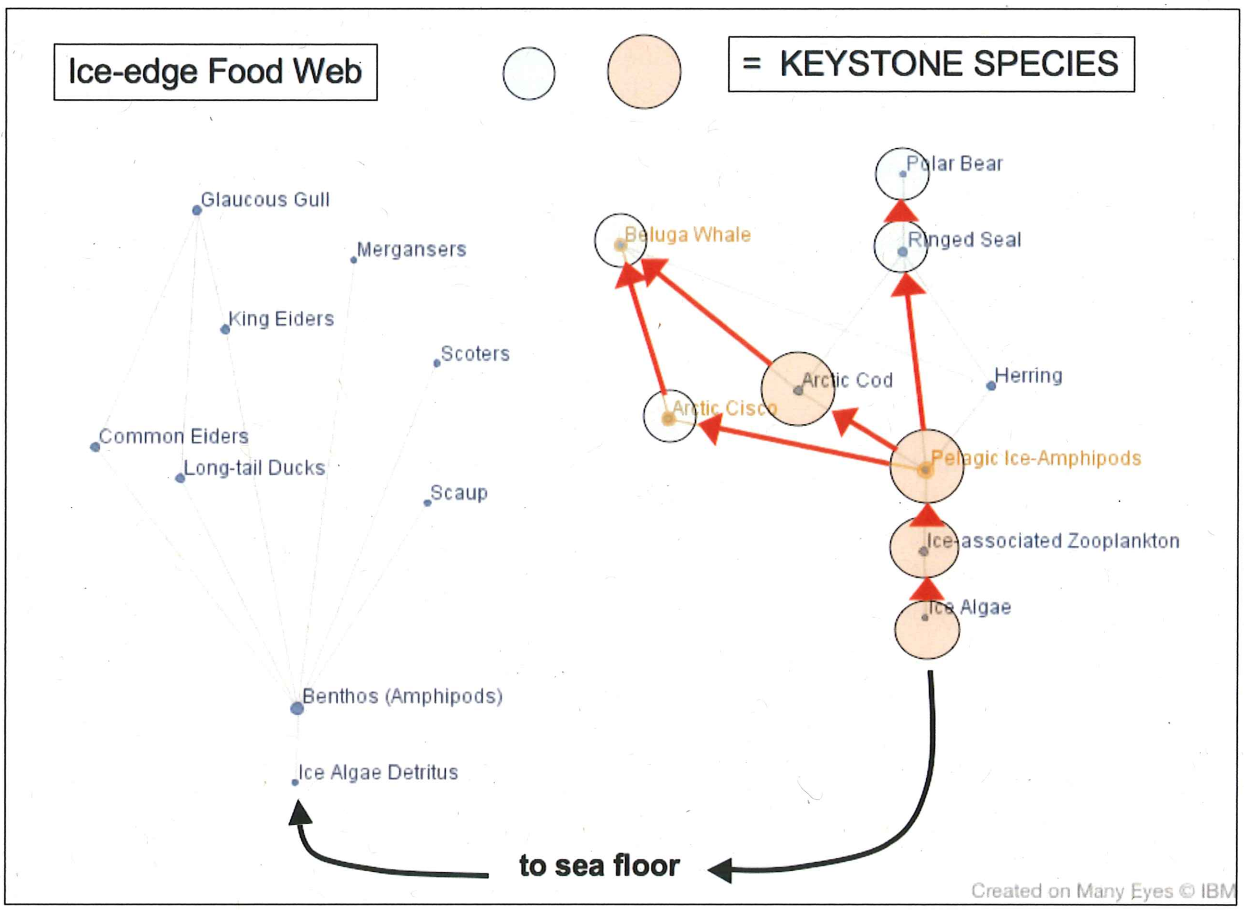

Figure 12. Food web of the ice-edge habitat. Orange circles are keystone species important for food-web integrity. Blue circles are also keystone species that, in addition, are important for Inuvialuit subsistence. Predator–prey relationships are based on published reports. Red arrows indicate predominant energy pathways.

3.6.3. Estuarine Food Web

The estuarine habitat created by the Mackenzie River extends over a considerable portion of the Mackenzie Shelf, so that the food webs of the marine and estuarine habitats overlap. Of the 66–70 different species of fish identified from the continental shelves of the Canadian Beaufort Sea and Amundsen Gulf (Coad and Reist 2004), >34 species use the River and its delta for rearing, overwintering, feeding, and migration (Percy et al. 1985). At the interface between the estuarine and marine habitats on the Mackenzie Shelf, there is intermingling of the ocean-based and river-based food webs. Here, mysids can be concentrated at ocean fronts where they are consumed by ringed seals and bowhead whales (Fig. 11; Harwood and Stirling 1992). Mysids are considered a keystone group and are consumed by a wide range of anadromous forage fish, including Arctic cod, Arctic cisco, least cisco, rainbow smelt, and saffron cod (Fig. 13). They are also a main food of Arctic charr/Dolly Varden, keystone species of primary importance to the Inuvialuit subsistence fishery.

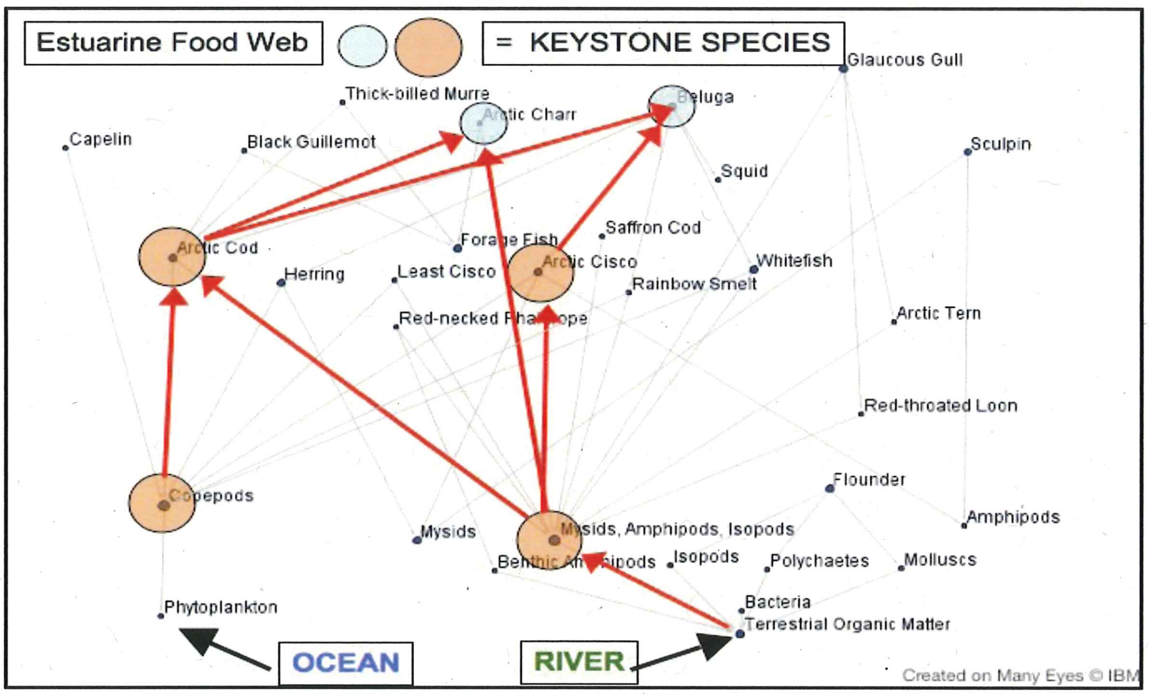

Figure 13. Food web of the estuarine coastal habitat. Orange circles are keystone species important for food-web integrity. Blue circles are also keystone species that, in addition, are important for Inuvialuit subsistence. Predator–prey relationships are based on published reports. Note that Arctic charr refers to both Arctic charr and Dolly Varden. Red arrows indicate predominant energy pathways.

The food web of the estuarine habitat is dominated by the Mackenzie River. Figure 13 illustrates the importance of keystone bottom-dwelling organisms such as epibenthic mysids, benthic amphipods, and isopods as key links between the terrestrial organic matter of the riverine ecosystem and the anadromous forage fish of the estuarine habitat. Loseto et al. (2009b) found that Saffron cod and least cisco are tightly coupled to the benthos in the estuarine habitat, and have food habits like those of bottom-feeding fish. Arctic cisco and rainbow smelt, in contrast, feed equally on pelagic and benthic prey. Arctic cod feed largely on pelagic copepods from the marine habitat. Loseto et al. (2009a) found that beluga whales feed on both food webs: older belugas feed on Arctic cod in the marine habitat, and juvenile belugas feed on a mixture of Arctic cod and other forage fish, mainly Arctic cisco, in the inshore, estuarine habitat. Arctic cisco and Arctic cod are keystone species among the wide array of forage fish in the estuarine food web because of their strong linkage to Arctic charr and beluga. Herring and whitefish, although not considered keystone species, are important components of the Inuvialuit subsistence fishery.

The Mackenzie and other coastal rivers deliver significant amounts of terrestrial organic carbon to the Arctic, estuarine, nearshore environment of the Beaufort Sea. Coastal erosion supplies an additional, but unknown, amount. Parsons et al. (1989) and Dunton et al. (2006) showed that terrestrial carbon is incorporated into estuarine food webs of the Mackenzie and Alaskan Beaufort Sea shelves. O'Brien et al. (2005) showed that terrestrial material is deposited on the Mackenzie Shelf by three mechanisms:

- transport by the Mackenzie River plume to the Shelf edge during freshet,
- resuspension of sediment during northwesterly gales, and
- erosion of steep coastlines during storm events.

The Mackenzie River carries ~1.5 million tonnes of carbon per year into the Beaufort Sea annually (Stein and Macdonald 2004). About half is particulate and half is dissolved. The material, derived from the land and from Mackenzie Delta lakes, is not easily broken down by microbial activity, so ~60% of the particulate material is preserved in the benthic sediments of the Beaufort Shelf. Nevertheless, high bacterial activity at nearshore sites indicates that terrestrial dissolved organic carbon is being broken down, and its chemical signature can be detected in the flesh of organisms in the estuarine food web (Cobb et al. 2008, Loseto et al. 2009b). (See also Section 3.8.2 *New Production* for a discussion of carbon and nitrogen inputs to the Beaufort Sea, and Section 3.4.4 *Dominance of Mackenzie River* for a discussion of sediment inputs.)

3.7. Keystone Species

Fisheries Implications: *Keystone species should be monitored in the context of climate change because they are thought to exert controlling influence on food webs. Arctic cod is central to food webs, yet there is very little knowledge about its population size, reproductive strategies, and migrations within the Canadian Beaufort Sea. Its sizeable aggregations make it vulnerable to industrial fishing. Polar bears and ringed seals are highly ice-dependent species, sensitive to climate change. Their food web depends on Arctic cod as prey. Bowhead whales feed in areas of oceanographic fronts where mysids and copepods are concentrated. These areas would also attract potential commercial fishers. Beluga whales and Arctic charr, of primary importance to Inuvialuit subsistence, are highly dependent on Arctic cod as prey throughout the study area.*

Keystone species are those species that play a critical role in maintaining the structure of their food web, to a degree disproportionate to their biomass (Table 4; DFO 2004b, 2006). The criteria identifying keystone species are:

- **Highly Influential Predator:** species that exert a strong effect on populations of their prey, e.g., polar bears, ringed seals, beluga whales, bowhead whales, and Arctic charr/Dolly Varden.

- **Forage Species:** species that are small and particularly abundant and, therefore, are important forage food for larger predators, e.g., Arctic cod, Arctic cisco, mysids, pelagic amphipods, and copepods.
- **Ecosystem Migration:** species that migrate seasonally between the Bering and the Beaufort seas, transferring energy, and potentially acting as disease vectors across ecosystem boundaries, e.g., bowhead whales and beluga whales.
- **Habitat Migration:** species that transfer energy from the marine and estuarine coastal habitats where they feed to the freshwater habitat where they spawn, e.g., Arctic charr (including Dolly Varden) and Arctic cisco.
- **Structural Communities:** species that are important because of the structure they provide for other species, like the ice-algae community that develops on the underside of sea ice.

Table 4 lists the keystone species identified in the Canadian Beaufort Sea, and Sections 3.7.1 to 3.7.8 briefly discuss the ecology of each group.

Table 4. Keystone species or communities in the Canadian Beaufort Sea (adapted from Cobb et al. 2008) listed in order of decreasing sensitivity to climate change and industrial development on the Beaufort shelves.

Species/Community	Scientific Name	Ecosystem Role
Arctic cod	*Boreogadus saida*	Key forage species
Polar bear	*Ursus maritimus*	Influential predator Tightly coupled to prey
Ringed seal	*Phoca hispida*	Influential predator Tightly coupled to prey/predator
Bowhead whale	*Balaena mysticetus*	Influential predator Nutrient transport across ecosystems
Beluga whale	*Delphinapterus leucas*	Influential predator Nutrient transport across ecosystems
Arctic charr	*Salvelinus alpinus*	Influential predator Nutrient export across habitats
Dolly Varden	*Salvelinus alpinus*	Influential predator Nutrient export across habitats
Arctic cisco	*Coregonus autumnalis*	Key forage species Nutrient export across habitats
Mysids	Mysidae	Key forage species
Pelagic amphipods	Hyperiidae	Key forage species
Ice-algae community		Primary producers Structural community
Herbivorous zooplankton community	Copepods	Key grazer species and key forage species

3.7.1. Arctic Cod

Arctic cod is a central keystone species in the Arctic marine ecosystem because of its abundance, widespread distribution, and importance in the diets of marine birds and other fish. Its small size (<25 cm) makes it a key forage species for a wide variety of predators (Hop et al. 1997). It is the main energy link between organisms of the ice-edge habitat and ringed seals and beluga whales (Bradstreet and Cross 1982). For example, in Admundsen Gulf, Arctic cod constitutes ~40% of the diet of ringed seals (Smith 1987). On the Mackenzie Shelf, it is the primary diet of adult belugas, and it is prominent in the diet of juvenile belugas feeding inshore (Loseto et al. 2009a). On the Alaskan Shelf, Arctic cod constitute >70% of the diet of beluga and ringed seals in late autumn and winter (Frost and Lowry 1984), and it was estimated that ~29,000 tonnes are consumed annually there by ringed seals, beluga whales, and marine birds (Frost and Lowry 1984). On the Canadian Beaufort shelves, adult Arctic cod constitute 52% of the diet of marine mammals and birds (Bradstreet et al. 1986) and influence the movements of these species (Craig et al. 1982).

The larvae of Arctic cod are the most widespread and commonest of larval fish species on the Beaufort Sea shelves, from the Chuckchi Sea to Amundsen Gulf, indicating Arctic cod's ecological significance to Beaufort Shelf ecosystems (Walkusz et al. 2008). Ichthyoplankton surveys in the Canadian Beaufort Sea conducted from 1984–1988 indicated that Arctic cod larvae constituted >90% of total catches in Amundsen Gulf and the southeastern Beaufort Sea, and 73% of those in Mackenzie Bay (Chiperzak et al. 1990, 2003a,b,c). This predominance of Arctic cod larvae in the icthyoplankton is consistent with the findings of earlier surveys (Hunter 1979, Ratynski 1983). The widespread distribution and high catches of Arctic cod demonstrate its importance in the food web because few other food sources of similar size or energy seem to exist in the Canadian Beaufort Sea ecosystem (Craig et al. 1982, Sekerak 1982, Craig 1984, Bradstreet et al. 1986).

Although Arctic cod is widely distributed at low densities throughout marine waters of the Canadian Beaufort Sea (Stewart et al. 1993), it can also be highly aggregated at certain times and places, making stock assessment difficult. Large schools of adults have been measured using hydro-acoustic methods, both in Lancaster Sound and along the Beaufort shelves as shown in Table 5. Schools in surface waters in bays along Lancaster Sound covered from 2–13 ha (Welch et al. 1993), and appeared to be forming in response to intense predation from beluga whales, ringed seals, and sea birds (Crawford and Jorgenson 1993). Schools at depth, however, seemed to be associated with water warmer than –1.4°C, in the Pacific Halocline, both along the Alaskan Shelf-slope in summer (Logerwell et al. 2010) and in Amundsen Gulf in winter (Benoit et al. 2008). It is not clear whether Arctic cod residing in these deep waters are feeding, seeking a temperature optimum, or avoiding predation from beluga whales and ringed seals. Along the Alaskan Shelf-break, between 100–300 m, Arctic cod concentrations coincided with foraging patterns by beluga whales (Logerwell et al. 2010). In Amundsen Gulf, larger cod remained below 180 m at all times, avoiding seal predation, whereas smaller cod in poorer condition migrated into copepod swarms to feed in the 90–150-m layer at night to avoid visual predation by shallow-diving immature seals (Benoit et al. 2010).

Table 5. Arctic cod density in schools observed on the Beaufort shelves and in Lancaster Sound.

Location	School Density (fish ha^{-1} x 10^3)	Depth (m)	Author
Franklin Bay, Amundsen Gulf	72–19,610	225	Benoit et al. (2008)
Alaskan Shelf	155	100–300	Logerwell et al. (2010)
Prudhoe Bay	0–22,691	<10	Moulton and Tarbox (1987)
Resolute, Lancaster Sound	6–159	Surface waters	Crawford and Jorgenson (1993)
Allen Bay, Lancaster Sound	20–83,250	Surface waters	Crawford and Jorgenson (1996)

A tentative hypothesis that emerges from the work on the Alaskan Shelf and Franklin Bay is that adult fish may congregate in the lower part of the Pacific Halocline (Fig. 5) in the autumn where temperatures are slightly warmer, and zooplankton from the Bering and Chukchi shelves are entrained. Adult fish may move slowly eastward with the Beaufort Undercurrent at a speed of 4 cm s^{-1} for seven months, accumulating in parts of Amundsen Gulf so that they can take advantage of early open water in the Bathurst polynya in the spring. After dispersal to surface waters, they may be returned to the western part of the Beaufort Sea by the Beaufort Gyre. This hypothesis needs to be tested.

The only quantitative estimate of the size of the pelagic Arctic cod population in the Beaufort Sea is from a 6280-ha sampling site on the Alaskan Shelf just to the east of the Barrow Trough (Logerwell et al. 2010). This site, which included the Shelf from 40 m and the Shelf-slope down to 500 m, was systematically sampled with hydro-acoustic gear and mid-water trawls. The estimates from the bottom trawls, for yearling and older Arctic cod, were 1.92 mt km^{-2} in the 40–100-m depth range, and 5.37 mt km^{-2} in the 100–500-m depth range.

The ecology of this important species is poorly understood. For example, Deibel at al. (2008) found that Arctic cod had the same body burden of mercury as near-bottom invertebrates and fish (*Anonyx* amphipods, shrimp, and flounder). This finding, along with lower mercury concentrations in cod than in estuarine fish such as Arctic cisco and Pacific herring, suggests that Arctic cod feed to a large extent near the sea floor where they may be exposed to high mercury levels in epibenthic prey (Byers et al. 2010). This observation needs to be confirmed. Similarly, the relation of the timing of spawning and egg hatching to overwinter survival is not clear (Deibel et al. 2008). The key question of whether Arctic cod numbers are more than required to satisfy the food requirements of all known predators (Welch et al. 1992) cannot be answered at this time. Benoit et al. (2008) estimated that Arctic cod biomass (30 mt) was sufficiently high to satisfy local predators if sampled densities were extrapolated to the whole of Franklin Bay. However, data are lacking to justify such extrapolation, and the cod concentration phenomenon observed in Franklin Bay has not been generalized by repeated observations. Further study is clearly warranted.

Arctic cod can be highly vulnerable to commercial fishing when they school in dense aggregations. For example, in shallow bays of Lancaster Sound, Crawford and Jorgensen (1996) measured schools that ranged from 2800–23,000 mt. These schools were observed in summer, and Welch et al. (1993) commented on their vulnerability to predators, estimating predation rates on the order of 20 tonnes (half a million fish) daily. However, dense aggregations have not been documented in shallow bays in the Beaufort Sea, possibly because higher turbidity on the Mackenzie Shelf makes dense schooling unnecessary for predator avoidance. Schools of year-plus Arctic cod found on the Alaskan Shelf were associated with salinity fronts between the estuarine and marine water masses (Moulton and Tarbox 1987). It is likely that commercial fishing for this species on the Beaufort shelves would target schools that frequent the frontal systems that eddy across the continental shelf, hotspots such as Cape Bathurst, or the shelf-slope within the Pacific Halocline from 100–300 m. These aggregations make it difficult to estimate overall biomass from catch rates because densely aggregated forage species are able to support high catch rates even when their abundance is declining (DFO 2010).

3.7.2. Polar Bear

Polar bears exert a strong effect on the food web through predation on ringed seals, themselves a major predator on several other keystone groups such as Arctic cod, mysids, euphausids, and ice-associated amphipods (Lowry et al. 1980). The strong predator–prey relationship of bears and seals means that the population health and abundance of these two species are closely linked (Stirling 2002). These two species are also highly ice-dependent and sensitive to the changing ice dynamics in the Arctic. Polar bear predation on ringed seals in Admundsen Gulf during the winter months takes place in offshore areas of active or moving pack ice and along the edges of fast ice or floes (Stirling and McEwan 1975, Stirling and Archibald 1977). Eighty percent of seals eaten are subadults with a large proportion of them being less then two years old (Stirling and McEwan 1975). Young seals are easier to capture and yield a higher energy density than older seals. Bearded seals are a secondary prey for polar bears on the Alaskan Shelf (Bentzen et al. 2007), linking polar bears, through bearded seals, to the benthic community.

3.7.3. Ringed Seal

Ringed seals are an ice-adapted species, depending on pack-ice habitat for pupping, foraging, moulting, and resting. They require stable ice with snow cover in which to construct lairs in which they give birth and raise their young (Smith and Stirling 1975). They are a keystone species because they are a top predator, feeding predominantly on Arctic cod in the winter and mysids during the summer. In the ice-edge habitat, they feed primarily on pelagic amphipods and Arctic cod. They are the key prey of polar bears and are important for Inuvialuit subsistence.

In the late summer, ringed seals have been observed in loose feeding aggregations at two locations considered hotspots in the Canadian Beaufort Sea. These hotspots are in waters deeper than 100 m near the shelf-break off the Tuktoyaktuk Peninsula (north of Cape Dalhousie), and north of the Yukon coast near the Mackenzie Trough (Fig. 9; Harwood and Stirling 1992). The locations were not used every year, but they were consistent over several years. Aggregations persisted for several weeks and, in some years, sea birds and bowhead whales were observed feeding in the same locations. The ringed seals in both locations were filled with mysids. Crustaceans, especially mysids, amphipods, and euphausiids, and Arctic cod were the dominant prey species in seals collected in Amundsen Gulf and near Herschel Island (Smith 1987). Other summer feeding aggregations near Holman, in Amundsen Gulf, fed wholly on Arctic cod. The pattern that emerges is that Arctic cod were the most important prey in all ringed seal age classes during the winter months, whereas in summer, pups and adults fed heavily on invertebrates, largely mysids, while adolescent seals preferred Arctic cod.

3.7.4. Bowhead Whale

Bowhead whales are highly dependent on dense aggregations of crustaceans such as copepods, mysids, euphausids, and hyperiid amphipods (Lowry et al. 2004), all of which have especially high lipid content and are, therefore, rich in energy (Bluhm and Gradinger 2008). They have also been seen to feed on epibenthic organisms at the sea bottom. In the southeastern Beaufort Sea, plankton in close proximity to feeding bowhead whales consisted of copepods predominantly (76–92%) along with gammarid and hyperiid amphipods, euphausiids, and isopods (Bradstreet et al. 1987). Bowheads feed in the frontal zones between estuarine and marine water masses on the Canadian Beaufort shelves (Harwood and Smith 2002). These frontal zones occur most frequently near the Mackenzie Shelf-break north of Cape Dalhousie and Herschel Island, and at Cape Bathurst (Fig. 9).

Bowheads move from the Bering Sea into the Canadian Beaufort Sea following ice flaw-leads in the spring. They move onto summer feeding grounds in the western half of Amundsen Gulf in deep water (200 m) under the Bathurst polynya (Fraker 1979, Fraker and Bockstoce 1980). In August, they move west into shallower waters on the Mackenzie Shelf to the east and west of the Mackenzie River Delta (COSEWIC 2009). Some adults frequent the ice edge in the offshore ice pack. Bowheads feeding on the Shelf, the ice edge, or the Shelf-slope may come into conflict with potential commercial fishing because these areas, where frontal currents concentrate zooplankton, are likely to attract both Arctic cod and fishermen.

Bowheads, like belugas, transport energy and nitrogen from the Beaufort Sea to the Bering Sea where they overwinter. The significance of this transfer is not known, although it could be important to a marine ecosystem in which nitrogen is limiting to primary production.

Bowhead whales feed primarily on copepods, but also mysids, euphausids, and pelagic amphipods. These groups can be concentrated by oceanic fronts at the estuarine–marine interface on the continental shelf, in the vicinity of troughs and other hotspots like Cape Bathurst and north of Herschel Island, as well as at the shelf-edge. Commercial fishing in these frontal zones could interfere with bowhead whale feeding, as these whales are known to avoid ship noise. Information concerning the locations of bowhead feeding can be found in Harwood and Ford (1983), Richardson (1985), Thomson et al. (1986), and Harwood and Smith (2002).

Bowhead whales in the southeastern Beaufort Sea are important to the Inuvialuit, who have a bowhead whaling tradition that dates back almost 3000 years (Raddi and Weeks-Doubleday 1985). Prior to commercial whaling, bowhead was harvested particularly at Cape Bathurst, the mouth of the Anderson River, at Atkinson Point, at Herschel Island, and along the Yukon coast (Reeves and Mitchell 1985). In recent years, the Inuvialuit harvested two bowhead whales in the Canadian Beaufort Sea for subsistence and cultural reasons.

3.7.5. Beluga Whale

Beluga whales are a keystone species in all major habitats of the Beaufort Sea. With a population size estimated at ~19,000 (Harwood et al. 1996) to ~39,000 (NOAA 1997), they are considered to exert a controlling influence on all food webs. Arctic cod is the main prey for adult whales feeding in the marine and ice-edge habitats, and Arctic cisco is the main prey for juveniles feeding in the inshore habitat (Loseto et al. 2009a, b). Adults may also prey on alternate forage fish like Arctic cisco, Pacific herring, least cisco, and rainbow smelt in the estuarine habitat.

Beluga whales move from the Bering Sea into the Beaufort Sea in the spring along ice flaw-leads far offshore, arriving off the west coast of Banks Island in late spring, coinciding with ice break-up. They then move to the southwest, following the seaward edge of the landfast ice along the Tuktoyaktuk Peninsula. They arrive in the estuary of the Mackenzie River around July (Fraker 1979). These inshore areas are important for calving and for rubbing of the skin on shallow gravel beds. At this time, some beluga whales are distributed widely throughout the offshore, and a number leave the estuary in July to travel to Amundsen Gulf. They dive to depths of 600 m along McLure Strait to the north of Banks Island, but it is not known what they feed on at those depths. Beluga feeding is not likely to conflict with potential commercial fishing because the whales appear to be widely dispersed while offshore, and they are in water too shallow for commercial fishing (<20 m) while in the estuarine environment. In addition, most important locations of their estuarine habitat are protected by the Tarium Niryutait MPA, established in 2010 (BSP 2010).

Belugas transport nutrients from the Beaufort Sea to the Bering Sea where they overwinter. The significance of this transfer is unknown, although it could be important to a marine ecosystem in which nitrogen is limiting to primary production.

Belugas are extremely important in the diet and culture of the Inuvialuit. Four Inuvialuit communities harvest ~100 per year (Section 3.1 *Inuvialuit Fishing and Hunting*).

3.7.6. Arctic Charr/Dolly Varden and Arctic Cisco

Arctic charr and Dolly Varden are major predators and Arctic cisco is an important forage species. They occupy the nearshore estuarine and marine habitats, and are ecologically significant species because they export much of their biomass from the marine into the freshwater habitat. Stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) showed that Arctic charr fed heavily in the marine habitat of the Beaufort Sea where the most common prey species was Arctic cod (Hoekstra et al. 2003).

Arctic cisco is one of the most abundant and widely distributed coregonids found in coastal waters of the Mackenzie Shelf westward of the Mackenzie River during summer (Craig 1984). As one- and two-year-old fish between 10 and 15 cm in length, they are important forage fish in the estuarine habitat. Feeding in the nearshore for up to seven years while over-wintering in the Colville River system, they transfer significant energy to the freshwater habitat of the Mackenzie River when they spawn (Fechhelm et al. 2007).

Arctic cisco and Arctic cod are keystone forage fish species in the estuarine habitat. Arctic cisco were commonly the main food item in belugas feeding inshore on the Mackenzie Shelf (Harwood et al. 1996, Harwood and Smith 2002) while Arctic cod (age 1) were the predominant fish species (98%) at the interface between the estuarine and marine water masses in shallow, open-water, nearshore areas at Prudhoe Bay (Moulton and Tarbox 1987). Arctic cod were associated with high concentrations of mysids and copepods in the frontal zone. Loseto et al. (2009a) showed that small belugas contain fatty acid markers that suggest they feed on inshore, estuarine forage fish, likely Arctic cisco.

3.7.7. Mysids, Pelagic Amphipods, and Ice-Algae

Mysids are important pelagic crustaceans because they aggregate in dense schools on the outer shelf at the interface between water masses, and are forage prey for a wide number of fish species, seals, and bowhead whales. Mysids and calanoid copepods are a preferred food for Arctic cod in the Beaufort Sea (Lowry and Frost 1981, Lacho 1986). Parsons et al. (1989) found that they were characteristic of the inshore, estuarine habitat, whereas in the offshore, marine habitat, pelagic hyperiid amphipods associated with ice edges were a key forage species for a wide variety of fish and for ringed seals (Lowry et al. 1980).

Pelagic amphipods are large (~20 mm) carnivorous amphipods that are important in Arctic ecosystems, where they play a pivotal role in the marine food web, comparable to euphausids in more temperate seas (Percy 1993). They form a trophic link between smaller zooplankton and many species of marine and anadromous fish (Bradstreet and Cross 1982), sea birds (Bradstreet 1982), and marine mammals, (Lowry and Frost 1984). They are an important food for adult Arctic cod.

Ice-algae are considered a keystone group because they are a unique community that begins to grow on the underside of ice a couple of months earlier than phytoplankton blooms (Apollonio 1965, Michel et al. 1996), providing energy to sympagic meiofauna, under-ice amphipods, and pelagic copepods (Lizotte 2001, Michel et al. 2002). Ice-algae store a large proportion of their production as energy-rich fat molecules (Lee et al. 2008), and they grow in long filaments and sheets that slough off and sink as ice melts, thereby diverting energy from the sea surface to benthic organisms that reside on the sea floor (O'Brien et al. 2005). The sympagic meiofauna consists of turbellarians, crustaceans, nematodes, and rotifers (Gradinger et al. 2005). The abundance of this ice-algae meiofauna is high in the nearshore fast ice (up to 350,000 animals m^{-2}), but decreases by about three orders of magnitude in ice over the Canada Basin (Gradinger et al. 2005). The macrofauna associated with ice-algae consists mostly of amphipods in abundances of 1–1000 m^{-2} in coastal areas (Carey 1985), dropping to 1–40 individuals m^{-2} in offshore pack ice (Gradinger and Bluhm 2004).

Primary production of the ice-algae community is significant and is estimated to contribute >25% of total Arctic primary productivity (Gosselin et al. 1997, Legendre et al. 1992). Regionally, ice-algae contribute 4–26% to total annual primary production in seasonally ice-covered waters and >50% in the permanently ice-covered central Arctic (Gosselin et al. 1997, Sakshaug 2004). Seasonally, the ice-algae community contributes 70–75% of total primary production (including ice-algae and phytoplankton production) during the spring as the ice melts

(Lee et al. 2008, Horner and Schrader 1982). However, they contribute <15% of total primary production over the whole year (Horner and Schrader 1982).

3.7.8. Copepods

The herbivorous zooplankton community is a mixture of herbivorous mysids, copepods, rotifers, ciliates, and heterotrophic dinoflagellates. It transfers energy from the primary producers (phytoplankton) to fish larvae and juveniles and many of the larger carnivorous zooplankters. During algal-bloom conditions, copepods, the most abundant herbivorous zooplankton by mass, in the size range of ~0.5–6.5 mm, transfer energy from phytoplankton in the general range of 0.02–0.20 mm to fish and invertebrate predators in the range of 10 mm and up. Herbivorous zooplankton consume phytoplankton in the upper water layers, thereby directing energy into the pelagic zone and away from benthic organisms on the sea floor. The largely herbivorous zooplankter *Limnocalanus macrurus* is a dominant forage link between phytoplankton and higher trophic levels. It is a very versatile and opportunistic copepod because of its tolerance to a wide salinity range, its ability in the adult stage to store high levels of energy as wax esters (allows it to survive when food is scarce), and its ability to be carnivorous when phytoplankton are scarce (Hirche et al. 2003). In the Canadian Beaufort Sea, this copepod made up 99% of the stomach contents of a bowhead whale hunted near Shingle Point in 1996 (Pomerleau et al. 2011).

There are three distinct zooplankton assemblages in the Canadian Beaufort Sea (Deibel et al. 2008): 1. a coastal community dominated by the small copepod *Pseudocalanus*, a herbivore and the most common prey of young-of-the-year Arctic cod, 2. a shelf-break community dominated by the copepods *Cyclopina* sp. and *Microcalanus* sp., and 3. an Amundsen Gulf–Cape Bathurst community dominated by *Oithona* sp., *Oncaea* sp., and the large copepods *Metridia longa* and *Calanus hyperboreus*. Zooplankton from Cape Bathurst fed on a high proportion of river-based material, whereas zooplankton from Amundsen Gulf did not. These findings suggest that there are three different types of food webs operating on the Canadian shelves, with differing proportions of food coming from the Mackenzie River and from the sea.

3.8. Primary Production

Fisheries Implications: *The rate of primary production on the Canadian Beaufort shelves is low, constrained by the rate of supply of nitrogen to the surface water. Ice cover and a strong salinity gradient prevent the wind from mixing deeper, richer water layers upwards. This scenario could change dramatically if summer ice cover retreats beyond the break in the continental shelf. Under these conditions, the wind could mix the nutrient-rich waters of the Beaufort Undercurrent onto the continental shelves, leading to increased primary production, possibly doubling it. The Mackenzie River does not contribute a significant amount of inorganic nitrogen to the shelves. However, it does contribute a large amount of organic carbon, and a substantial amount of organic nitrogen that finds its way into the marine food web. This contribution has not been quantified.*

3.8.1. Total Production

Overall, the rate of primary production of phytoplankton on the Mackenzie Shelf and in Amundsen Gulf is characteristic of low-productivity (oligotrophic) waters. Sakshaug (2004) compared the productivity of the Beaufort Sea with that of other interior shelves and locations in the Arctic Ocean. The productivity of the Beaufort Sea is 30–70 g C m^{-2} y^{-1}, which is similar to the three other interior shelves on the Eurasian side of the Arctic Ocean (Tremblay and Gagnon 2009), and lower than that of the two inflow shelves. In general, interior shelves like the Beaufort support primary productivity levels that are from 20–70 g C m^{-2} y^{-1}, roughly five to 10 times less than levels of inflow shelves like the Chuckchi Sea and parts of the Barents Sea (Carmack and Wassmann 2006). The latter are considerably enriched by the inflow of high-productivity water from the Pacific Ocean and the North Atlantic Ocean, respectively. The only other known areas of high productivity in the Arctic Ocean are those enriched through vigorous tidal mixing, e.g., Barrow Strait (Prinsenberg and Bennett 1989) or upwelling, e.g., the Northwater polynya. Productivity reaches 150–200 g C m^{-2} y^{-1} in these areas.

Productivity in the Beaufort Sea is limited by light during the Arctic winter, and then by nutrients, primarily nitrate, in the summer. The nitrate is used to produce protein within the marine food web. These limitations become clearer with an explanation of the seasonal sequence of events on the Mackenzie Shelf. In the autumn, the concentration of nitrate in surface waters generally increases as storms, particularly easterly winds, blow surface water offshore. The estuarine circulation causes surface waters to be replaced with nitrate-laden water from deeper offshore. During the winter, as heavy brine is extruded from the thickening ice, sinks to the sea floor, and crosses the Shelf to deeper water, it causes further mixing that brings deep, nitrate-rich water into the upper layers. The nitrate remains unused all winter because the light is too low for photosynthesis. However, once the light penetrates the melting ice, the phytoplankton blooms as it uses up the nitrate, and primary productivity is high. The bloom follows the retreating ice edge as it melts, and can form a moving band of high productivity up to 50 km wide. However, once phytoplankton has exhausted the nitrate, the rate of productivity falls and, except for infrequent upwelling events, it is then limited by the rate at which nitrate can be recycled within the euphotic zone (Lavoie et al. 2009, Brugel et al. 2009, Carmack et al. 2004). Secondary consumers, including Arctic cod, contribute to this recycling, so that removing them by fishing not only slows down the rate of recycling, but also removes nitrate from the marine nutrient cycle.

For primary productivity in surface waters to increase substantially, further inputs of nitrate must come from deeper water. However, deeper water is essentially isolated from the euphotic zone by the halocline. Fresh water remaining from the melted ice, together with Mackenzie River water, mix into surface waters forming a buoyant, low-salinity cap that prevents nutrient-rich water mixing upwards from denser water below (Carmack and Macdonald 2002). Water layers in the marine habitat are described in Section 3.4.1 *Marine Habitat.*

3.8.2. New Production

Primary production resulting from new nitrate entering the euphotic zone is called "new" production, as opposed to "total" primary production, which includes production resulting from nitrate being recycled in the upper water layer. Total production includes both types of production. The rate of new productivity governs the rate of fishery removals. Dugdale (1976) showed that the amount of nitrate removed with biomass as yield from a marine system cannot exceed the amount of new nitrate transported into the euphotic zone, if the system is to remain at steady state. If nitrate is not continually injected into the marine ecosystem, productivity will eventually run down, as the nitrate it contains is sedimented to the sea floor and eventually buried.

Primary productivity based on new nitrogen is very low in the Beaufort Sea, on the order of 17–23 g C $m^{-2} y^{-1}$ (Sakshaug 2004), 16–23 g C $m^{-2} y^{-1}$ (Macdonald et al. 1987), and 5–8 g C $m^{-2} y^{-1}$ (Carmack et al. 2004). Brugel et al. (2009) measured new productivity in Franklin Bay, Amundsen Gulf as only 18 g C $m^{-2} y^{-1}$, but suggested that existing estimates of new productivity on the Beaufort shelves should be increased by 15% to account for productivity occurring from mid-September to the end of October, which is usually missed. That correction would put estimates of new productivity for the Canadian Beaufort shelves in the range of 17–29 g C $m^{-2} y^{-1}$. The Beaufort Sea is considered to be an ecosystem whose primary productivity is starved by the availability of nitrogen (Tremblay and Gagnon 2009), and where it is recognized that the external supply of nitrogen to the euphotic zone sets the upper yield of organic matter production (Tremblay et al. 2006).

The low productivity of the Canadian Beaufort Sea seems to be reflected in the lower number and diversity of sea birds, marine mammals, and benthic biomass on the Mackenzie shelves relative to more productive Arctic marine ecosystems like Lancaster Sound and the Chuckchi Sea (see Section 3.9.4 *Indicators of Productivity)*. It must also be remembered that the Beaufort shelves are an ecosystem in which there is probably a substantial seasonal removal of nitrogen by migratory birds, bowhead whales, and beluga whales, further constraining its productive capacity. No information could be found to assess this loss.

The Mackenzie River does not supply significant inorganic nutrients to the marine habitat because critical nutrients like phosphate and nitrate are taken up by phytoplankton even before the freshwater plume advances to the sea. Nitrate is exhausted first, ensuring that it remains the limiting nutrient on the Canadian Beaufort shelves (Macdonald et al. 1987, Simpson et al. 2008).

On the Mackenzie Shelf of the Beaufort Sea, terrestrial carbon material brought to the Sea by the Mackenzie River and by coastal erosion is detectable in benthic organisms. The low rate of primary production and a rich terrestrial carbon supply results in the terrestrial carbon being incorporated into food webs to a greater extent than occurs in more productive regions (Carmack and Wassmann 2006, Parsons et al. 1989). Terrestrial carbon has been detected by stable isotope methods and shown by fatty acid analysis to extend to the Mackenzie Shelf-break near the Cape Bathurst area (Deibel et al. 2008), but its contribution to primary productivity has not been quantified.

3.9. Secondary Production

***Fisheries Implications**: The Mackenzie Shelf exhibits lower productivity than the Alaska Beaufort Shelf or the Chukchi Shelf, as indicated by benthic biomass. Causative factors are its distance from the productive waters of the Bering Sea, and the suppressive influence of the Mackenzie River. Benthic biomass appears to increase on the Mackenzie Shelf east of the Mackenzie Delta, but data are lacking for Amundsen Gulf.*

Fisheries yield estimates for the Canadian shelves are also low. Although direct information is lacking for fisheries yield in the Canadian Beaufort Sea, a comparison with other marine *systems based on primary productivity predicts a maximum fisheries yield of between 0.2–0.6 mt km^{-2} y^{-1}. A fisheries survey on the nearby Alaskan Shelf estimated that a sustainable yield of Arctic cod (which made up 81% of the fish catch) would be 0.25 mt km^{-2} y^{-1}, similar to theoretical yield estimates on the Canadian Shelf.*

The low productive potential of the Canadian Beaufort Shelf is further substantiated by its lower diversity of marine mammals, a lower density of sea birds, and by lower indices of reproduction in ringed seals and polar bears, compared to other parts of the Arctic.

3.9.1. Benthic Biomass

"Benthic fauna indicate interannually persistent sites of carbon deposition versus food-limited regions" (Grebmeier et al. 2006a, p. 332) and, therefore, are a good indicator of productivity. In contrast to the adjacent Bering and Chukchi seas, the Beaufort Sea is characterized by relatively low benthic faunal biomass and low productivity (Fig. 14; Dunton et al. 2005). There is a clear gradient from the Chukchi to the Beaufort Sea. Benthic biomass on the Bering and Chuckchi shelves is 100–300 g m^{-2} compared to 5–25 g m^{-2} on the Alaskan Beaufort Shelf and 0.01–25 g m^{-2} on the Canadian Shelf. The Chuckchi Sea receives Pacific Ocean water from the Bering Sea, rich in nutrients and biogenic material that settles to the sea floor (Carmack and Wassman 2006). As Bering Sea water flows over the Chuckchi Shelf, it turns easterly to flow along the edge of the Shelf. Some of it is entrained onto the western edge of the Alaskan Shelf, contributing to the intermediate level of benthic biomass there. Further east, benthic biomass decreases along the Alaskan Shelf, to reach a minimum off the mouth of the Mackenzie River.

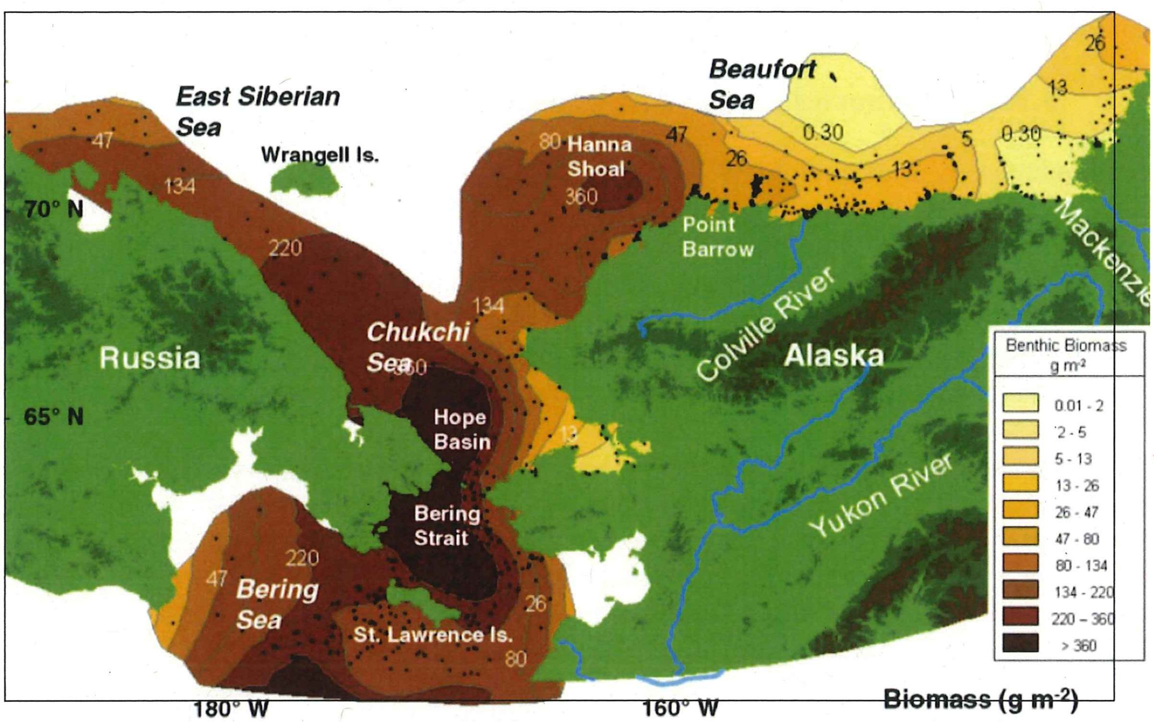

Figure 14. Spatial variation in benthic biomass (g m^{-2}) recorded in numerous studies for the period from 1971–1995. Black points denote locations of quantitative benthic grab samples. (From Dunton et al. 2005.)

On the Mackenzie Shelf, there are four recognizable zones of benthic biomass (Table 3; Wacasey 1975). In the estuarine zone, species diversity is low (Wacasey 1975), caused by high salinity fluctuations, high sedimentation rates over the Shelf immediately off the River (see Section 3.4.4 *Dominance of Mackenzie River* for sedimentation rates), and low productivity caused by turbidity (Wacasey 1975, Carmack et al. 2004). The transitional zone, where marine and estuarine waters mix, has a higher benthic biodiversity, but relatively low biomass, caused by ice scour. Highest biomass was found in the marine zone just outside the ice-scour zone. Biomass increased to the Shelf-break and decreased with depth thereafter. Benthic biomass increases towards the eastern end of the Mackenzie Shelf (Fig. 14), and Wacasey (1975) attributed this to increased productivity. More recent work by Conlan et al. (2008) showed that the density of benthos reaches a maximum on the Mackenzie Shelf near Cape Bathurst, but then decreases further east in Amundsen Gulf, becoming similar to densities on the Mackenzie Shelf and Shelf-slope.

Recent work with $\delta^{13}C$ provided information about benthic–pelagic coupling along the Beaufort Sea shelves. (Dunton et al. 2006) suggested that benthic food webs on the Chukchi and Alaskan shelves derive carbon from the rich plankton of the Bering Sea, and are tightly coupled to this source, whereas benthic food webs in the Canadian Beaufort receive more carbon from terrestrial sources, and are not so tightly coupled to productive processes in the pelagic zone. Both Dunton et al. (2005) and Conlan et al. (2008) showed, using $\delta^{13}C$, that benthic organisms on the western and central parts of the Mackenzie Shelf are consuming carbon derived from terrestrial peat, either from the Mackenzie River or from coastal erosion. This finding contrasts with organisms from Amundsen Gulf, which derive carbon from marine phytoplankton.

3.9.2. Fisheries Yield (Alaskan Shelf)

Fisheries productivity, or even biomass, on the Canadian Beaufort shelves, is unknown. There have been no systematic surveys of demersal and pelagic fish (other than larval fish) in the Canadian Beaufort Sea, although some locations have been fished with gill nets, beach seines, fyke nets, and small mid-water trawls (e.g., Majewski et al. 2006). In fact Byers et al. (2010, p. 40) stated: “The distribution and ecology of deep-water, off-shelf fish communities of the Canadian Beaufort Sea remain mostly unstudied. This is likely due, in part, to inaccessibility due to ice-cover and (until recently) a historical lack of industrial interest in abyssal regions”.

However, a systematic fish survey from the Alaskan Beaufort Shelf (Logerwell et al. 2010) may provide an approximation of fisheries biomass on the Canadian Beaufort shelves. It should be kept in mind, however, that evidence suggests the Canadian shelves may be less productive than the Alaskan Shelf because they are less influenced by inflow from the productive Bering Sea, and there may be other productivity differences brought about by the massive depositional environment caused by the Mackenzie River.

The Alaskan Shelf survey took place from the edge of Barrow Trough to ~109 km east, and fished from 40–500 m, crossing the Shelf-break. A standardized bottom-trawl survey quantified the distribution and density of demersal fish. Biomass estimates were produced for two depth strata (40–100 m and 100–500 m), and the two estimates were summed to provide a total biomass estimate of 18 kg ha^{-1} for a 6280-ha area of the Shelf (Table 6). Arctic cod made up

81% of the catch, while Bering flounder and walleye pollock together made up another 4%. The depths sampled were considered appropriate for a potential commercial fishery on the continental shelf and upper continental slope, but unlikely to occur in very shallow, nearshore areas.

On the same 6280-ha sampling site of the Alaskan Shelf, pelagic mid-water trawls and hydro-acoustic gear measured biomass estimates for Arctic cod of 19.2 kg ha^{-1} in the 40–100-m depth range, and 53.7 kg ha^{-1} in the 100–500-m depth range (Logerwell et al. 2010). These densities may be compared with the estimate of unfished biomass for demersal Arctic cod from otter trawls, 18 kg ha^{-1} (= 1.8 mt km^{-2}, Table 6). The results of this fisheries survey on the Alaskan Shelf suggest that regardless of what species a commercial fishery targets, Arctic cod may constitute a significant by-catch (NPFMC 2009).

The biomass of demersal fish on the Alaskan Beaufort Shelf considered to have commercial potential is shown in Table 6. Demersal fish were only 6% of the catch by mass; the overwhelming biomass was brittle stars. Arctic cod dominated fish catches, comprising 81% of fish biomass. Eelpouts made up 11% of the fish catch while Greenland halibut were 0.7%, and walleye pollock and Pacific cod together (neither of which is reported from the Canadian Beaufort Sea) made up 2%.

Table 6. Catch per unit effort biomass and maximum sustainable yield estimates for commercial fish and benthic invertebrates in the Beaufort Sea. (Modified from NPFMC 2009.)

Estimates from trawl survey in the Alaskan Beaufort Sea between longitude 155°W and 151.9°W, and from 40-m water depth; area: 6280 km^2.		
Species	**Unfished Biomass** ($mt\ km^{-2}$)	**Maximum Sustainable Yield** [1] ($mt\ km^{-2}\ y^{-1}$)
Snow crab	0.8	0.05
Arctic cod	1.8	0.25
Walleye pollock Pacific cod Greenland halibut	0.6	Not calculated: species did not meet criteria for commercial species
Estimates of fish yield for the Beaufort shelves based on a mean primary productivity estimate on the Beaufort shelves of 50 g C m^{-2} y^{-1}. (After Iverson 1990 and Nixon 1982.)		
		Yield ($mt\ km^{-2}\ y^{-1}$)
Carnivorous fisheries yield (estimated from Iverson 1990; see Fig. 15)		0.2–0.6
Fisheries yield (estimated from Nixon 1988; see Fig. 16)		0.48

[1]Maximum sustainable yield: the largest long-term average catch or yield that can be taken from a stock. Calculated using standard stock-recruitment methodology (NPFMC 2009).

The Alaskan Shelf survey calculated that the maximum sustainable yield of Arctic cod was 0.25 mt km^{-2} y^{-1} (Table 6). Arctic cod made up most of the demersal fish biomass, so its maximum sustainable yield may be compared with a theoretical calculation of total fish yield on the Canadian Beaufort shelves (0.2–0.6 mt ha^{-1} y^{-1}), which was based on primary productivity (see Section 3.9.3 *Predicted Fishery Yield*). The two estimates are similar, suggesting that potential fisheries yield on the Beaufort shelves is indeed low. Porta and Ayles (2013) discussed the history of commercial fishing efforts in the Canadian Beaufort Sea, and suggested there is not enough exploitable surplus biomass to support large sustainable commercial fisheries. This suggestion was supported by examples of attempted and failed commercial fishing endeavours over the past 40 years.

3.9.3. Predicted Fishery Yield

A theoretical approximation of fisheries yield for the Beaufort shelves can be calculated based on a general relationship between primary production and fisheries production developed by Iverson (1990). He compared 10 marine systems in the open ocean and on continental shelves, which shared the following oceanographic characteristics with the Beaufort shelves: 1. they were seasonally stratified over much of their area, and 2. none were strongly mixed by upwelling or tides. Iverson (1990) found a linear relationship in which carnivorous Fisheries Production (i.e., fish and squid production—not to be confused with catch or yield) = –3.73 + 0.095 x Primary Production (Fig. 15). Applying Iverson's relationship to the primary productivity of the Beaufort shelves predicts a fish *production* of 1.0 mt km^{-2} y^{-1}. Iverson then showed that fisheries catch as a percentage of fish production ranged between 20% and 60% with an average of 25% (Iverson 1990, fig. 6). These calculations suggest that the Canadian Beaufort shelves would supply a fisheries yield of between 0.2 and 0.6 mt km^{-2} y^{-1}, in approximate agreement with the Alaskan survey estimate of 0.25 mt km^{-2} y^{-1} for Arctic cod, which made up 81% of the fish catch in that study.

The comparative work of Nixon (1988) also suggests a low fisheries yield estimate for the Canadian Beaufort shelves. He compared fisheries yield and primary production in a number of marine ecosystems, including upwelling systems, estuaries, and continental shelves (Fig. 16), and found that the natural logarithm of Fisheries Yield could be calculated as (1.55 x ln Primary Production – 4.49). Applying this equation to the Beaufort shelves (assuming an average annual primary productivity value of 50 g C m^{-2} y^{-1}) predicts a fisheries yield of 4.8 kg ha^{-1} y^{-1}, which is equivalent to 0.48 mt km^{-2} y^{-1}. This theoretical calculation tends to confirm that potential fish yield on the Canadian Beaufort shelves is at the lower end of all marine systems studied.

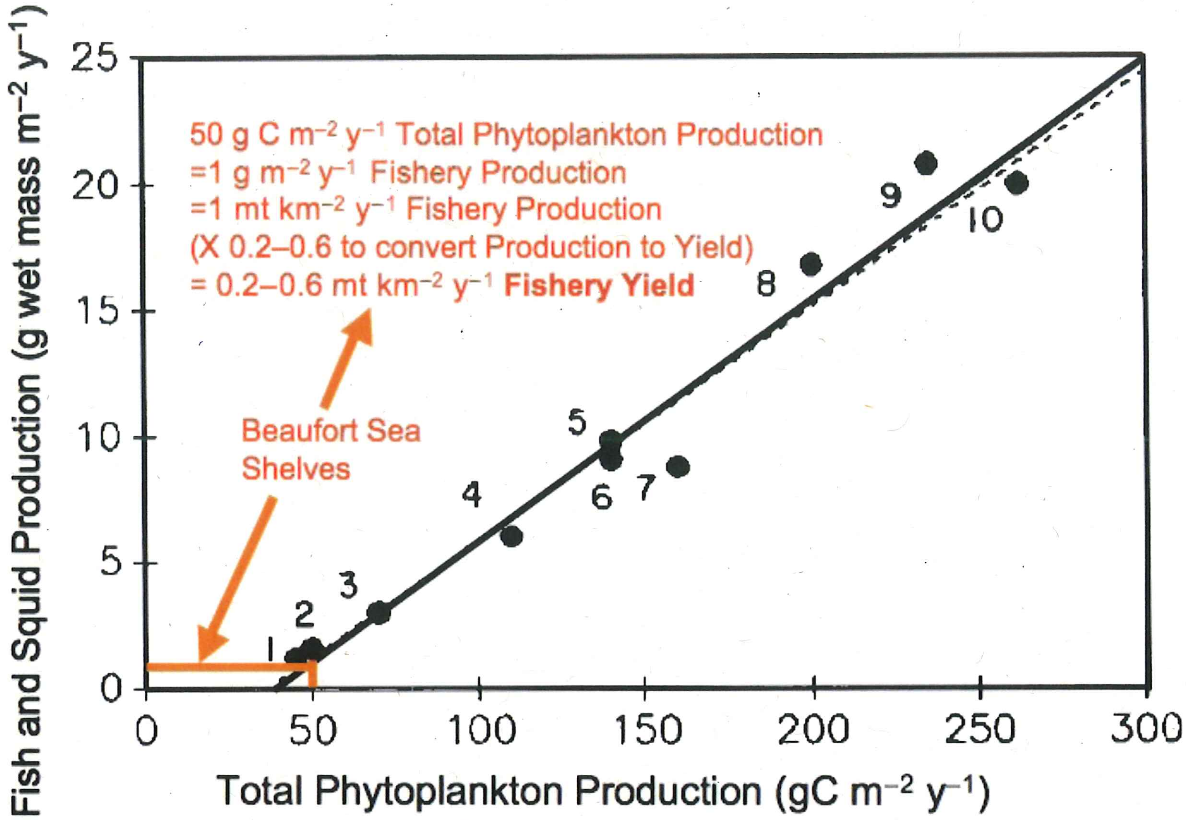

Figure 15. Carnivorous fish plus squid biomass production as a function of total phytoplankton production for open-ocean and coastal environments: 1–Atlantic Ocean Gyre center; 2–Atlantic Ocean Gyre boundaries; 3–waters off Hawaii; 4–Bothnian Sea; 5–Gulf of Riga; 6–Gulf of Finland; 7–Baltic Sea proper; 8–Nova Scotian Shelf; 9–Gulf of Maine; 10–Mid-Atlantic Bight. (From Iverson 1990.)

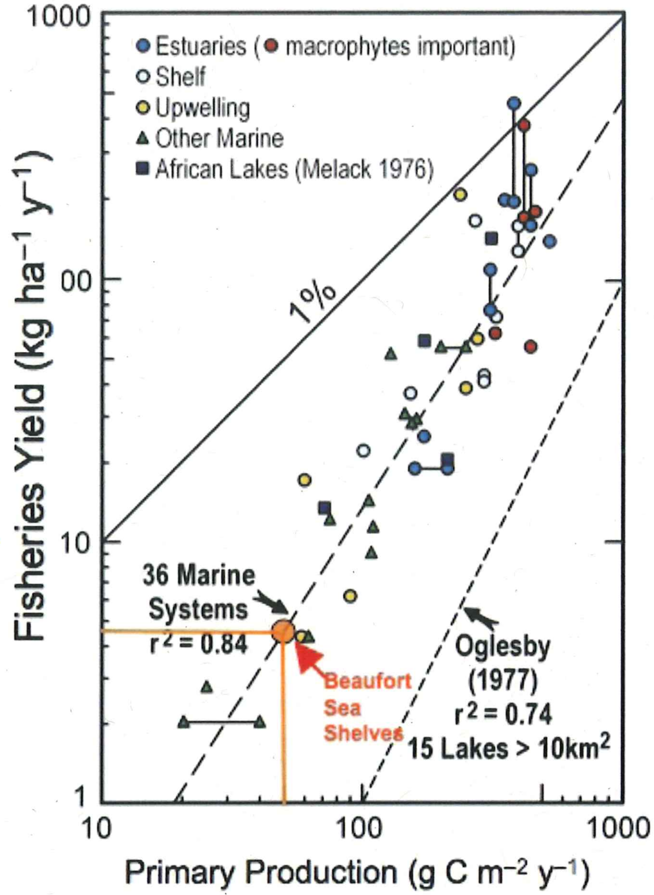

Figure 16. Fisheries yield per unit area as a function of primary production per unit area in a variety of estuarine and marine systems compared with the regression obtained by Oglesby (1977) for large lakes. The fisheries landings were converted to carbon assuming C is 10% of fresh mass (Gulland 1970). Data sources for marine systems are given by Nixon (1982) and Nixon et al. (1986). (From Nixon 1988.)

3.9.4. Indicators of Productivity

The Beaufort Sea is not a highly productive marine ecosystem. Comparisons with other parts of the Arctic, examining different levels of the food web, suggest that the productivity of the Beaufort Sea is limited. The following section provides some examples from top predators.

Marine Mammal Diversity: The diversity of marine mammals in the eastern Beaufort Sea is significantly lower than in some other parts of the maritime Arctic, such as Baffin Bay to the east and the Chukchi Sea to the west. In the eastern Beaufort Sea, marine mammal diversity is restricted to polar bears, ringed seals, bearded seals, bowhead whales, and white whales. Grey whales, killer whales, and walruses have been observed but are uncommon. By comparison, Baffin Bay, in addition to these species, has large numbers of narwhals, harp seals, hooded seals, and Atlantic walrus. Similarly, in the Chukchi Sea, there are several additional and abundant species of marine mammals not found in the eastern Beaufort Sea, including grey whales, Pacific walrus, spotted seals, and ribbon seals (Stirling 2002).

Polar Bear Reproduction: Polar bears, living at the top of the marine food web in the Arctic, are a clear indicator of the health and productivity of the food web on which they depend. Female polar bears reach sexual maturity a full year later in the Beaufort Sea than elsewhere, and some litters of cubs have longer weaning periods (Stirling 2002). This delay is a consequence of lower overall productivity in the Beaufort Sea ecosystem in comparison with other areas of the Canadian Arctic such as Lancaster Sound (Stirling and Øritsland 1995). Polar bear productivity is closely linked to the productivity of ringed seals, their major prey (see Section 3.7.2 *Polar Bear*).

Ringed Seals: Ringed seals are abundant, and found everywhere, so they are another good indicator of the health and productivity of the ecosystem. Their density and condition is estimated relatively easily, with acceptable accuracy, and can be used for long-term monitoring as an indicator of large-scale changes resulting from natural or unnatural phenomena (e.g., Stirling et al. 1982, Stirling and Lunn 1997). The density of ringed seals is lower in the eastern Beaufort Sea compared with similar areas of the eastern and High Arctic. For example, seal densities in mixed pack and fast ice in Barrow Strait (High Arctic) were twice as high as those in the Beaufort Sea. Seal densities in offshore pack ice in northwestern Baffin Bay were 4–5 times higher, and off southwestern Baffin Island and Ungava Bay, were 7–10 times higher than those in comparable habitats in the Beaufort Sea (Stirling and Øritsland 1995). Similarly, seals in the Beaufort Sea take longer to become sexually mature. Only 20% of four-year old female ringed seals and 29% of five-year olds taken in the Beaufort Sea were sexually mature, compared with 40% and 60% for the same age groups in western Baffin Bay along the east coast of Baffin Island (Smith 1973, 1987). These differences in densities and seal condition among areas are assumed to reflect differences in the levels of marine primary productivity.

Sea Birds: A paucity of sea birds in the Canadian Beaufort Sea suggests that it is less productive than other Arctic waters. For example, in most polar oceans, sea birds such as murres (auks) and black-legged kittiwakes are important components of marine ecosystems. These birds require small fish to feed their young, and large colonies of murres in the eastern Canadian Arctic consume tons of Arctic cod daily (Gaston and Jones 1998a), routinely diving to reach schools of fish at 60–80 m depth (Falk et al. 2000). In both the Bering Sea to the west of the Beaufort Sea and the marine waters of the Canadian eastern Arctic, there are many large seabird colonies, several supporting >300,000 birds. For example, the Jones Sound/Lancaster Sound region of the Canadian High Arctic is an important area for breeding sea birds such as northern fulmars, glaucous and Thayer's gulls, black-legged kittiwakes, thick-billed murres, and black guillemots. The southeastern Beaufort Sea, however, supports only two small seabird colonies: a colony of ~800 thick-billed murres on the cliffs of Cape Parry, overlooking the Amundsen Gulf, and a colony of ~100 black guillemots nesting within rock piles and old buildings at Herschel Island on the Mackenzie Shelf.

It remains unexplained why so few pelagic sea birds breed in the Beaufort Sea. The existence of 30 km of unoccupied cliff habitat at Nelson Head on Banks Island, directly across Amundsen Gulf from Cape Parry, and within 30 km of recurrent open water in the Bathurst polynya, suggests that pelagic seabird populations are neither limited by a lack of suitable nesting habitat nor distance to open water. The absence of pelagic sea birds nesting at Nelson Head suggests that the offshore area of the Beaufort Sea is less productive than regions at similar latitudes in both the eastern Canadian Arctic and the Bering Sea (Dickson and Gilchrist 2002). This conclusion is consistent with the findings of Tremblay et al. (2008) who found that primary production in Amundsen Gulf in Franklin Bay was strongly limited by nutrients.

4. Fisheries Management

Management of fisheries and marine mammal resources in the Inuvialuit Settlement Area takes place within the context of Canada's Fisheries Act and the Oceans Act, in a collaborative and cooperative manner between DFO and the Inuvialuit, as a result of the signing of the IFA in 1984. Examples of this collaboration are:

- the Beaufort Sea Beluga Management Plan, the Tarium Niryutait MPA,
- MPA development such as the Darnley Bay Area of Interest,
- the Beaufort Sea Strategic Regional Plan of Action, and
- the proposed Beaufort Sea Regional Environmental Assessment.

Canada's Oceans Act is founded on the principles of sustainable development, integrated management, and the precautionary approach. It encourages the development of integrated oceans management (IOM) plans, using marine conservation tools such as MPAs. Fisheries and Oceans Canada (DFO) and the Inuvialuit, in cooperation with federal and territorial departments, have developed an IOM Plan for the Beaufort Sea (BSPO 2009). The Plan sets out a vision for the area and contains a number of ecosystem-based management objectives and strategies needed to achieve a sustainable future for the region. The planning process may eventually lead to the sustainable use of offshore fish species. If that happens, an IFMP would be desireable as an instrument to ensure the sustainability of a fishery and to protect habitats and food webs from the impact of a fishery.

An IFMP is being considered because the possibility of longer ice-free summers in the Canadian Beaufort Sea will create the opportunity for commercial fishing on the continental shelf. At the same time, many keystone species, important to marine food-web integrity, are being stressed by environmental changes being felt in the Arctic. Some of the stressed species currently provide food for Inuvialuit communities, and others are of conservation concern and are listed under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Therefore, the removal of any fish from the Beaufort Sea in commercially viable quantities must be assessed for its impact on food webs, and to determine whether keystone species, species important to Inuvialuit, or COSEWIC-listed species may be negatively affected. An ecosystem-based and precautionary approach to commercial fishing is required, in which information is gathered before fishing is permitted, to ensure that food webs, already re-structuring under climate change, are not further disrupted, and that any fishery is sustainable from an ecosystem point of view.

4.1. Policy Framework

Canada's Sustainable Fisheries Framework provides the foundation for ecosystem-based and precautionary approaches to fisheries management. These approaches are designed to ensure continued health and productivity of Canada's fisheries, while protecting biodiversity and fisheries habitat. They embrace the following policies:

- A Fishery Decision-making Framework Incorporating the Precautionary Approach (DFO 2009c)
- New Emerging Fisheries Policy (DFO 2008)
- Policy on New Fisheries for Forage Species (DFO 2010)
- Policy for Managing the Impacts of Fishing on Sensitive Benthic Areas (DFO 2009b).

The fishery decision-making framework ensures precautionary treatment for species and habitats when designing an IFMP. The information requirements for each of the above policies are shown in Table 7, and addressed in Section 4.2 *Information Needs*.

An IFMP for a new fishery must have a long-term perspective, setting reference points prior to the fishery that will guide management action. The reference points are designed to control the degree of fishing so that the target stock remains healthy, so that predators depending on the target species are not impacted, and so that benthic habitat is not damaged.

Table 7. Information requirements for developing a commercial fishery under Canadian fishery policies.

Policy	**Information Required**		
Precautionary Approach Framework	Reference Points[1] to be applied to the metrics for: • Fishery management, e.g., stock assessment (spawning biomass) • Impacts to food web, e.g., forage requirements of predators, e.g., beluga whales • Impacts to habitat, e.g., polynyas, upwelling zones		
	Target Species	**Impacted Species**	**Environment**
New Emerging Fisheries Policy	-Abundance (catch per unit effort) -Distribution -Productivity	-Impact on dependent species	-Impact on habitat
Policy on New Fisheries for Forage Species	-Stock status, i.e.,: • spawning biomass • theoretical exploitation rate (maximum sustainable yield) • age composition • growth rate • reproductive success • limit reference points for productivity • distribution, aggregations[4]	-By-catch of non-target species -Stock status of dependent species -Limit reference points for productivity of dependent marine predators[2,3]; e.g.,: • growth rates • condition factor • reproductive output • food requirement of dependent marine predators -Ecosystem models	-Precautionary Approach must be taken. (See "Precautionary Approach Framework" above.)
Policy for Managing the Impacts of Fishing on Sensitive Benthic Areas		-Biological features, e.g.,: • major forage species • top fish predators • seabird populations • marine mammal populations • threatened or endangered species and species of "Special Concern" as assessed by COSEWIC • key primary and secondary plankton producers -Impacts of fishing on non-target (by-catch) species, with particular emphasis on: • Species At Risk Act (SARA)–listed species, • forage species	-Benthic habitat features -Physical features (e.g., tidal mixing zones, convergence zone, polynyas, upwelling zones, topography, thermal hot vents, etc.) -Structural features (e.g., deepwater corals, sponge reefs, macrophyte beds, etc.) • location • community composition -Ecological/biological significance of benthic features
By-catch Policy		-Currently under development	

[1]Definition of Reference Points: Pre-agreed harvest decision rules designed to achieve a desired [ecological] outcome by affecting the [fisheries] removal rate. [Fishery] management actions should be made in relation to reference points (DFO 2009c).

[2]Predator that obtains a significant part of its annual food ration from the forage species.

[3]Used when forage stock is patchy and difficult to quantify and predator status may be a better indicator of forage abundance.

[4]Predators may depend on local aggregations of forage fish rather than overall forage-fish biomass.

4.2. Information Needs

Managing a new, emerging fishery, particularly for a forage species like Arctic cod, requires a wide variety of ecosystem and stock information. First, stock-status information, such as abundance, distribution, and productivity, is required for the target species. If a species forms dense aggregations, fishers will target them. These species need special precaution because catch per unit effort may not indicate stock biomass; the fish may continue to be found in high concentrations until stock size is very low. Second, information is required on food requirements of the main predators to ensure that fishing will not impact their food supply. In most cases, the population size of top predators is difficult to measure, so some measure of predator productivity or condition is required to provide a reference point to guide the rate of forage fish removal. Third, information is required about benthic habitats that may be impacted, including their location and ecological significance. Fourth, impacts on species caught incidentally in the fishery, the by-catch, must be evaluated. Last, potential impacts of the fishery on any fish, sea birds, or marine mammals listed by COSEWIC and the Species at Risk Act (SARA) must be assessed. More specifically, the following information is required:

- initial estimates of stock distribution, abundance (biomass), and productivity (natural mortality) of the target species;
- stock status, food requirements, and productivity measures for major predators of target species;
- evaluation of physical, structural, and biological features of benthic habitat that might be impacted;
- evaluation of the impact of species caught as by-catch in the target fishery; and
- evaluation of potential impacts on COSEWIC-listed species.

The continental shelves of the Canadian Beaufort Sea and Amundsen Gulf contain 66–70 recorded species of marine fish (Coad and Reist 2004). A few of these are caught commercially elsewhere and, therefore, might be fisheries targets in the Beaufort Sea if commercial quantities could be identified. Snow crab is also known to inhabit the Alaskan and Canadian shelves (Logerwell et al. 2010, Porta and Ayles 2013). Potential fishery targets are:

- Arctic cod (*Boreogadus saida*),
- Pacific herring (*Clupea pallasi*),
- Greenland halibut (*Reinhardtius hippoglossoides*), and
- snow crab (*Chionoecetes opilio*).

The types of potential fisheries that might be contemplated are: a demersal fishery—e.g., trawling—for Arctic cod; a demersal fishery—e.g., trawling or long-lining—for Greenland halibut; trap fishing for snow crabs; and purse seining for Pacific herring.

Table 8 lists potential fishery target species, and their predators that may be impacted by fishing, including COSEWIC species. It also shows habitats that may be at risk.

Table 8. List of potential commercial species for which information is required by IFMPs under the Sustainable Fisheries Framework. Footnotes indicate keystone species, species of significance to Inuvialuit subsistence, and species of interest to COSEWIC.

Target Species	**Predator Species**	**By-catch species**	**Habitat**
Arctic cod (trawl fishery)	-Beluga whale [1,2] -Ringed seal [1,2] -Polar bear (by association with ringed seal) [2] -Arctic charr/Dolly Varden [1,2] -Thick-billed murre -Black guillemot -Ross's gull [3] -Ivory gull [3]	-Saffron cod -Pacific herring[2] -Arctic cisco [1,2] -Capelin -Benthic invertebrates	-Cape Bathurst -Mackenzie Shelf-break -Mackenzie Trough–Kugmallit Trough
Pacific herring[2] (seine fishery)	Same as for Arctic cod		
Greenland halibut (trawl or long-line fishery)	Unknown	Unknown	-Cape Bathurst? -Mackenzie Shelf-break and slope
Snow crab (pot fishery)	Unknown	Unknown	Mackenzie Shelf-slope

[1] Keystone species.
[2] Inuvialuit subsistence.
[3] COSEWIC-listed.

State of Fisheries Knowledge: The offshore Beaufort Sea has been almost unsampled by ichthyologic and fisheries oceanographic expeditions. Coad and Reist (2004) listed the marine fishes of the Canadian Arctic, by geographic area, and provided a summary for the Canadian Beaufort Sea. Information on Canadian Arctic fishes, including ecology, may be found in the *Encyclopedia of Canadian Fishes* (Coad 1995).

Most fisheries sampling has taken place on the continental shelves, and Hopcroft et al. (2008), Jarvela and Thorsteinson (1999), Logerwell et al. (2010), and Byers et al. (2010) provided detailed summaries of these investigations. Most knowledge of Arctic fishes is about freshwater and anadromous fishes, with information about offshore marine species being extremely limited. In the Canadian Beaufort Sea, several studies have examined fish populations within Tuktoyaktuk Harbour, Kugmallit Bay, and nearshore sites within Mackenzie Bay (McAllister 1962, Kendal et al. 1974, Percy 1975, Bond 1982, Lawrence et al. 1984, Baker 1985, Bond and Erickson 1987, 1989, Chiperzak et al. 1991). Chiperzak et al. (2003a,b,c) and Hopky et al. (1994) reported on larval and postlarval fishes from the Canadian Beaufort Sea Shelf, and Lacho (1991) reported on stomach contents of fish from Tuktoyaktuk Harbour. However, until recently, relatively few studies have focused on offshore fish populations (Galbraith and Hunter 1975, Frost and Lowry 1983, Kavik-Axys Inc. and LGL Limited Environmental Research Associates 2001, Majewski et al. 2006, 2009a,b, 2010, Lowdon et al. 2011). These offshore studies mostly sampled larval and juvenile fish with mid-water trawls, and generally showed that, although Arctic cod larvae and juveniles dominate the deeper-water stations of the Beaufort Shelf (with staghorn sculpin larvae second in abundance), Pacific herring larvae dominate nearshore waters. Majewski et al. (2009a,b) sampled fish larvae offshore to a depth of 225 m, but fishing activites were exploratory in nature, so no quantitative estimates of biomass were made. A number of these studies are simply data reports, and Hopcroft et al. (2008, p. 69) suggested: "These studies have produced a large body of data that should be mined, and such an effort appears to be under way (see Coad and Reist 2004)".

4.2.1. Target Species

Arctic Cod (see also Section 3.7.1 *Arctic Cod*): The information required for Arctic cod (Table 7) is abundance (catch per unit effort), distribution, size and age composition, growth rate, fecundity, spawning biomass, and year-class strength. From these measurements, it is possible to estimate potential yield and harvest rates.

There are presently no quantitative estimates of the size or distribution of the Arctic cod population in the Canadian Beaufort Sea, and the ecology of this important species is poorly understood (Cobb et al. 2008). A recent systematic survey on the Alaskan Shelf (Logerwell et al. 2009) provided stock-assessment information there. However, extrapolation of specific stock-assessment information from that study to the Mackenzie Shelf is problematic because the Mackenzie Shelf is dominated by the Mackenzie River, whereas the Alaskan Shelf is influenced by the Bering Sea inflow. These differences may bring about substantially different food-web dynamics on the two shelves. Growth rates and mortality rates of Arctic cod, measured from otoliths found in predator stomachs (ringed seals and beluga whales), are known to differ over large geographic areas (western to eastern Arctic) and over years (Bradstreet et al. 1986). Sampling for Arctic cod on the Canadian shelves has mostly been inshore, with beach seines, gill nets, fyke nets, and epipelagic trawls for fish larvae and young-of-the-year fish (Bradstreet et al. 1986, Cobb et al. 2008).

A systematic sampling program, using benthic and mid-water trawls and hydro-acoustic gear in a design directly comparable with work done on the Alaskan Shelf (Logerwell et al. 2010), is recommended to establish Arctic cod abundance, distribution, and productivity for the Canadian Beaufort shelves.

Arctic cod are known to form dense schools. Aggregations have been found throughout the year, making them vulnerable to fishing. Extreme aggregations, seen in shallow bays of Lancaster Sound where fish appear to be avoiding marine mammal and bird predation, have not been observed in the Beaufort Sea (Table 5). Nevertheless, aggregations of 155,000 fish ha^{-1} have been found near the Shelf-break on the Alaskan Beaufort Shelf, and much higher densities have been seen under ice cover in the deep water of Franklin Bay. The possibility of feeding aggregations in areas where copepods are concentrated by ocean fronts on the Mackenzie Shelf has not been explored. There is evidence from the work of Logerwell et al. (2009) and Benoit et al. (2008) that the life cycle of Arctic cod may be linked to large-scale current systems in the

Beaufort Sea and to the Bathurst polynya, but this possibility needs further examination. Arctic cod aggregations on the Canadian Beaufort shelves should be investigated with hydro-acoustic gear to determine the vulnerability of this species to localized fishing (e.g., with seine nets).

Pacific Herring: This species is most abundant east of the Mackenzie Delta, particularly in Tuktoyaktuk Harbour and Tuktoyaktuk Peninsula, Liverpool Bay/Husky Lakes, and Cape Bathurst areas (Stewart et al. 1993). Mature herring have been captured in Kugmallit Bay (Chiperzak et al. 1991), and they are reported to spawn in Tuktoyaktuk Harbour and the Fingers Area of Liverpool Bay, an area of high tidal flow (Bond 1982, Gillman and Kristofferson 1984, Shields 1985). Shields (1985) estimated the spawning-stock biomass of Pacific herring in the Fingers Area of Liverpool Bay was between 2.6–13.8 mt—too little to sustain a viable commercial fishery despite several attempts (Porta and Ayles 2013). Very little is known about migration patterns or reproductive biology of Pacific herring in the Beaufort Sea region (Shields 1985). Pacific herring were not caught in the Alaskan Shelf survey. There is no information about the abundance or productivity of Pacific herring in the Canadian Beaufort Sea, and information about distribution is limited to site records from gill net/fyke net surveys.

Greenland Halibut: Greenland halibut is known to inhabit the Canadian Beaufort Shelf-slope from 11 specimens caught by long-line at a depth >400 m (Chiperzak et al. 1995). One female was sexually mature, suggesting that there is a reproducing population. The catch of Greenland halibut in the Alaskan Shelf-slope survey suggested that biomass there may be too low to support a commercial trawl fishery (NPFMC 2009), but no information is available about abundance, distribution, or productivity in the Canadian Beaufort Sea.

S***now Crab:*** Snow crab have been caught in the Canadian Beaufort Sea (Porta and Ayles 2013), but there is no information available about abundance, distribution, or productivity there. Maximum sustainable yield calculated for snow crab in the Alaskan survey was too low for a commercial fishery (NPFMC 2009). Snow crabs are caught in pots. By-catch rates for gadids in the Bering Sea fishery for snow crab are typically on the order of 0.5% (individual gadids caught per individual snow crab caught), which has been interpreted as a negligible value (NPFMC 2009).

4.2.2. Predator Species

A fishery targeting Arctic cod would reduce the food source for its predators: beluga whales, ringed seals, and Arctic charr/Dolly Varden. Avian predators that could be affected are loons, gulls, terns, black guillemots, and thick-billed murres. Any impact on ringed seals would be transmitted to polar bears because the two species are tightly linked in the food web. Among the species potentially affected, beluga whales, ringed seals, polar bears, and Arctic charr/Dolly Varden are keystone species and important for Inuvialuit subsistence (see Sections 3.6 *Food Webs* and 3.7 *Keystone Species*). Several species, such as ivory gulls, Ross's gull, and polar bears, are listed as endangered, threatened, or of special concern, respectively, to COSEWIC. Information is required for these species, which would provide an indicator of predator-food insufficiency that could be linked to Arctic cod removal rate.

Beluga Whale (see also Section 3.7.5 *Beluga Whale*): Beluga whales feed heavily on Arctic cod, although they also feed opportunistically on other forage fish. Juveniles feed on Arctic cisco inshore. The cost-effective Fisheries Joint Management Committee (FJMC) beluga whale monitoring program should be continued; it provides population variables, health indices such as body condition, and tissue samples that can be used to determine food sources as indicated by fatty acids (Loseto et al. 2009a). These metrics can be used to define reference points for the impact of Arctic cod removal on dependent beluga predators.

Ringed Seal (see also Section 3.7.3 *Ringed Seal*): The community-based Beaufort Sea Ringed Seal Monitoring Program in the Canadian Beaufort Sea should be continued (http://www.beaufortseals.com/index.htm). It provides measures of body condition and two variables of seal reproduction (ovulation rate and percent pups in the harvest). A telemetry component provides information on seal movements. These metrics can be used to define reference points for the impact of Arctic cod removal on ringed seals.

Polar Bear (see also Section 3.7.2 *Polar Bear*): Listed as "of special concern" under COSEWIC (2008), polar bears feed primarily on ringed seals. Population densities of polar bears and ringed seals are, therefore, tightly coupled and removal of Arctic cod would likely result in an impact on ringed seals and polar bears. They are considered a keystone species because of their unique position at the apex of the ice-edge food web, and they are important for Inuvialuit subsistence. They have not been designated under SARA. Stable isotope analysis, fatty acid analysis, and body condition metrics can all be used to monitor the food preference of polar bears. These metrics may be used to assist in defining reference points for the impact of Arctic cod removal on dependent predators, i.e., ringed seals. Monitoring of polar bear density continues under the Inuvialuit–Inupiat Polar Bear Management Agreement in the Southern Beaufort Sea.

Arctic Charr/Dolly Varden (see also Section 3.7.6 *Arctic Charr/Dolly Varden and Arctic Cisco*): Populations of Arctic charr/Dolly Varden along the Canadian Beaufort Sea are monitored closely by the FJMC and DFO, and documented as stock-status reports (DFO 1999, 2001, 2004a). Stock assessments may be used to define reference points for the impact of Arctic cod removal on dependent predators, i.e., Arctic charr/Dolly Varden.

***Murre/Guillemot*:** Both thick-billed murres and black guillemots are predators on Arctic cod. Sea birds provide an opportunity to monitor the type of forage fish they are consuming as they bring fish back to the nest. For example, thick-billed murre foraging has indicated a replacement of Arctic cod by capelin in Hudson Bay (see Section 5.2.3 *Range Extensions*). Information about seabird breeding success is an indicator of overall prey availability. Populations of thick-billed murres at Cape Parry and black guillemots on Herschel Island could be monitored to assess the impact of Arctic cod removal by a fishery in the Beaufort Sea. Long-term records have been collected on black guillemots by park staff at Herschel Island.

Ross's Gull, Ivory Gull: Ross's gull is listed as threatened, while the ivory gull is listed as endangered by both COSEWIC and SARA (see Section 4.2.8 *Species Protection and Species at Risk*). Both are found in the Canadian Beaufort Sea, and are known to feed on Arctic cod from studies in the Chukchi Sea (Divoky 1976) and the Northwater polynya of Baffin Bay (Karnovsky et al. 2009). There is no information from the Canadian Beaufort Sea with which to assess the impact of a potential Arctic cod fishery on these species.

4.2.3. By-Catch Species

Saffron Cod, Pacific Herring, Capelin, and Arctic Cisco: These four species are potential by-catch species in a fishery for Arctic cod in the Canadian Beaufort Sea. Saffron cod and Pacific herring have been captured in open water on the Mackenzie Shelf (Lawrence et al. 1984). Large but variable numbers of capelin *Mallotus villosus* have been reported in the Amundsen Gulf region, and large concentrations have been reported in Sachs Harbour and near the Holman Island area (Cobb et al. 2008). None of these species were listed as by-catch species in the Alaskan Shelf trawl survey reported in NPFMC (2009), although the Alaskan Shelf offshore is much less estuarine than the Mackenzie Shelf.

4.2.4. Habitat–Benthos

The Canadian *Policy for Managing the Impacts of Fishing on Sensitive Benthic Areas* requires information on the biological, physical, and structural features of benthic habitat. To avoid harm to sensitive benthic habitat requires mapping the location and extent of benthic habitat types, including information on whether their features, communities, or species are ecologically important where fishing activities are being proposed. The policy then applies a risk assessment, as formulated in the *Precautionary Approach Framework,* to fishery management decisions.

Zoobenthos are a biological component of the benthic habitat. Knowledge about the benthos on the Canadian Beaufort shelves is summarized in Section 3.4.5 *Benthic Habitat.* Important reviews of the benthos in the Chukchi and Beaufort seas were recently prepared by Grebmeier et al. (2006a) and Dunton et al. (2006), respectively. In an excellent synthesis of information about the Arctic Ocean and Beaufort Sea in particular, Hopcroft et al. (2008, p. 56) pointed out: "Benthic ecosystems in general integrate water column processes over longer periods than planktonic and sea ice communities (Piepenburg et al. 1997) due to the relatively slow growth and high longevity of many polar benthic marine organisms (Brey and Clarke 1993, Arntz et al. 1994). Benthic organisms are, therefore, less affected by inter-annual variability or smaller-scale fluctuations in water column productivity than the pelagic, usually shorter-lived fauna (Carey 1991). Hence, *benthic fauna indicate interannually persistent sites of carbon deposition versus food-limited regions (Grebmeier et al. 2006b) and are, therefore, a useful indicator of potential change in a system* [Mathias italics]. Long-term changes due to climatic impacts are likely to be reflected in the benthic community on temporal scales of years to decades (Piepenburg et al. 2001, Dunton et al. 2005)". In this context, the detailed study of benthic community structure of the Canadian Beaufort shelves done by Conlan et al. (2008) and Aitken et al. (2008) as part of the CASES project should stand as a useful baseline from which to observe future ecosystem change.

On the other hand, as Hopcroft et al. (2008, p. 61) pointed out: "Benthic biomass and community structure appear to have different major environmental determinants. *Arctic benthic biomass is largely driven by carbon supply but community structure can be dependent on bottom structure, current conditions, and other physical forces* [Mathias italics] (Grebmeier et al. 1989, Grebmeier and McRoy 1989, Feder et al. 2005, 2007)". The CASES project confirmed that benthic community structure on the Canadian shelves varied in response to physical variables, but the study has not published biomass estimates, so no indicator of sedimenting carbon supply on the Canadian shelves is available. The lack of benthic biomass data is a serious information gap in view of its value as a long-term "integrator" of overlying oceanographic processes, and as a regional extension of the benthic biomass data shown in Fig. 14 into Amundsen Gulf. The value of biomass information from grab samples is further demonstrated by the fact that it provides an approximation of the biomass that would constitute by-catch in a trawl fishery for Arctic cod (Table 9). It may be possible to reconstruct approximate biomass estimates for the CASES sample set using species-specific mass data from related samples or from the literature (V.E. Kostelyev, Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, NS, Canada, B2Y 4A2).

Table 9. Benthic biomass estimated by grab samples and from trawl catch. Data come from the Alaskan Beaufort Sea between longitude 155°W–151.9°W and from 40–500 m deep. The area sampled was 6280 km^2.

Type of Sample	**Biomass ($mt\ km^{-2}$)**
Grab	26–47[1]
Trawl survey	27.6[2]

[1] Range, estimated by eye from Fig. 14.
[2] From NPFMC 2009.

Chapman and Kostylev (2007, 2008) assembled data on marine benthos, collected between 1951–2000 in the Canadian Beaufort Sea, and organized the data into a guide to aid in future research on Arctic benthos. These data should be mined and combined with those in Conlan et al. (2008) to produce a comprehensive picture of benthic biomass for the eastern Beaufort Sea, similar to that produced by Dunton et al. (2005) (Fig. 14).

4.2.5. Physical Habitat Features

Cape Bathurst: The area north and west of Cape Bathurst is characterized as a unique habitat in the Canadian Beaufort Sea in terms of tidal currents, upwelling events (Fig. 10), the high density of its benthic community (Fortier et al. 2008), and its importance to many species. The benthic richness suggests that the increased pelagic productivity at this place is tightly coupled to the sea-floor community. The benthic community directly supports bowhead whales and ringed seals (frequently), grey whales (infrequently), and thousands of eiders and long-tailed ducks (annually). Disturbance of the benthic community by trawling is likely to reduce the productivity of the Cape Bathurst hotspot. Community composition is known from only four sample sites at ~160 m (Conlan et al. 2008). No measurements of biomass were published. A more detailed examination of the extent and productivity of this site is warranted. There is some evidence that the epibenthos at Cape Bathurst is important for bowhead bottom feeding and for grey whales. The impact of trawling on the epi- and infauna of Cape Bathurst is unknown, but could be detrimental to feeding by bowhead whales, ringed seals, grey whales, and sea birds.

Mackenzie Trough and Mackenzie Shelf-Break North of Cape Dalhousie: Trough habitats and the Mackenzie Shelf-break north of Cape Dalhousie are hotspots for upwelling, enhanced productivity, and current-mediated concentration of zooplankton. Impacts of commercial fishing at this hotspot could arise from interference with feeding activity by bowhead whales and ringed seals. Although there is information about the reaction of ringed seals and bowhead whales to ship traffic (Richardson 1985, Richardson and Malme 1993, Mackenzie Gas Project 2005), there is no information to assess how interference with whale or seal feeding at these localized hotspots would impact their growth and survival. There is evidence that an epifauna of pelagic gammarid and hyperiid amphipods, euphausiids, and isopods may be important in the Mackenzie Trough (Bradstreet et al. 1987). If so, then disturbance of the sea floor by commercial fishing could impact the productivity of the epibenthic community. A more detailed characterization of this habitat is warranted.

Canadian Beaufort Sea Shelf-Slope: This area is a potential habitat for northern wolffish, a threatened species under COSEWIC and SARA (Table 10). Although northern wolffish can be found in deep water on a silt bottom, there is no information about their existence on the offshore shelf-slope of the Canadian Beaufort Sea.

4.2.6. Structural Habitat Features

Fingers Area of Liverpool Bay: Traditional knowledge has identified this site as one where Pacific herring spawn, and where local areas are ice-free all winter. It is characterized by high tidal currents (Carmack and Macdonald 2008) that result from constriction as the tide moves through a narrow channel. It has also been the site of a failed commercial fishery for Pacific herring (Porta and Ayles 2013). The type of gear (seine or gill net) used to catch spawning herring is unlikely to impact the benthic habitat.

Pingos, Gas Vents, Mud Volcanoes, and Artificial Islands: The location of many of these features has been mapped by the Geological Survey of Canada. There is little information about the benthic community or associated fauna at these sites. Cobb et al. (2008, p. 20) stated: "Mud volcanoes (pingo-like features) are geological formations located along the seafloor of the southern Beaufort Sea. These formations occur as single features or as several hundred in long corridors. A recently discovered corridor is the "Garry Knolls" area, located west of Richards Island and extending northwest to the Shelf break. Mud volcanoes appear to be widespread in the [Canadian Beaufort Sea], and their ecological implications are currently being investigated".

4.2.7. Inuvialuit Subsistence

The top 10 species in the Inuvialuit subsistence harvest from the marine environment are beluga whale, broad whitefish, Arctic charr/Dolly Varden, ringed seal, inconnu, humpback whitefish, and cisco (Table 2). Those species dependent on forage fish are beluga, ringed seals, Arctic charr/Dolly Varden, and inconnu (Lacho 1991). Arctic cod and Pacific herring are two forage species widely distributed in the estuarine environment that could be targeted by a commercial marine fishery. Removal of these species, both in the adult and sub-adult stage, could impact their estuarine and marine predators with negative consequences to Inuvialuit subsistence harvesting. Little is known about the quantitative importance of marine forage fish in the diets of their estuarine predators. This information would be required to assess the impact of commercial fishing on estuarine and marine predators.

4.2.8. Species Protection and Species at Risk

Marine species identified as requiring protection in the Beaufort Sea ecosystem (Table 10) are pigheaded (blackline) prickleback, northern wolffish, bowhead whales, and grey whales (SARA 2009, COSEWIC 2001, 2004, 2009, GNWT 2010).

Pigheaded (Blackline) Prickleback: The blackline prickleback is a small, benthic, predatory fish of the marine habitat that can also tolerate estuarine conditions. It is found in the Husky Lakes, Liverpool Bay, Kugmallit Corridor, and Herschel Island Ecologically Significant Areas (Fig. 8, Appendix 2) of the Beaufort Sea. It is fairly abundant in Tuktoyaktuk Harbour. It is thought to inhabit deep water but to spawn in shallow water. It is also known from the Bering Sea and North Pacific, but the Beaufort Sea population appears to be isolated (COSEWIC 2003). It is considered "Data Deficient" and, therefore, would not be protected by SARA legislation. There is no information about whether it would appear as by-catch in a potential trawl fishery on the Candian Beaufort shelves. It was not listed in the offshore catches of Majewski et al. (2009a,b).

Northern Wolffish: The northern wolffish is a large, bentho-pelagic, predatory fish living in deep waters, generally >100 m. It was found in Prince Albert Sound at western Victoria Island and at Mould Bay at Prince Patrick Island. The latter is in the marine habitat within the Albert Islands/Safety Channel/Kagloryuak River Ecologically Significant Area (Fig. 8, Appendix 2). It is an Atlantic species that is designated as "Threatened" (COSEWIC 2001, SARA 2009) because its populations have declined >90%. By-catch mortality by offshore trawlers and long-liners in the Atlantic Ocean is considered a threat. In addition, activities that disturb the ocean bottom, such as trawling, may damage wolfish nests and eggs on the sea bottom. Although it can be found over a silty bottom, it is believed to use large rocks for shelter and nest-building (DFO 2011a), so is unlikely to be found on the Canadian Beaufort Shelf-slope. There is no information about its presence as by-catch in a potential trawl fishery on the Candian Beaufort shelves.

Bowhead Whale: Bowhead whales are found primarily along the south and west coasts of Banks Island, in the Amundsen Gulf, near the Baillie Islands, along western Tuktoyaktuk Peninsula in the ice flaw-lead near the shelf-break (Fig. 9), and in the Bathurst polynya, Kugmallit Corridor, and Cape Bathurst Ecologically Significant Area (Fig. 8). Bowhead whales in the Beaufort Sea are listed as of "Special Concern" by COSEWIC (Table 10) because they had been hunted almost to extirpation in the 1800s and have only recovered to about half of their estimated population numbers at present. Considered a keystone species in the Canadian Beaufort Sea, they are susceptible to underwater noise from ships, to collision with ships, and to climate change as the ice recedes. Considerable literature documents the effects of underwater noise and shipping activity on bowhead whales (e.g., Richardson 1985, Richardson and Malme 1993). Commercial fishing activities would have to address these potential impacts on bowhead whales under SARA and possibly also the Marine Mammal Regulations of the Canada Fisheries Act.

Table 10. Rare/Depleted and/or Sensitive marine species, their corresponding conservation status in the Beaufort Sea ecosystem, and the habitat and Ecologically Significant Area they occupy.

Common Name	Scientific Name	Conservation Designation	Habitat	Ecologically Significant Area
Ivory gull[1]	*Pagophila eburnean*	Endangered–SARA Endangered–COSEWIC Endangered–GNWT[2]	Ice-edge pack ice	Bathurst polynya, Herschel Island, Mackenzie Trough
Ross's gull	*Rhodostethia rosea*	Threatened–SARA Threatened–COSEWIC No Status–GNWT	Ice-edge pack ice	Bathurst polynya, Herschel Island, Mackenzie Trough
Pigheaded (blackline) prickleback	*Acantholumpenus mackayi*	Data Deficient–SARA Data Deficient–COSEWIC No Status–GNWT	Marine	Husky Lakes, Liverpool Bay, Kugmallit Trough, Herschel Island
Northern wolffish	*Anarchichas denticulatus*	Threatened–SARA Threatened–COSEWIC Threatened–GNWT	Marine	Albert Islands/Safety Channel/ Kagloryuak River
Bowhead whale[3]	*Balaena mysticetus*	Special Concern–SARA Special Concern–COSEWIC Special Concern–GNWT	Marine	Banks Island flaw-lead, Bathurst polynya, Mackenzie and Kugmallit Troughs, Liverpool Bay
Grey whale[4]	*Eschrichtius robustus*	Special Concern–SARA Special Concern–COSEWIC Special Concern–GNWT	Marine	Mackenzie Trough, Liverpool Bay
Polar bear	*Ursus maritimus*	No Status-SARA Special Concern–COSEWIC Special Concern–GNWT	Ice edge	Bathurst polynya, Banks Island flaw-lead

[1] The 2006 COSEWIC assessment of the ivory gull determined that it is endangered, and the species is currently being considered for addition to Schedule 1 of SARA.
[2] GNWT (2010).
[3] Bering–Chukchi–Beaufort population.
[4] Eastern North Pacific population.

Grey Whale: Grey whales migrate each year from their winter calving grounds in Mexico to their summer feeding areas in northern Alaska and the Bering Sea, and some migrate into the Canadian Beaufort Sea to feed. They occupy the marine habitat and frequent the Mackenzie Trough and Liverpool Bay (Cape Bathurst) Ecologically Significant Areas (Fig. 8). Although they are not as numerous as bowhead whales, they are important because they plough the sea floor, filtering the larger benthos and stimulating nutrient regeneration throughout the water column (COSEWIC 2004). They are designated as of "Special Concern" by SARA (Table 10) because of their susceptibility to underwater ship noise, collision with ships, and killer whales. Fishing activities would have to address these potential impacts under SARA.

4.2.9. Transboundary Issues

There are several reasons why an IFMP for the Canadian Beaufort Sea might consider transboundary issues: 1. Offshore fish stocks like Arctic cod move freely between the Alaskan and Mackenzie Beaufort shelves; 2. Ocean currents like the Beaufort Undercurrent, the Atlantic Current, and Alaskan Coastal Current move from west to east across the national boundary, whereas others such as the Beaufort Gyre travel east to west, carrying biological organisms as well as contaminants; 3. Marine mammals, such as bowhead, beluga, and occasionally killer and grey whales, migrate back and forth across the boundary; and 4. Many anadromous fish that are important for both Inuvialuit and Inupiat subsistence fisheries move across the boundary.

5. Impacts of Climate Change

5.1. Climate Change and Productivity

Fisheries Implications: *Recent research suggests that productivity of the Canadian Beaufort shelves will slowly increase because of a longer growing season and a larger open-water area in summer. Other factors include an enhanced frequency of upwelling and changes in wind patterns. However, there is a great deal of uncertainty about how much and how rapidly these changes will occur. Changes in the Mackenzie River are expected to impact the Canadian Beaufort Sea positively and negatively, but there is also uncertainty regarding future river flows.*

5.1.1. Expanded Growing Season

Although ice loss from the Beaufort Sea may be slower than for other parts of the Arctic Ocean, the trend is clear. Ice in the Beaufort Sea is expected to retreat earlier and farther offshore. The implications of ice retreat for the productivity of the Beaufort shelves are considerable, and they include the following aspects:

5.1.1.1. Larger Open-water Area

The dramatic loss of summer ice in the Arctic Ocean in 2007 (Fig. 3; see Section 3.2.1 *Ice Loss from the Arctic Basin*) has been attributed to a number of factors, the main ones being anomalous winds moving the ice rapidly out of the Arctic Ocean through the Fram Strait (Ogi and Yamazaki 2010) (30% effect), and stable air masses and cloud-free skies that allowed exceptional sunshine to shine on and melt an already weakened ice field (Kay et al. 2008) (70% effect). The exposed open water absorbed much more heat than when ice-covered, which led to further melting of the Arctic sea ice (Perovich et al. 2008), the well-known "ice-albedo" positive-feedback effect.

The decline in the extent of both summer and winter ice is expected to continue, mainly because of the ice-albedo feedback (Barber et al. 2008b), but also because the rapid loss of Arctic sea ice in recent years has created a fundamental change in the atmospheric circulation of the Northern Hemisphere that has also sped up the loss of sea ice (Serreze et al. 2009). Overland and Wang

(2010) described a second positive-feedback mechanism, acting from the newly open water to the atmosphere, which leads to further loss of ice. Heat stored in the Arctic Ocean during the summer open-water period is returned to the atmosphere in the following autumn, which has a direct impact on the temperature of the atmosphere over the Arctic. It has raised the temperature of about half of the depth of the lower atmosphere (the troposphere) by 1°C. This change has resulted in warmer, more easterly winds, especially north of Alaska and Canada, which lead to further warmer temperatures over the Arctic, and to advection of ice out of the Arctic Ocean through the Fram Strait. Indeed, the surface air temperature at Tuktoyaktuk has increased by 1.6 ± 0.4°C since 1974 (Melling et al. 2005; H. Melling, Institute of Ocean Sciences, Sidney, BC, Canada, V8L 5T5 personal communication).

5.1.1.2. Longer Growing Season

Over the decades to come, global warming will shorten the duration of the seasonal ice cover by earlier ice break-up and later freeze-up. Smith (1998) used satellite data, predominantly from the Beaufort Sea, to estimate that the melt season increased by ~5.3 days per decade from 1979–1996. Earlier break-up will significantly increase underwater light availability because ice now lingers through May and June, which are months of strong sunlight (Carmack and Wassmann 2006). In the autumn also, Brugel et al. (2009) measured significant primary production in the Beaufort Sea to the end of October. The growing season of the Beaufort Sea is slowly lengthening towards six months. Several years of continued reduction in ice cover between 2004–2007 caused the growing season of the Arctic Ocean to increase, in some areas, by as much as 100 days. This change was seen by satellite imagery as increases in the amount of chlorophyll-*a* in the sea (Arrigo et al. 2008). Seventy-percent of the increase was attributed to lengthening of the growing season. Most of the rest of the increase was caused by the increased open-water area available for photosynthesis. However, in the Beaufort Sea, a longer growing season does not guarantee higher productivity—that can only be attained if the longer growing season is accompanied by increased nitrate supply on the continental shelves.

5.1.2. Enhanced Upwelling

The main constraint on the productivity of the Beaufort shelves today is the low degree of vertical mixing in the water column, caused primarily by ice cover, and secondarily by the strong vertical salinity gradient that remains after the ice melts. The latter limits the transfer rate of nitrate into the upper productive layers of the ocean and, thus, constrains productivity. If currently ice-covered shelves continue to warm, and if ice cover retreats over the coming decades, then the constraints mentioned above will be relaxed, and it is possible that vertical mixing will be enhanced and productivity will increase. Carmack and Chapman (2003) suggested that a significant increase in upwelling can be expected when seasonal first-year ice retreats beyond the shelf slope-break. They suggested that shelf productivity is extraordinarily sensitive to the location of the ice edge in summer, which acts like a "switch" for the supply of nitrate to the shelf. When the ice edge remains shoreward of the shelf-break, upwelling is ineffective at bringing nitrate-rich Pacific water onto the shelf, and visa versa when the ice edge retreats well seaward of the shelf-break. The transition is abrupt, changing suddenly from one state to the other, for only moderate changes in the position of the ice edge. When this transition happens, Carmack and Chapman (2003) expected a 20- to 40-fold increase in the flux of nutrients onto the shelf. This increase would not necessarily translate into an equivalent increase in primary productivity, but it would certainly increase. Leong (2005) suggested a doubling of present levels of productivity for Arctic shelves in general. The position of the ice edge relative to the shelf slope-break is a condition that should be carefully monitored during the coming decades.

5.1.3. Variable Wind Effects

Winds in the Beaufort Sea have a strong effect on the productivity of marine waters on the continental shelves by mediating the following three processes (Williams et al. 2006):

***Estuarine Circulation*:** Estuarine circulation over the Mackenzie Shelf that enhances upwelling depends on easterly winds. Pickart et al. (2010) found, on average, that an easterly wind speed of 6–7 m s^{-1} results in a significant upwelling event in the Beaufort Undercurrent (Fig. 5), as measured by salinity changes. The upwelling lags the winds ~18 hours. In general, persistent high pressure over the southern Beaufort Sea creates a clockwise circulation over the Canada Basin, and easterly or northeasterly winds over the Mackenzie Shelf, which drive surface waters offshore and lead to upwelling. Upwelling generally leads to higher productivity on the Shelf. Easterly and northeasterly winds are generally persistent in April, May, and June, but become more variable in July and August. October also has strong easterly winds. Wind speeds in both the April–May and November–October periods at Tuktoyaktuk have been decreasing slightly over the past 50 years (Fissel et al. 2009).

Beaufort Gyre and Multi-Year Pack Ice: Winds over the Canada Basin drive the polar ice pack and the surface Polar-Mixed Layer beneath it to rotate in a clockwise direction in the Beaufort Gyre. When the rotation is strong, multi-year ice is retained in the Canada Basin and compressed against the Canadian Archipelago, causing heavier ice concentrations in the southwest Beaufort Sea (Barber and Hanesiak 2004). When the rotation is weak or anticlockwise, multi-year ice tends to be lost from the Canada Basin and moves out of the Arctic readily, through the Fram Strait east of Greenland. Ice conditions can have a strong effect on the productivity of the Beaufort shelves, increasing it particularly when multi-year ice is reduced by a weakening of the Beaufort Gyre.

The strength and direction of the Beaufort Gyre is controlled by wind patterns that are part of a much larger atmospheric circulation pattern, the Arctic Oscillation (AO). The AO is a repeating cycle in which high atmospheric pressure lies for 4–8 years over the Beaufort Sea (positive AO), and then moves for 4–8 years over Greenland (negative AO). When the AO is positive, ice is retained in the Beaufort Sea; when it is negative, ice tends to be lost from it (Proshutinsky et al. 2005). The causes of the AO are not well understood, but it is thought that the upper atmosphere over the Arctic is influenced by global atmospheric weather patterns (Serreze et al. 2009).

Coastal Erosion and Turbidity: Winds over the Mackenzie Shelf can erode coastlines, delivering sediment to the nearshore and suppressing productivity through increasing turbidity. Wind speeds generally increase in September over the Mackenzie Shelf, and the severest storms tend to occur between September and November, often blowing from the northwest (O'Brien et al. 2005). A common feature of the most damaging storms is the presence of open water, which limits the damping of both waves and the wind-driven storm surge by sea ice. In the Beaufort Sea, year-to-year variations in the duration and extent of the open water range from a few weeks and several kilometres of wind fetch, to 8–10 weeks and hundreds of kilometres of fetch, in late summer and early autumn. Coastal erosion is expected to increase (Jorgenson and Brown 2005) as the open-water season lengthens, the open-water area widens, storminess increases (Kolstad and Bracegirdle 2008), and sea level rises by ~3 cm per decade (Manson and Solomon 2010). Winds then create storm surges that severely erode the coastline, bringing large amounts of sediment onto the Shelf (Solomon et al. 1994, Huntington et al. 2007). The sediments are redistributed the following summer, increasing turbidity of the water, suppressing primary productivity, and smothering benthic organisms (Carmack and Wassmann 2006).

Uncertainties about Productivity: Firm predictions about productivity are difficult because scientists caution that present climate models are unable to project future wind conditions, or to project how increased air temperatures, ice melt, and freshwater runoff will influence the vertical stability of the water column. The degree of vertical mixing that will occur in the Arctic Ocean is thus uncertain; there are several factors associated with warming and ice melt that would both increase and decrease the stratification of ocean water on the shelves. For example, Tremblay et al. (2008) pointed out that increasing ice melt on the Arctic shelves will leave more fresh water in the upper water layers, which would increase stratification of the Arctic Ocean and tend to prevent mixing. They also suggested that, as surface waters become warmer, they also become lighter (increases stratification), but that a warmer climate will increase evaporation from the sea surface, making it saltier and heavier (decreases stratification). Polyakov et al. (2007) suggested that the export of multi-year ice from the Arctic is conducive to salinization, which should weaken stratification of the surface layer and make it more susceptible to mixing by storms.

This susceptibility is also increased by the lengthening of the ice-free period, which exposes surface waters to direct wind forcing during early spring or late autumn (Tremblay and Gagnon 2009). In summary, there are cautious predictions of increased productivity for Arctic continental shelves, surrounded by a considerable degree of uncertainty.

5.1.4. Mackenzie River Effects

Changes in the flow rate of the Mackenzie River could have significant effects on productivity of the Mackenzie Shelf. Increased river flow is likely to expand the estuarine habitat and associated food web along the inshore part of the Shelf, whereas decreased flow is likely to shrink it. Changes in the timing of the river freshet and river temperature may affect the regional climate by influencing the seasonal break-up of sea ice at the mouth of the Mackenzie River. The River melts landfast ice off the River mouth about two weeks earlier than anywhere else along the coast, and most of the melting is caused by warm water in the River that arrives about a week after water level peaks at the Arctic Red River (Dean et al. 1994).

Increased river flow is expected to freshen surface waters over the Shelf, increasing water-column stratification and tending to suppress mixing processes that would otherwise bring nutrients onto the Shelf. Increased flows during the winter might also increase regional ice extent in the Beaufort Sea (Mysak and Lin 1990). However, whether climate change modifications to the River will change the degree of vertical mixing in the ocean will largely depend on how changes in the freshwater balance interact with atmospheric forcing of the upper ocean.

Normally, the Mackenzie River does not deliver large amounts of dissolved inorganic nitrogen and phosphorous, which would fertilize productivity on the Shelf, but rising discharge and contributions of melted permafrost to effluent waters may increase the nutrient load in coastal waters. The effect, however, is likely to be local in nature because inorganic nutrients are consumed quickly by marine inshore waters. However, this scenario may not hold for dissolved organic nitrogen. Recent data from the southeast Beaufort Sea showed that, even after nitrate is exhausted from the water column, phytoplankton productivity continues, suggesting that another source of nitrogen is available, possibly derived from organic nitrogen delivered by the River. (see Tremblay and Gagnon 2009 for a discussion).

The effect of Mackenzie River sediments on light transmission in coastal waters and its impacts on the benthos have been mentioned in Section 3.4.4 *Dominance of Mackenzie River*. Further discussion of organic matter inputs to the Mackenzie Shelf by the River may be found in Section 3.6.3 *Estuarine Food Web*.

Carmack and Chapman (2003) suggested that, if current warming trends and predictions for the Arctic hold, then within 20 years the summertime retreat of the ice edge past the Shelf-break may occur every year over the entire Arctic Ocean, with significant physical and, especially, biological consequences. A shift toward temperate conditions could lead to erosion of large amounts of shallow-water sediments as the system adjusts to the new wave and river-plume climate. For example, if ice melts early, so that the Mackenzie River mouth has no ice cover during the spring freshet, then the shallow 2-m bar of sediment at the River mouth could be washed out, and the suspended sediment could reduce light penetration into Shelf waters (Carmack et al. 2006). Similarly, if ice forms later in the summer, the open water combined with north winds could cause rapid coastal erosion, suspended sediment in shallow water, and the blanketing of the sea floor with sediment. The latter will have a negative impact on benthic communities that will be smothered by increased sediment loads, and a negative impact on the nearshore pelagic community because increased turbidity will lower productivity. Carmack et al. (2006) predicted that the Arctic's nearshore sediments will become an unstable place.

Uncertainties about the Mackenzie River Flow: However, it is still uncertain whether the flow rate of the River will increase or decrease because of climate change. Climate models consistently indicate greenhouse gas loading will produce a net increase in streamflow across the Arctic Ocean drainage basin, owing primarily to an increase in total cold-season precipitation. This increase has been observed in Eurasian rivers, but not in North American rivers. Several Eurasian rivers show upward trends over the last century, but it is not clear that these observed trends are driven by precipitation (melting glaciers and permafrost could be alternatives). In contrast, Arctic discharge from much of Canada appears to be decreasing, with significant downward trends observed in several rivers. The tributaries of the Mackenzie, the Peace, and the Athabasca rivers, are among the rivers with declining discharge, although there has been no statistically significant change in the flow of the Mackenzie itself (see Finnis et al. 2009 for a discussion). Analysis of the annual discharge of 45 rivers draining northern Canada reveals a declining trend of 11% from 1964–1989, but since 1989, there has been an average increase in discharge of 15%. Flow records for the Mackenzie River and the Yukon River, which are most likely to impact the Beaufort Sea, however, suggested little change over the entire period (Dery et al. 2009).

Furthermore, there is disagreement about the future flows of the Mackenzie River. Climate models predict the annual flow of the Mackenzie River will increase by 21% by 2050 with climate warming (Manabe et al. 2004), but it is generally believed that climate warming will cause reduced Mackenzie River flows because increases in evapotranspiration as temperatures increase are expected to exceed any increases in precipitation (Rouse et al. 1997), and because glaciers that feed Mackenzie tributaries are receding (Schindler and Smol 2006).

5.2. Food-Web Restructuring

Fisheries Implications: *Food webs in all habitats in the Canadian Beaufort Sea will be impacted as ice conditions change. Polar bears and ringed seals are expected to decline, beluga and bowhead whales may be less affected, and killer whales and grey whales may increase. Changing environmental signals will impact migrating species like sea birds and anadromous fish that may find their migrations from one habitat mis-matched to environmental conditions in another. The Arctic will slowly be invaded by boreal fish and invertebrate species from the south, as is already observed in the Alaskan Beaufort Sea. Arctic cod may face increased competition from boreal species like capelin or from colonizing Atlantic cod. Phytoplankton body size may decrease, leading to a re-structuring of the size spectrum of the marine food web, with implications for productivity.. Evidence is emerging to suggest that marine food webs will shift in favour of the pelagic community at the expense of the benthic community. Last, continuing acidification of Arctic waters will prevent some species from sequestering calcium from sea water for use in their skeletons. There is much uncertainty about specific changes, but it is certain that food webs will be restructured as some species benefit and others suffer. A precautionary approach should be taken to commercial fishing because removal of Arctic cod, a keystone forage fish, from food webs would only increase stress on its major predators at a time when they are responding to major change.*

5.2.1. Ice-Adapted Species

Sea ice in its various forms acts as a platform, not only for the growth of ice-algae on the underside, but also for seals that raise their pups in birth lairs, and for polar bears that hunt seal pups on the ice (Stirling and Derocher 1993, Stirling et al. 1993). It is also an ice road for hunters and families to travel the sea and the land in winter (Huntington et al. 2007). Marine organisms require the ice to different degrees. Arctic cod feed on the epontic community on its undersurface, avoiding predators amongst its crevices. Polar bears use it for almost all of their seal hunting because they do not hunt in water. The most critical period for bears is in the spring when they gain most of their annual body fat. Bears may also use the ice for hibernation, as an alternative to sites on land. Ringed seals depend on the ice for birthing and rearing their pups in birth lairs beneath the snow. Newborn ringed seals are vulnerable to early ice break-up, which prematurely melts out their birth lairs, exposing them to weather and predation and decreasing their survival (Smith and Harwood 2001). Change in landfast ice extent or duration would have a direct influence on ringed seals and on the bears that hunt them.

Diving, fish-eating birds rely on the ice as a refuge in a different way. Thick-billed murres rely on floating ice to concentrate Arctic cod feeding and sheltering below it. For example, thick-billed murres in Hudson Bay find it more difficult to catch Arctic cod in years when there is little ice. Fish are more accessible to murres when they concentrate near the ocean surface in open-water leads beneath the ice (Dickson and Gilchrist 2002).

Bowhead and beluga whales have adapted to migrate from the Bering Sea into the Beaufort Sea to exploit key habitats and rich food resources. Their ability to move long distances beneath pack ice (Richard et al. 2001) frees them from predation by killer whales. Reduced ice cover might lead to an expanded range for killer whales, making them more prevalent in the Beaufort Sea to the detriment of bowhead or beluga whales (Carmack 2002).

Species that are most certain to change are those most tightly adapted to ice conditions. Arctic marine mammals, as long-lived species, are ill-equipped to respond quickly to rapid climate change. However, as Moore and Huntington (2008) pointed out, the less marine mammals depend on the ice, the more resilient they will be to change. Moore and Huntington (2008) grouped marine mammals from the Chuckchi Sea together with those from Beaufort shelves and concluded that:

1. Polar bear, ringed seal, and bearded seal are species reliant on sea ice as a platform for resting, breeding, and/or hunting, and will be affected negatively;
2. Beluga whale, bowhead whale, and spotted seal are species associated with sea ice and are adapted to the marine ecosystem of which ice is a key part, and would be affected both positively and negatively; and
3. Grey whales and killer whales are species that migrate seasonally but are obstructed by sea ice enroute, and would benefit.

A comparison by Laidre et al. (2008) came to similar conclusions, except these authors thought ringed seals and bearded seals would be among the marine mammals least affected by climate change, based on their circumpolar distributions, large population sizes, a varied diet, and flexible habitat requirements, compared with species that were more restricted in distribution, less abundant, or habitat specialists.

It is difficult to predict the response of each species to climate change because, so far, climate models do not deal effectively with local weather events and, even if they could, some species are likely to benefit in the short term from less severe ice, but in the long term will suffer from excessive loss of ice. For example, the body condition of polar bears and seals is known to decline in severe winters with heavy ice. Yet in warm years, seal pups are susceptible to warm springs and rain that destroys the birth lair where they rest, and warm springs with early ice break-up has forced polar bears off the ice in Hudson Bay before they have fully fattened. Warmer summers with less ice could have pervasive effects on other marine mammals (Laidre et al. 2008) if warmer summers encouraged the movement of predators like killer whales into the Beaufort Sea in large numbers.

5.2.2. Environmental Signals

Reist et al. (2006) emphasized the importance of the "coupling" of environmental signals, such as photoperiod and declining water temperature in the autumn, to initiate reproduction and migration in anadromous fish in the Beaufort Sea. They cautioned that "de-coupling" of signals will occur as the climate changes, with profound impacts on anadromous fish. For example, Arctic cisco hatch in the Mackenzie River, migrate west along the coast in a brackish corridor to the Colville River, where they mature, and then return to the Mackenzie (Gallaway et al. 1983, fig. 14). This complex migration pattern is intimately linked to the supply of fresh water and its distribution in coastal waters, which is partly controlled by the ice (Carmack 2002).

Dickson and Gilchrist (2002) suggested that a greater expanse of open water could cause storm tides to occur earlier in the year. Storm tides during egg incubation would detrimentally affect thousands of birds nesting in low-lying areas along the coast. This type of uncoupling of events will be exacerbated by a predicted sea-level rise (Maxwell 1997). It would increase frequency of flooding of the shallow spits, islands, and river deltas that are important nesting sites for many species. In the long term, there is no guarantee that lost coastal nesting habitat will be replaced because nesting habitat is determined largely by surficial geology (Boyd and Diamond 1994).

5.2.3. Range Extensions

Globally, the Arctic Ocean is expected to suffer the highest rates of species invasions, as species seek refuge from inhospitably high temperatures at lower latitudes. Concurrently, some localized species extinctions will occur because further northward migration is not possible (Cheung 2009). Southern fish and invertebrate species are often limited by water temperature in the northern part of their range. Perceptible increases in water temperatures in northern seas have led to northern range extensions for several species. Examples from a recent trawl survey on the Chukchi and Alaskan Beaufort shelves (Logerwell et al. 2010) are: Pacific cod (*Gadus macrocephalus*), walleye pollack (*Theragra chalcogramma*), festive snailfish (*Liparis marmoratus*), eyeshade sculpin (*Nautichthys pribilovius*), and bigeye sculpin (*Triglops nybelini*) (Logerwell et al. 2009).

In the Canadian Beaufort Sea, there is the possibility that Pacific salmon may be able eventually to compete with Arctic charr/Dolly Varden (Babaluk et al. 2000). Chum salmon are the most abundant salmon species in the area. By contrast, pink salmon are recorded infrequently and coho salmon have been reported only twice. Chinook and sockeye salmon have been harvested irregularly in small numbers since the 1990s. Climate change may eventually enhance the ability of Pacific salmon to colonize the Beaufort Sea, but there is presently no evidence of newly established populations, and insufficient data to say that salmon are increasing in frequency (Stephenson 2006).

Small temperature changes can have far-reaching effects. In the northern Bering Sea, a 2°C increase in bottom-water temperatures led to a northward shift of the pelagic-dominated marine ecosystem that was previously limited to the southeastern Bering Sea (Grebmeier et al. 2006b), with impacts on pelagic and benthic ecosystems, including marine mammals and sea birds. For example, the replacement of Arctic cod by capelin in the diet of thick-billed murres at Digges Island in Hudson Bay could foreshadow eventual changes in the Canadian Beaufort Sea. In a period of 15 years, the dominant forage fish changed from a polar species to a boreal one. The change was attributed to loss of sea ice and warming of the ocean (Fig. 17; Gaston et al. 2003).

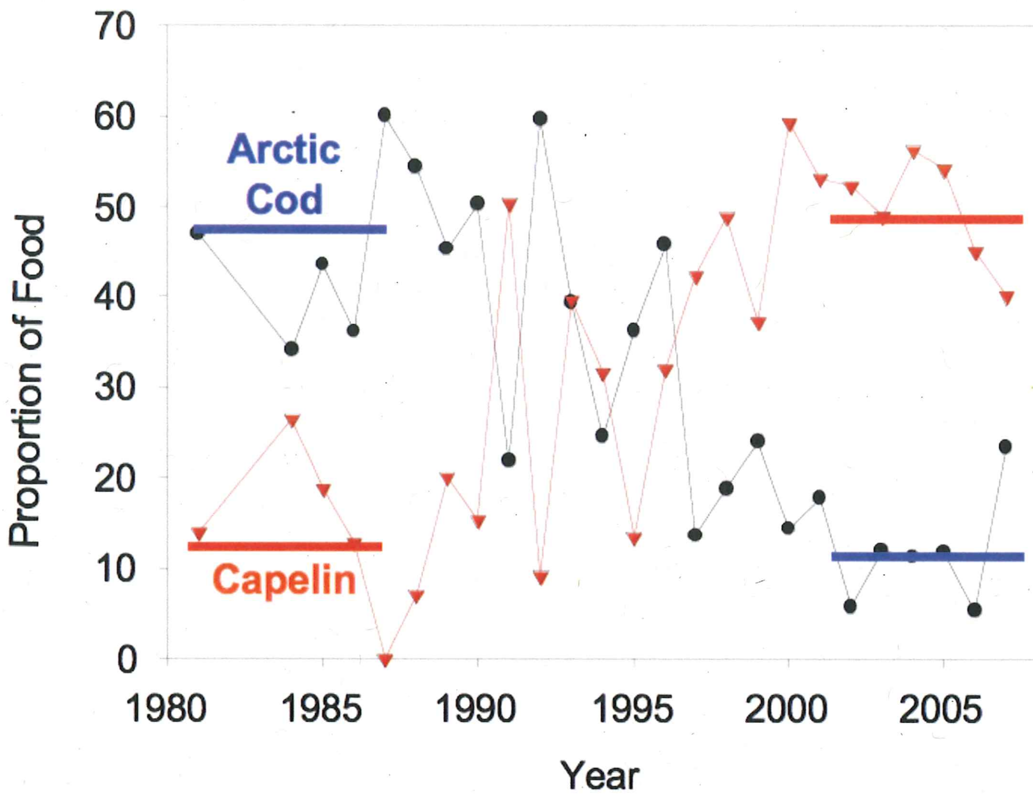

Figure 17. Proportion of Arctic cod *Boreogadus saida* and capelin *Mallotus villosus* fed to nestling thick-billed murres at Coats Island between 1981–2007. No data for 1982 and 1983. Horizontal bars are eye-fitted to first and last six data points. (Modified from Gaston et al. 2009.)

5.2.4. Food-Web Size Spectrum

As the climate warms, the earliest species to change may be the smallest ones with rapid life cycles that allow immediate responses to food-web structure and community composition. If the amount of fresh water increases in the upper layers of the Arctic Ocean, it is possible that vertical mixing will decrease. This decrease will lead to nutrient depletion, smaller phytoplankton cells and, thereby, to changes in the size of the herbivorous zooplankton, with consequences for the larvae of marine fish such as Arctic cod. Small phytoplankton cells are generally associated with nutrient-poor waters (Irwin et al. 2006), and the size of marine phytoplankton has decreased over geologic time in response to increasing marine stratification (Finkel et al. 2007).

Li et al. (2009) have already detected such a change in the Canada Basin of the Beaufort Sea. In just four years of increasing temperatures, large phytoplankton species have declined while smaller species ("picoplankton", <2 μm) have increased. As predicted, the warming Arctic Ocean has increased stratification and decreased nutrient levels. Smaller phytoplankton can maintain their position in the euphotic zone and absorb nutrients better than larger phytoplankton. This shift in the size structure of the phytoplankton community is expected to lead to an altered food web because the size structure of the planktonic community has a strong influence on the amount of carbon that can be exported (as fisheries harvest, or burial in the sediments) from the ecosystem. Marine systems based on picoplankton tend not to support large exports of biogenic carbon.

5.2.5. Distribution Changes

Climate change is expected to result in changes in the relative numbers or distribution of prey organisms. Even small changes can have large effects on predators and food webs. For example, in the Gulf of Alaska, warmer sea temperatures are thought to have affected the distribution of forage fish, causing mass starvation of >120,000 common murres (Dickson and Gilchrist 2002). In the Canadian Beaufort Sea, the reduction of ice cover on the Mackenzie Shelf is expected to affect zooplankton distribution patterns, to the potential advantage of *Pseudocalanus* spp. (Darnis et al. 2008). Arctic cod prey primarily on the naupliar stage of this copepod (Michaud et al. 1996, Last 1980), so initially at least, its proliferation should improve the early survival and population levels of the Arctic cod, increasing food availability for the food web that depends on this small fish. However, the larvae of Atlantic cod (*Gadus morhua*) also feed on the naupliar stages of *Pseudocalanus* spp. and, in the long term, the reduction of the sea-ice cover is predicted to bring about an "Atlantification" of the Canadian Arctic shelves and possibly the replacement of the present Arctic cod-dominated ecosystem by an Atlantic cod-dominated ecosystem (Barber et al. 2006).

5.2.6. Benthic/Pelagic Coupling

Climate change is likely to affect the productivity of the benthic community by changing the proportion of algal productivity reaching the sea floor, instead of being consumed in the water column by the pelagic community. High pulses of primary production seem to be exported to the sea floor when the ice melts late in the season. For example, Forest et al. (2010) found in Amundsen Gulf that the greatest downward export of particulate carbon was not during a year of protracted ice-free conditions, but rather in a year when the ice cover retreated late, starting eastward off Cape Parry. A similar pattern was found in the Bering Sea by Overland and Stabeno (2004), and Bluhm and Gradinger (2008) suggested that this pattern may be a generalized outcome of a warming climate. These authors suggested that continued warming of the Arctic Ocean and earlier ice melt will reduce the pulse of carbon to the benthic community, favouring the pelagic community instead. In the Canadian Beaufort Sea, warming would reduce food supplies to the benthic community of the flaw-leads and for those animals that depend on it, such as bearded seals, long-tailed ducks, and eiders. On the other hand, in the short term at least, warming will likely ensure that open-water leads in the Beaufort Sea do not close during the birds' spring migration, an occurrence that has led to mass mortalities in years with heavy ice and late thaw (Dickson and Gilchrist 2002). Some potential but unused habitat (e.g., cliffs along the coast of Banks Island) may become occupied should global warming increase the regional productivity or shift the ocean from a benthic (invertebrate)- to a pelagic (fish)-dominated system.

Examples of this type of food-web restructuring can already be seen in the Bering Sea (Grebmeier et al. 2006b), where the ice-dominated, shallow ecosystem favouring benthic communities and bottom-feeding sea ducks, such as spectacled eiders, and marine mammals including walrus and grey whales, is being replaced by one dominated by pelagic fish. Overland and Stabeno (2004) documented how benthic-feeding fish like Greenland halibut, sole, and flounder in the Bering Sea are being replaced by more pelagic groundfish like walleye pollack and Pacific cod.

5.2.7. Acidity

The Arctic Ocean is especially vulnerable to ocean acidification resulting from rising atmospheric carbon dioxide levels because carbon dioxide is more soluble in colder waters. Moreover, the brackish surface waters resulting from fresh waters discharged by rivers reduces the buffering capacity of the sea water. The concentration of carbon dioxide in the atmosphere is now ~383 parts per million, ~37% higher than before industrialization (Doney et al. 2009). “Because approximately one third of the CO_2 released has been absorbed by oceans, they are becoming more acidic. The uptake of CO_2 by seawater increases the concentration of hydrogen ions, lowering the pH and, in changing the chemical equilibrium of the inorganic carbon system, reduces the concentration of carbonate ions (CO_3^{2-}). Carbonate ions are required by marine calcifying organisms to produce calcium carbonate ($CaCO_3$) shells and skeletons. Therefore, the effects of decreased CO_3^{2-} concentrations on marine organisms may place some species at risk” (Yamamoto-Kawai et al. 2009, p. 1098) because they will have difficulty building their shells. Organisms most affected will be shellfish such as clams, mussels, and oysters, cold-water corals, coralline algae, starfish, sea urchins, various plankton groups such as pteropods, and foraminiferan and coccolithophore algae (Fabry et al. 2009). However, not all calcifying species will be affected the same. Very few organisms have been tested so far, but of 45 tested, 28 were affected negatively, and 14 were affected positively (Doney et al. 2009). The implication for productivity on the Beaufort shelves is significant, given the dominance of shell-building mollusks and echinoderms comprising the benthos.

Ocean water that is “undersaturated” with either the aragonite or the calcite forms of calcium carbonate becomes unfavourable for shell-building organisms. Climate models predict that 5% of the Arctic Ocean will become undersaturated in aragonite calcium carbonate within 4–7 years, and this proportion will rise to 50% in 30–40 years. The beginning of this phenomenon has already been detected in the Beaufort Sea (Yamamoto-Kawai et. al., 2009). These authors attribute this early loss of carbonate from Arctic waters to the recent extensive melting of sea ice in the Canada Basin, and to the retreat of the ice edge well past the shelf-break, allowing deep, aragonite-undersaturated water to upwell onto Arctic continental shelves. Yamamoto-Kawai et al. (2009) expected that populations of both planktonic and benthic calcifying organisms in the Canada Basin are now being affected because of the rapid decrease in carbonate availability. These groups are important elements of the food web, so the Arctic ecosystem requires close observation to predict possible impacts on marine organisms, fisheries, and biogeochemical cycles.

Doney et al. (2009, p. 18) also suggested that “photosynthesis rates of some cyanobacteria may be enhanced under elevated aqueous CO_2, especially in conjunction with warming, and that there may be a wide range of possible effects on nutrient cycling, including increased nitrogen fixation rates. Phytoplankton growth may also be influenced by CO_2-driven changes in acid–base chemistry and trace metal availability. Similarly, the pH gradient across cell membranes is coupled to numerous critical physiological/biochemical reactions within marine organisms, ranging from such diverse processes as photosynthesis, to nutrient transport, to respiratory metabolism. [However,] the impact of ocean acidification on this biochemistry is barely understood".

Another effect of ocean acidification is that low-frequency sound will travel further underwater. A decrease in pH of 0.3 units will cause a 40% increase in sound transmission because there will be fewer carbonate and borate ions to absorb underwater sound. To put this into a time perspective, the pH in the central Pacific Ocean has dropped ~0.05 units in the past 17 years, and it is estimated that sound will travel 70% further underwater by 2050 (Brewer and Hester 2009). This change has obvious implications for whales but it is unknown how marine mammals will respond. Sound transmission will be easier, but background noise will also be higher at the lower frequencies of the marine mammal communication range.

5.3. Climate Change Uncertainties

There is great uncertainty about the impact of climate change on marine ecosystems. The *Marine Systems* chapter of the Arctic Climate Impact Assessment report (ACIA 2005, Leong 2005, p. 454) stated: "Climate change scenarios for the [Arctic] ocean are very uncertain as most models focus mainly on changes in the atmosphere. Such models are not definitive about changes to ocean circulation, deepwater formation, or the fate of major ocean fronts. Therefore, the conclusions drawn in this chapter regarding likely changes in the marine ecosystem are based on scenarios determined from the projected changes in the atmosphere coupled with the present understanding of how atmospheric forcing influences the ocean, as well as the output from a few ocean models".

Nevertheless, ACIA (2005) does make predictions about changes in the atmosphere (Table 11) and in the ocean (Table 12). These predictions are meant to apply to the Arctic marine system as a whole, rather than to any specific locale.

ACIA (2005) predicted that, by 2020, the annual mean air temperature would rise by 1–1.5°C, and most of the warming will occur in the winter. Storm intensity may increase in the Beaufort Sea, and the effects of winds will be stronger where sea ice retreats. A 2% increase in precipitation and a 5-cm rise in sea level are predicted. Continental shelves are expected to be ice-free during the summer by 2020 (more recent work suggests 2050 ± 20 years; Barber et al. 2008a) with a 6–10% reduction in the extent of ice in the winter. The ice-free season will be longer by 10 days. The depth of the Polar-Mixed Layer will deepen in areas with reduced ice cover and increased winds. Light will increase in duration and extent as ice retreats, and nutrients will increase substantially on shelves where the ice retreats beyond the shelf slope-break.

ACIA (2005) did not address specific predictions to the unique features of the Beaufort shelves, such as the Mackenzie River and its drainage basin, the Beaufort Gyre and its influence on ice conditions, or the Beaufort Undercurrent and its effect on productivity. Local predictions for the Canadian Beaufort Sea have even less certainty than ACIA predictions for the whole Arctic. ACIA (2005) stated: "Present climate models are unable to project future wind conditions, or to project how increased air temperatures, ice melt, and freshwater runoff will influence the vertical stability of the [Arctic Ocean] water column. The amount of vertical mixing that will occur is thus uncertain. Such information is required in order to project the effects of climate change on vertical heat and nutrient fluxes" (Leong 2005, p. 521); and "Projections of change in the Bering, Chukchi, and Beaufort Seas, the Canadian Archipelago, Baffin and Hudson Bays, and the Labrador Sea are highly uncertain as many important aspects of these regions (e.g., the presence of fast ice, strong seasonality, complex water mass structure, through flow) are not included in the current global climate models. The following discussion is thus highly speculative. These seas are expected to experience the general changes in sea ice, sea surface temperature, mixed-layer depth, currents, fronts, nutrient and light levels, air temperature, winds, precipitation and runoff, sea level, and cloud cover summarized in [Table 11 and Table 12], **but owing to their more southerly latitude and contact with terrestrial systems, the changes may be greater and perhaps faster**" (Leong 2005, p. 476; Mathias bold).

Regardless of the uncertainties, it seems very likely that the habitats, food webs, and patterns of nutrient flow of the Beaufort shelves will shift, just as they already have in the more southerly Bering Sea and Hudson Bay, subjecting some species to great stress. It would be prudent to minimize additional stress on food webs and species to maximize their resilience for re-organizing and adapting to the changing climate. Commercial fishing on the Beaufort shelves at this time would likely stress existing food webs.

Table 11. Changes in surface and boundary forcing based on model projections and/or extrapolation of observed trends. Unless otherwise specified, these projected changes are very likely to happen. (From Leong 2005.)

	2020	2050	2080
Air temperature			
Annual mean[1]	1–1.5°C increase	2–3°C increase	4–5°C increase
Winter	2.5°C increase	4°C increase	6°C increase in the central Arctic
Summer	0.5°C increase	0.5–1.0°C increase	1°C increase
Seasonality	Reduced seasonality (warmer winters compared to summer)		
Interannual variability	No change	No change	No change
Wind			
Means	Although changes in winds are expected, there is at present no consistent agreement from general circulation models as to the magnitude of the changes in either speed or direction		
Storm frequency	Possible increase in storm intensity regionally (Labrador, Beaufort, Nordic seas); in general, winter storms will decrease slightly in intensity because the pole-to-equator temperature gradient decreases		
Storm tracks	Probable northward shift in storm tracks		
Regional issues	In areas of sea-ice retreat, there will be an increase in wind-driven effects (currents, waves) because of longer fetch and higher air–sea exchange		
Precipitation/runoff			
Mean[2]	2% increase	6% increase	10% increase
Seasonality	Decreased seasonality in runoff related to earlier snow melt. Seasonality in precipitation unclear		
Snow on ice	1–2% increase	3–5% increase	6–8% increase
Sea level	5 cm rise	15 cm rise	25 cm rise
Cloud cover			
General	3% increase	5% increase	8% increase
Spring, autumn	4–5% increase	5–7% increase	8–12% increase
Winter, summer	1–2% increase	3–5% increase	4–8% increase
Cloud albedo	Not available	Not available	Not available

[1] These numbers are averages and should be higher in the central Arctic and lower over southern regions.
[2] Based on the estimates of precipitation minus evaporation in Chapter 6 of ACIA (2005).

Table 12. Summary of changes projected in ocean conditions according to the five ACIA-designated models relative to baseline conditions. Unless otherwise specified, these projected changes are very likely to happen. THC refers to Thermohaline Circulation. (From Leong 2005.)

	2020	2050	2080
Sea ice			
Duration	Shorter by 10 days	Shorter by 15–20 days	Shorter by 20–30 days
Winter extent	6–10% reduction	15–20% reduction	Probable open areas in High Arctic (Barents Sea and possibly Nansen Basin)
Summer extent	Shelves likely to be ice-free	30–50% reduction from present	50–100% reduction from present
Export to North Atlantic	No change	Reduction beginning	Strongly reduced
Type	Some reduction in multi-year ice, especially on shelves	Significant loss of multi-year ice, with no multi-year ice on shelves	Little or no multi-year ice
Landfast ice	Possible thinning and retreat in southern regions	Probable thinning and further retreat in southern regions	Possible thinning and reduction in extent in all Arctic marine areas
Sea surface temperature			
Winter/summer (outside THC regions and depending on stratification and advection)	An increase by about the same amount as the air temperatures in ice-free regions No change in ice-covered regions		
Seasonality	All shelf seas to undergo seasonal changes	30–50% of Arctic Ocean to undergo seasonal changes	50–100% of Arctic Ocean to undergo seasonal changes
Mixed-layer depth	Increase during summer in areas with reduced ice cover and increased wind		
Currents	In regions affected by THC, modifications to the THC will change the strength of the currents		
Ocean fronts	Fronts are often tied to topography but, with altered current flows, may rapidly shift their position		
Light exposure	With decreasing ice duration and areal extent, more areas to be exposed to direct sunlight		
Nutrient levels	Substantial increases over the shelf regions due to retreat of the sea ice beyond the shelf-break	High levels on shelves and in deep Arctic basins; higher levels due to deeper mixed layer in areas of reduced ice cover	

6. IFMP Recommendations

Fisheries Research:

1. The development of an IFMP for the Canadian Beaufort Sea is difficult without adequate information about the density, abundance, and biomass of fish on the continental shelf (Section 4.2 *Information Needs*). To rectify this deficiency, a standardized pilot survey should be carried out, ideally on the two open-water shelves: one on the Mackenzie Shelf and one in Amundsen Gulf. Different sections of the water column should be sampled. Demersal fish and benthic invertebrates should be assessed using standardized bottom trawl gear and methods. Pelagic fish abundance should be assessed using hydro-acoustics and midwater net tows. At the same time, the distribution of zooplankton should be sampled with small-meshed bongo nets and physical oceanographic data should be collected with conductivity-temperature-depth instruments. A stratified sampling scheme should be used and the depth range sampled should be consistent with the capability of commercial fishers. The value of sampling results would be considerably enhanced if methods conformed to a survey recently carried out on the Alaskan Shelf (see Logerwell et al. 2010, for methods).

2. There is evidence that the Beaufort Undercurrent transports Arctic cod into Franklin Bay, which acts as a retention mechanism so that cod can take advantage of early ice break-up in the Bathurst polynya of Amundsen Gulf. Research should continue to elucidate the role of the Beaufort Undercurrent, Franklin Bay, the polynya, and even the potential role of the Beaufort Gyre in Arctic cod migration and life-history patterns.

Food-Web Research:

1. Analysis of food webs on the Canadian Beaufort shelves indicates that Arctic cod is a keystone forage species that supports a wide variety of dependent predators (Section 3.6 *Food Webs*. Many of these predators are important for Inuvialuit subsistence. For some predators like beluga whales, Arctic cod is a major prey. Arctic cod should remain at its current carrying capacity to maintain the food-web structure of the marine ecosystem. To assess the potential impact of a fishery on dependent marine predators, existing monitoring programs for beluga whales, ringed seals, and Arctic charr/Dolly Varden should be continued. Monitoring could be expanded to include pelagic-feeding seabird predators like guillemots and murres, and possibly benthic-feeding sea birds such as eiders and long-tailed ducks. Analysis of stable isotopes and fatty acids in the food web (e.g., Loseto et al. 2009a,b), predator stomach analysis, and condition metrics should be used to monitor predator dependence on Arctic cod. Arctic cod abundance from systematic surveys should be combined with integrated modeling approaches (e.g., Wieckowski et al. 2010) to assess potential impacts of fishing on pelagic food webs. The recent Beaufort Ecosystem Research Initiative announced by DFO (http://www.dfo-mpo.gc.ca/science/publications/article/2010/05-10-10-eng.html) is a promising approach for integrating some of the above information. As Bluhm and Gradinger (2008, p. S93) pointed out: "In our view, only holistic ecosystem monitoring approaches, combining ocean-observing systems and Arctic [predator] and prey distribution and biomass surveys with modeling efforts, will provide the tools to detect, predict, and evaluate [ecosystem-level] changes in the next decades".

2. The benthic community is poorly understood, particularly its productivity compared to the pelagic community, relationships within the benthic food web, and inter-relationships between benthic fauna and demersal fish and invertebrates. To assess the potential impact of fishing on the benthic community, studies of food-web relationships of the benthic community and demersal fish should be carried out using standard stomach-content studies, and stable isotope and fatty acid analysis.

Habitat Research:

1. The upwelling area at Cape Bathurst (Fig. 10) should be a research priority because, as an area of enhanced productivity, it would be targeted by a potential commercial fishery. Its distinctive and abundant benthic fauna, and its value as an Ecologically Significant Area for bowhead whale (and occasionally grey whale) feeding, could be compromised by bottom trawling. As an area of enhanced upwelling, it may serve as a model for the potential effects of climate change on increased shelf-break upwelling. Relationships between primary productivity, benthic/pelagic coupling, and secondary productivity at this site should be clarified.

2. The importance for Arctic cod of the Cape Bathurst hotspot, and at other hotspots such as frontal systems off the Mackenzie Shelf-break and at Mackenzie and Kugmallit troughs, should be examined with hydro-acoustic gear, pelagic trawls, and satellite imagery (Belkin et al. 2008, 2009).

Ecosystem Research:

Fisheries productivity is low, limited by a short growing season, and by nitrogen during the open-water season. Fisheries productivity is expected to increase with primary productivity in response to climate change. The main forcing factors on primary productivity of the Canadian Beaufort shelves are: 1. the position of the summer ice edge in relation to the shelf-break, 2. the open-water wind speed and direction as it affects upwelling, vertical mixing, and coastal erosion, and 3. changes in the Mackenzie River flow rate, timing of the freshet, and organic carbon and nitrogen loading to the shelves. These forcing factors should be monitored on a long-term basis, and related to atmospheric and climatic forcing, with a view to forecasting change in the productivity of the Canadian Beaufort Sea ecosystem.

Measurement Issues:

1. In view of the uncertainty surrounding the long-term trends in ice concentration, ice extent, and ice thickness in the Canadian Beaufort Sea, and their implications for commercial fishing on the Canadian Beaufort shelves, it is recommended that scientific issues around satellite measurements be resolved, and that monitoring of ice by moored upward-looking sonar or by satellite on the shelves be continued.

2. There is a wide discrepancy in the estimates of primary productivity measured by satellite imagery of chlorophyll-*a* in surface waters and estimates made by shipboard methods of various kinds. Satellite measurements of primary productivity in the Beaufort Sea are five times higher than estimates from shipboard measurements. For example, the Beaufort Sea is considered a Class II, moderately productive ecosystem, with productivity estimated by satellite at 150–300 $g\ C\ m^{-2}\ y^{-1}$ (Belkin et al. 2008), whereas shipboard measurements

estimate primary productivity at 30–70 g C m^{-2} y^{-1}. This discrepancy remains unresolved, although it is well known that turbidity can interfere with chlorophyll-*a* measurements from satellite, and turbidity from the Mackenzie River can extend as far offshore as the shelf slope-break in the Beaufort Sea. Research should be continued to resolve this measurement issue because satellite measurements offer a valuable synoptic view and considerable savings over shipboard measurements in assessing productivity in the Beaufort Sea.

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8. Appendices

8.1. Acronyms Used in this Report

ACIA – Arctic Climate Impact Assessment
AO – Arctic Oscillation
BSStRPA – Beaufort Sea Strategic Regional Plan of Action
CASES – Canadian Arctic Shelf Exchange Study
CFL – Circumpolar Flaw-Lead system study
COSEWIC – Committee on the Status of Endangered Wildlife in Canada
DFO – Fisheries and Oceans Canada
EBSA – Ecologically and Biologically Significant Area
FJMC – Fisheries Joint Management Committee
IFA – Inuvialuit Final Agreement
IFMP – Integrated Fisheries Management Plan
IOM – Integrated Ocean Management
IPCC – Intergovernmental Panel on Climate Change
IPY – International Polar Year
LOMA – Large Ocean Management Area
MGP – Mackenzie Gas Project
MPA – Marine Protected Area
NOAA – National Oceanographic and Atmospheric Administration
NOGAP – Northern Oil and Gas Action Program
PERD – Program of Energy Research and Development
SARA – Species at Risk Act
SHEBA – Surface Heat Budget of the Arctic Ocean
THC – Thermohalene circulation

8.2. Ecologically Significant Areas

List of areas with high ecological or biological significance in the Canadian Beaufort Sea. Data summarized from Cobb et al. (2008, sec. 17) and DFO (2004b).

Area	Physical Element	Ecological Significance
Herschel Island/ Yukon North Slope[1] Includes the Firth River mouth, Herschel Island and the Yukon North Slope south along the coastline to the opening of Shallow Bay	Corridor of fresh water from shore to 120 km creates estuarine conditions, moving west to east	Estuarine habitat along the coast is a migration and feeding area for anadromous fish
	Sandy barrier islands close to shore and sand spits provide shallow, protected water for wading birds	Major staging/feeding area for thousands of phalaropes and brant
	Steep seabed slope into the Mackenzie Trough causes boundary between water masses or upwelling of nutrients, stimulation of productivity	Feeding area for beluga, bowhead whale High density of benthos and zooplankton
	Abandoned human dwellings provide nesting sites for sea birds in absence of cliff habitat	Black guillemot nesting in abandoned human dwellings feed young with fish
	Ice flaw-lead is frequent here	Polar bear breeding and denning area
Shallow Bay[1] Mouth of Shallow Bay and southern Mackenzie Bay	Freshwater/saltwater mixing zone at western mouth of Mackenzie River provides fresh water, heat, gravel sediments	Feeding, calving, and skin-rubbing area for beluga whale
	Freshwater and saltwater mixing zone in shallow water	Feeding area for herring Migration area for anadromous fish, white-fronted goose
Mackenzie Trough[2] Extends from the 50-m– 300-m depth contour	Mackenzie Trough, 530 km long, 35 km deep, and 120 km wide, cuts across the continental shelf from 50 m depth to 300 m depth, and provides conduit for nutrient-rich deep water to penetrate onto the Shelf, stimulating productivity	Feeding area for bowhead whale in summer Breeding and feeding area for polar bear in late autumn and winter
Beluga Bay[1] Western mouth of the Mackenzie River within the 10-m depth contour	Shallow-water area surrounded by islands provides productive refuge from killer whales	Feeding, calving, and skin-rubbing area for beluga whale
	Mackenzie River provides land-based carbon and nutrients to raise productivity	Migration staging area for tundra swan and brant
		Feeding area for herring
	Land-fast ice zone	Polar bear denning area
Beaufort Sea Shelf-Break[2] The outer length of the continental shelf in the Beaufort Sea Island as a corridor	Upwelling of nutrient-rich Pacific water onto the Shelf; periodic fertilization of Shelf waters	Feeding area for bowhead whale
	Region of pack ice	Feeding area for polar bear

List of areas with high ecological or biological significance in the Canadian Beaufort Sea. Data summarized from Cobb et al. (2008, sec. 17) and DFO (2004b) – *continued.*		
Area	**Physical Element**	**Ecological Significance**
Kugmallit Corridor [1] Kittigazuit Bay north to the Kugmallit Trough at 50 m depth; within Toker Point and Summer Island as a corridor	Sediment deposits at James Shoal	Beluga nursery and rubbing area
	Freshwater plume from east branch of Mackenzie River during open-water season; in winter, freshwater Lake Herlinveaux lies beneath the ice	Feeding area for herring and feeding and overwintering area for anadromous fish
	Underwater pingos, gas vents, and ice scours	Feeding area for ringed seal
Husky Lakes[1] Entire Husky Lakes area	Unique estuary	Breeding/nursery area for brant
	Gravel shoals, strong tidal flows	Spawning area for herring
Liverpool Bay[1] Includes Liverpool Bay, area west of Baillie Island and Cape Bathurst to the depth of the 50-m contour	Upwelling of nutrient-rich Pacific water onto Shelf; periodic fertilization of Shelf waters	Rich benthos provide feeding area for sea ducks and staging area for migratory birds such as brant and tundra swan
	Topographic oceanic eddies appear west of Baillie Island, causing upwelling of nutrient-rich Pacific water	Area of high primary productivity
Horton River[2] Western coast of Franklin Bay	Sea bed slopes steeply causing upwelling of deep nutrient-rich water near estuary of Horton River	High productivity area, rich benthos, and feeding area for Arctic charr
Hornaday River[1] **and Pearce Point**[2] Southern end of Darnley Bay near Paulatuk, including Hornaday and Brock river systems	Large coastal estuary system	Feeding area for Arctic charr, bowhead whale, and ringed seal Spawning and feeding area for herring
De Salis Bay[1] Southern end of Darnley Bay	A shallow, highly stratified, breached-lake, tidal basin with dense hypersaline water at depth (Bennett et al. 2009)	Nursery area for brant and sea duck Feeding area for seal, beluga, and bowhead whale Large schools of Arctic cod observed
Thesiger Bay[1] Extends offshore from Cape Kellet to Cape Lambton, including Sachs Harbour	Major flaw polyna with ice edges	Spawning and feeding area for capelin
	Freshwater and marine habitats	Feeding area for sea duck, seal, and polar bear

List of areas with high ecological or biological significance in the Canadian Beaufort Sea. Data summarized from Cobb et al. (2008, sec. 17) and DFO (2004b) – *continued.*

Area	Physical Element	Ecological Significance
Walker Bay[2] and **Minto Inlet**[2] Includes Ramsay Island and extends from Berkeley Point to Cape Peter; south coastline of Minto Inlet from Kuujjua River to Cape Ptarmigan	Large coastal estuary; freshwater and saltwater mixing	Denning area for seal and polar bear Rearing and feeding area for capelin and sea duck
	Large coastal estuary; freshwater and saltwater mixing	Migration route for Arctic charr and migratory birds
Albert Islands[1]**/Safety Channel**[1] Includes Queen Bay, Jack Bay, and the Albert Islands; eastern part of Prince Albert Sound, including the Kuuk and Kagloryuak rivers	Estuarine sound with freshwater and saltwater mixing	Migration route for Arctic charr, migratory birds Feeding area for Arctic charr, seal, and whitefish
	Location of flaw-lead and ice edges in land-fast ice	Feeding area for capelin and sea duck Feeding and denning area for seal and polar bear
Cape Bathurst Polynya[1] General area of entrance to Amundsen Gulf; boundary varies	Ice polynya with open water and ice edges in winter. Mackenzie flaw-lead extends west to Herschel Island	Feeding area for ringed seal and polar bear
Viscount Melville Sound[2] Eastern extent of McClure Strait to W 110°, the easterly LOMA boundary	Deeper water area within McClure Strait	Beluga males migrate hundreds of km to this area and repeatedly dive to the sea floor to feed
Banks Island Flaw-Lead [2] Area off western shore of Banks Island	Ice flaw-lead with open water and ice edges in winter	Feeding area for migrating sea birds, sea ducks, and for ringed seal and polar bear

[1] These areas are designated as Ecologically and Biologically Significant Areas (EBSAs) by Cobb et al. (2008) using evaluation criteria from DFO (2004b) and available information.
[2] There is sufficient information to conclude the area is likely an EBSA, but insufficient information exists to complete an evaluation.