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ORIGINAL PAPER

The first demersal trawl survey of benthic fish and invertebrates in the Beaufort Sea since the late 1970s

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Abstract This study represents the first demersal trawl survey of marine fishes and invertebrates in offshore waters of the Beaufort Sea since 1977. Species composition, distribution, and abundance of demersal fish and benthic invertebrates were assessed with standard methods and demersal trawl gear by the Alaska Fisheries Science Center. Fishes made up 6% of the total catch weight, and invertebrates made up the remaining 94% of the catch weight. A total of 32 species of fish were identified, two taxa were identified to genus and one to family, and 174 taxa of invertebrates were identified. The most abundant demersal fishes were polar cod (*Boreogadus saida*), eelpouts (*Lycodes* spp.), Bering flounder (*Hippoglossoides robustus*), and walleye pollock (*Theragra chalcogramma*). The most abundant invertebrates were notched brittle stars (*Ophiura sarsi*), snow crab (*Chionoecetes opilio*), mussels (*Musculus* spp.), and the mudstar (*Ctenodiscus crispatus*). We documented or confirmed extension to the known ranges of four species of fishes: walleye pollock, Pacific cod (*Gadus macrocephalus*), festive snailfish (*Liparis marmoratus*), and eyeshade sculpin (*Nautichthys pribilovius*). We also documented the presence of commercial-sized snow crab (*Chionoecetes opilio*), which has not previously been recorded in the North American Arctic.

Keywords Beaufort Sea · Marine fishes · Snow crab · Polar cod · *Boreogadus saida*

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Introduction

Trends of ocean warming and declines in Arctic sea ice increase the potential for the northward migration of fish and invertebrate species from the North Pacific ecosystem to subarctic and Arctic ecosystems (IASC 2004; Grebmeier et al. 2006a, b; Mueter and Litzow 2008; Mueter et al. 2009). A change from Arctic to subarctic conditions in the northern Bering Sea is taking place, with a shift from benthic communities to communities dominated by pelagic fish species (Grebmeier et al. 2006a, b). Similar changes have already been documented in many Atlantic and North Sea fish communities, which has shown a northward trend in distributions over the last several decades (Beare et al. 2004; Perry et al. 2005). The effects of recent record-breaking ice recessions in the Arctic (Stroeve et al. 2007, 2008; Greene et al. 2008; Boe et al. 2009) on marine fish communities are unknown because data are limited or nonexistent. In addition to ocean warming, Arctic shelves are likely to be impacted by exploration and development of oil and gas resources (MMS 2008; Gautier et al. 2009). Currently, several million acres have been leased for oil and gas exploration in the Chukchi and Beaufort seas (MMS 2008). There are several potential impacts on marine organisms as a result of oil and gas exploration, such as seismic exploration (Engås et al. 1996; Slotte et al. 2004), and building and operating subsea pipelines or oil spills (Boesch and Rabalais 1987). In the context of climate change and the shifting of marine ecosystems, increases in anthropogenic activities such as oil and gas development, and potential fisheries development, we conducted a survey of the Beaufort Sea shelf in 2008. Our aim was to contribute to a baseline for future monitoring of offshore marine fish and invertebrate communities in this Arctic ecosystem.

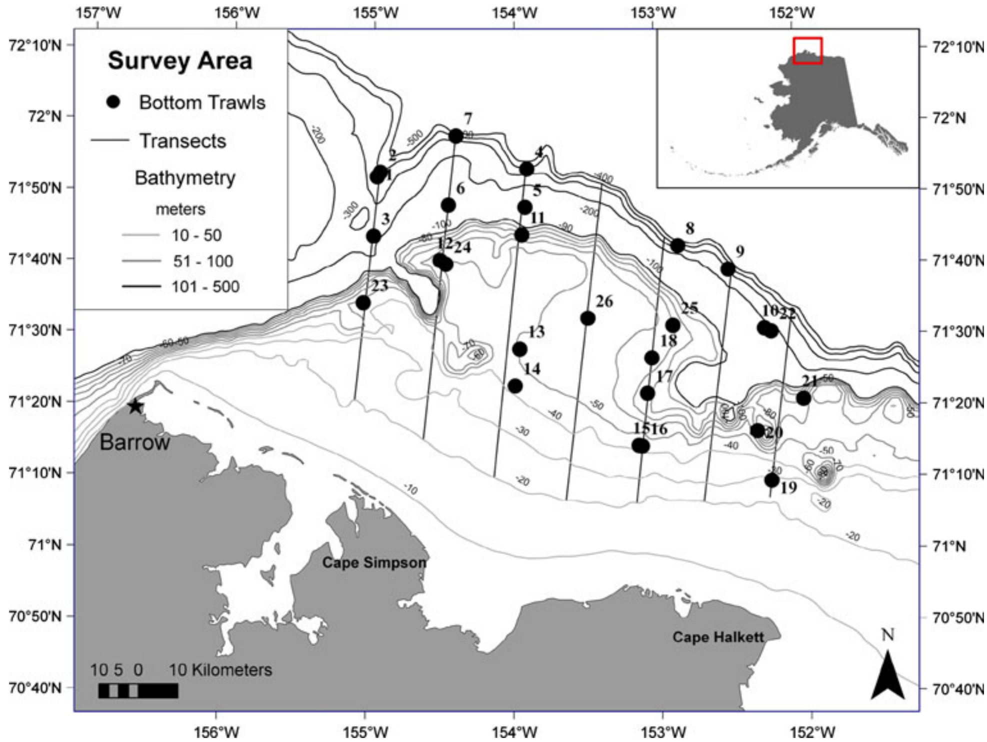

Fig. 1 Demersal trawl locations and transects, Beaufort Sea, August 2008. Demersal trawl numbers are also shown

The first survey of Beaufort Sea offshore marine fishes was conducted opportunistically from a US Coast Guard cutter during 1977 (Frost and Lowry 1983). The survey focused on fish and benthic invertebrates in the offshore from west of Point Barrow to the Canadian Beaufort Sea border (Frost and Lowry 1983). In 1977, polar cod (*Boreogadus saida*) was the dominant fish species captured, followed by the Canadian eelpout (*Lycodes polaris*) and twohorn sculpin (*Icelus bicornis*). The majority of subsequent fish studies in the Beaufort Sea focused on anadromous fishes in estuaries, inlets, river deltas, or lagoons (Bond and Erickson 1997; Gallaway et al. 1997; Jarvela and Thorsteinson 1997; Underwood et al. 1997; Moulton and Tarbox 1987). A few studies have examined the occurrence of marine fishes in nearshore waters (<20 m deep), often in the transition zone between marine and brackish waters (Craig et al. 1982; Craig 1984; Moulton and Tarbox 1987; Jarvela and Thorsteinson 1999).

The 2008 Beaufort Sea survey was the first dedicated survey of offshore marine fishes and invertebrates using demersal trawl gear and standard survey methods as conducted by the National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center (AFSC). This technique allowed the density of demersal fishes and benthic invertebrates to be quantified in a way that is comparable to contemporary standardized surveys of the Bering and Chukchi seas. The 2008 survey was designed to document the distribution and abundance of key ecological species, particularly polar cod (*Boreogadus saida*). Polar cod are important prey for seabirds and marine mammals and are in turn important consumers of secondary production (Frost and Lowry 1981, 1983; Bradstreet et al. 1986; Jarvela and Thorsteinson 1999). To assess differences and similarities between Arctic and North Pacific ecosystems, we compare this survey's results with the 2008 NMFS-AFSC demersal survey of the Bering Sea (Lauth and Acuna 2009) and the most recent NMFS demersal survey in the Chukchi Sea (Barber et al. 1997). To identify possible changes in the Beaufort Sea over the last 30 years, we compare our results to those of the 1977 Beaufort Sea survey (Frost and Lowry 1983). We also examine our results in the context of known species ranges and document northerly range extensions for some species.

Materials and methods

Survey area

The survey was conducted between August 6 and 22, 2008, aboard the F/V *Pacific Explorer*. The survey area started at approximately 71°N and 155°W and extended out to 72°N and 152°W in the Beaufort Sea, Alaska (Fig. 1). There were 26 demersal trawls of which 22 were successful (Table 1). Bottom depths of successful trawls ranged from 40 to 470 m. Distance fished for each bottom trawl ranged from 0.4 km to 3.6 km (Table 1). An attempt was made to evenly distribute trawl station locations along transect lines

Table 1 Demersal trawls conducted during the 2008 Beaufort Sea survey

Trawl no.	Start latitude (DD)	Start longitude (DD)	Bottom depth (m)	Distance fished (km)	Bottom temperature °C	Tow time (min)	Lined or unlined net	Total catch weight (kg)	Comments
1	71.88	−154.97	428	3.60	0.5	30	Lined	No catch	Lost codend
2	71.89	−154.95	470	1.12	0.5	10	Lined	694.93	
3	71.74	−154.99	198	1.35	−0.1	15	Lined	751.34	Net tore, replaced
4	71.90	−153.91	347	1.28	0.6	15	Lined	1881.89	
5	71.81	−153.92	143	1.26	−1.2	15	Lined	1846.51	
6	71.81	−154.46	158	1.45	−1.4	15	Lined	9502.65	
7	71.98	−154.41	322	1.64	0.5	15	Lined	2028.50	
8	71.72	−152.84	318	1.39	0.5	15	Lined	1382.47	
9	71.66	−152.49	302	1.51	0.6	15	Lined	1984.08	
10	71.52	−152.25	175	1.52	−0.8	15	Lined	2359.84	
11	71.75	−153.94	66	1.39	−0.7	15	Lined	419.10	
12	71.69	−154.52	50	1.51	1.8	15	Lined	251.08	
13	71.48	−153.96	49	1.34	1.5	15	Lined	339.30	
14	71.39	−153.99	41	1.36	1.8	15	Unlined	No catch	Lost whole net
15	71.25	−153.13	41	1.42	1.0	15	Unlined	No catch	Lost codend
16	71.25	−153.11	41	0.39	1.0	5	Unlined	19.45	
17	71.37	−153.07	75	0.45	0.3	5	Unlined	256.35	
18	71.46	−153.04	64	0.56	0.7	5	Unlined	87.81	
19	71.16	−152.23	30	0.42	1.3	5	Unlined	No catch	Large net tear
20	71.28	−152.31	50	0.57	−0.4	5	Unlined	38.74	
21	71.35	−151.99	83	0.62	−1.4	5	Unlined	27.45	
22	71.51	−152.20	178	0.70	−0.4	5	Unlined	77.74	
23	71.58	−155.05	44	0.62	−0.1	5	Unlined	43.05	
24	71.68	−154.48	50	0.57	−0.9	5	Unlined	52.78	
25	71.53	−152.89	59	0.61	−0.9	5	Unlined	35.52	
26	71.55	−153.48	52	0.48	1.2	5	Unlined	10.59	

Latitude and longitude in decimal degrees, bottom depth (m), distance fished (km), bottom temperature (°C), tow time (minutes from trawl brake set to haul back), net type (lined or unlined), and total catch weight (kg) for all demersal trawls conducted. "No catch" in the "Total catch weight" column indicates the gear was lost or damaged resulting in no catch sample

(Fig. 1). However, due to the presence of sea ice during the first 6 days of the survey along with areas of untrawlable habitat (e.g. boulders, high relief), demersal trawls were limited to areas that would minimize gear loss or damage.

Survey design

To obtain abundance estimates of demersal fishes and benthic invertebrates, all trawls were conducted in concordance with standards set by the AFSC's Resource Assessment and Conservation Engineering (RACE) Division (Stauffer, 2004). The net was an 83–112 Eastern otter trawl built to standards detailed in Stauffer (2004), with a 25.3-m (83 ft) headrope and a 34.1-m (112 ft) footrope. In addition, a small-mesh liner was used for trawls 1–13 in order to catch relatively small Arctic fishes. The mesh liner was 3.8 cm and covered the entire bottom body of the net, the wings, the top and bottom of the intermediate (i.e., mesh between the trawl doors and codend), and the codend. The original field plan was to conduct the entire survey with the lined nets. However, the nets were irreparably damaged during the first half of the survey, so trawls 14–26 were conducted with unlined nets. To address the change in gear, we returned to two stations previously sampled with the lined net and repeated the trawl with the unlined net. We refer to these two sets of trawls as "paired trawls" because they occurred at the same location, but they were sampled 4 days apart. The results from the paired trawls are presented below, but statistical analyses of fish diversity and abundance were not made within each pair of trawls, because only one observation with each gear type was made. A comparison between the paired trawls was not reasonable due to depth differences among the two stations (Table 1).

All analyses are presented by lined and unlined net types. With the exception of one station, all the stations between 100 and 500 m bottom depth were sampled with the lined net and tows were 15 min. Twelve stations in the 40- to 100-m depth range were sampled with the unlined net and tows were 5 min. This confounding of net type and depth was not intentional but resulted from the fact that ice covered the shallow depths early in the survey when the lined nets were in use. Tow time was reduced later in the survey to minimize damage to the remaining nets.

Net height and width were measured with Netmind acoustic net mensuration equipment during trawling operations (Northstar Technical Inc., St. John's, Newfoundland). Trawl footrope contact with the seafloor was monitored at 1-s intervals using a calibrated bottom contact sensor (BCS). The BCS consisted of a tilt sensor inside a stainless-steel pipe attached at the center of the footrope. Bottom contact data were used to estimate distance fished.

Survey sampling

The entire catch for each trawl (with the exception of trawl 6, see below) was weighed on a motion-compensated marine Marel scale. When the total catch weight was <200 kg, the entire catch (fish and invertebrates) was sorted to the lowest possible taxonomic level, counted, and weighed (trawls 16, 18, and 20–26). However, due to large catch sizes and the high number of taxa, the most common method of sampling the trawl catch was sub sampling (trawls 2–13 and 17). A random subsample of the entire catch was weighed, and fishes were sorted to the lowest taxonomic level possible. In the case of invertebrates, a sub-subsample (i.e. a sample of the subsample) was taken due to the high taxa diversity and quantity of invertebrates caught. Within the sub-subsample of invertebrates, taxa were sorted to the lowest taxonomic level, counted, and weighed. Trawl 6 was estimated to be between 9 and 10 metric tons, too large to weigh the catch in its entirety. The volume of the codend was estimated using the formula for the frustum of a cone where h is the height of the cone, R is the radius at the lower base of the cone, and r is the radius at the upper base of the cone:

$$V = \frac{\pi h}{3}\left(R^2 + Rr + r^2\right). \quad (1)$$

Using this formula and a catch density estimate, the weight of the entire catch was calculated. A subsample was then removed and processed as above.

Net width and distance fished were used to calculate area swept, which was then used to determine catch per unit effort (CPUE). Mean CPUE was estimated for all fish taxa and the top 24 invertebrate taxa for both lined and unlined net types. Catch per unit effort (CPUE) was calculated as both kilograms and numbers per hectare from the weight or number of each species or taxon divided by the area swept for each trawl. Because the net liner likely increased the catch density of fish, the CPUE (kg/ha or No./ha) for each trawl was averaged separately for each net type (lined and unlined). Zero catches were included in the CPUE calculations.

All fish taxa found in the subsamples were collected for confirmation of field identification in the AFSC's taxonomic laboratory (J. Orr and D. Stevenson, AFSC, pers. comm.). All specimens were photographed with the trawl number for proper assignment when species identification was verified or changed. Specimens were counted, weighed, and preserved in a 10% formaldehyde and seawater solution buffered with sodium bicarbonate.

Biological sampling

Biological information was collected from polar cod (*Boreogadus saida*) and walleye pollock (*Theragra chalcogramma*). For each trawl, up to 150 polar cod were randomly collected from the catch subsample, and the sex and fork length (nearest 1.0 cm) were recorded. In addition, for each trawl, a subset of 25 of the 150 polar cod were weighed to the nearest gram, and the otoliths were excised and preserved in a 95% solution of ethyl alcohol. Also, the stomachs and ovaries were removed for future analysis. All walleye pollock in the trawl subsamples were sexed, the fork length measured, weighed, and the otoliths were removed for aging.

Snow crabs (*Chionoecetes opilio*) were randomly selected from three of the trawls to obtain measurements. Carapace length, width (mm), weight (g), and sex were recorded. Also, average individual crab weight for all trawls was calculated from the total crab catch weight and numbers found in the subsample.

Ecosystems comparisons and historical observations

To assess the differences and similarities between Arctic ecosystems (e.g., Chukchi and Beaufort seas) and North Pacific ecosystems (e.g., Bering Sea), we compare our results with those from recent surveys of the Chukchi and Bering seas. Demersal trawl surveys of the Bering Sea are conducted annually by the AFSC. The most recent comparable demersal trawl survey of the Chukchi Sea was conducted in 1990 (Barber et al. 1997). All three surveys used the same gear and standardized methods. Only stations that employed the unlined nets are shown for the 2008 Beaufort Sea survey. Sample sizes between the surveys were highly unbalanced ($n = 10$ in the Beaufort Sea vs. $n = 375$ in the Bering Sea), so 95% confidence intervals for mean CPUE from the Bering Sea survey are shown for comparison to point estimates of CPUE for both the Beaufort and Chukchi sea surveys in lieu of a formal statistical comparison (i.e., ANOVA). The data necessary to compute confidence intervals for the Chukchi survey CPUE were not presented in Barber et al. (1997).

Finally, we compare our results with those of the 1977 Beaufort Sea survey (Frost and Lowry 1983). The 1977 survey extended from 164°W to 141°W. Only seven of the 33 stations visited in August–September 1977 occurred in the 2008 Beaufort Sea survey area. However, we compare the 2008 survey results with those reported from all 33 stations sampled in 1977. A statistical comparison between the survey in 1977 and 2008 was not possible due to the confounding effects of gear type, and area surveyed, so we examined the differences in fish catch between the two surveys qualitatively.

Results

Abundance and distribution of marine fishes

Fishes were 6% of the total weight captured in the trawls and 34 taxa of fishes were identified (Table 2). Polar cod (*Boreogadus saida*) was 92% of the total number of fish captured and 80% of the total weight. The second most abundant taxon were eelpouts (*Lycodes* spp.) that made up 3.5% of the total number of fishes captured and 13% of the total weight (Table 2). Approximately six species of sculpins were identified, but collectively their total CPUE was less than 0.1 kg/ha. Together, Bering flounder (*Hippoglossoides robustus*) and Greenland halibut (*Reinhardtius hippoglossoides*) made up only 0.3% of the total numbers of fish captured in the trawls. The leatherfin lumpsucker (*Eumicrotremus derjugini*) and fish doctor (*Gymnelus viridis*) each had a CPUE of 0.01 kg/ha or less and only occurred in the 40- to 100-m depth range (Table 2, unlined net).

Polar cod was the only fish species that occurred at all trawl stations. The highest CPUE (kg/ha) for polar cod was on the shelf between 100 and 500 m deep, in the westernmost half of the survey area. Polar cod CPUE was consistent from west to east (25.8–58.6 kg/ha) along the deepest part of the survey area (between the 300 and 500 m depth contours). Walleye pollock distribution was similar to that of polar cod, but pollock CPUE values were an order of magnitude smaller (0–6.4 kg/ha). The highest pollock CPUE was found in the western part of the survey area, primarily in the 100- to 500-m depth range.

The CPUE (No./ha) for fish found in the paired trawls is summarized in Table 3. For all taxa of fishes, the CPUE was generally larger in the lined net catch than the unlined net catch. In addition, 11 of the 15 taxa that were captured in trawl 12 with the lined net were missing in the corresponding "paired" trawl (trawl 24) using the unlined net.

Polar cod and pollock biological characteristics

In total, 1,494 polar cod were sexed and lengths measured (701 males and 793 females). In addition, a subset of 730 polar cod were individually weighed and their otoliths were collected (331 males and 399 females). Of these 730 polar cod that were aged, 59% were age-1, 33% were age-2, 7% were age-3, and 1% were age-4. The mean length for polar cod for both sexes and all trawls combined was 113 mm (±28 SD) (Fig. 2). The mean length for males was 108 mm (±23 SD) and for females 120 mm (±31 SD) (Fig. 2). The mean length for polar cod captured in the lined nets was 118 mm (±30 SD). The mean length for polar cod captured in the unlined nets was 104 mm (±20 SD). The mean individual weight for polar cod in all trawls combined was 12 g (both sexes combined; ±10 SD). The mean individual weight for males was 10 g (±6 SD) and for females was 15 g (±11 SD). A length-weight relationship for polar cod (males and females combined) was determined using Ricker's (1973) model: weight (g) $= 1.47 \times 10^{-5} \times$ length (mm) $^{2.8313}$. Mean weight (and lengths) for polar cod exhibited spatial variation. Larger cod, with a mean weight between 12 and 30 g (mean length of 118 cm), were primarily distributed in the 100- to 500-m depth range. Smaller cod, with a mean weight less than 12 g (mean length of 104 cm), were primarily distributed in the 40- to 100-m depth range (Fig. 3).

A total of 99 walleye pollock were collected from the trawl subsamples (51 males, 44 females, 4 unsexed). Mean fork length for walleye pollock was 145 mm (both sexes combined; ±32 SD) (Fig. 4). The mean length for male pollock was 155 mm (±43 SD) and for females, 170 mm (±45 SD) (Fig. 4). There were nine pollock age-1, 71 pollock age-2, 11 pollock age-3, and two pollock age-4 (6 specimens could not be aged) (Fig. 5). Length-at-age is shown in Fig. 5, along with Bering Sea walleye pollock collected in 2008. The length for age-2 pollock in the Beaufort Sea survey ranged from 110 to 203 mm, whereas the length for age-2 pollock in the Bering Sea ranged from 160 to 300 mm.

Invertebrates

Invertebrates made up 94% of the total weight captured and 174 taxa were identified. The top 24 taxa that comprised 99% of the total invertebrate catch weight are summarized in Table 4. Of the invertebrates, the notched brittle star (*Ophiura sarsi*) made up 41%, and snow crab (*Chionoecetes opilio*) made up 10% of the total catch weight for all trawls combined. The highest CPUE for snow crab was found in the 100- to 500-m depth range.

Table 2 Mean catch per unit effort, CPUE (±1 SD) in numbers and weight of fishes caught in lined versus unlined demersal trawl nets during the 2008 Beaufort Sea survey

Scientific name	Common name	Mean CPUE (No./ha) lined net	Mean CPUE (No./ha) unlined net	Mean CPUE (kg/ha) lined net	Mean CPUE (kg/ha) unlined net
Boreogadus saida	Polar cod	1,953 (±3,324)	849 (±2,397)	39.64 (±68.96)	6.11 (±16.63)
Lycodes raridens	Marbled eelpout	54 (±135)	0	4.60 (±10.88)	0
Lycodes polaris	Canadian eelpout	26 (±52)	<1 (±1)	1.41 (±3.05)	0.01 (±0.02)
Hippoglossoides robustus	Bering flounder	8 (±11)	1 (±1)	1.26 (±1.66)	0.10 (±0.10)
Theragra chalcogramma	Walleye pollock	36 (±45)	7 (±12)	1.18 (±1.77)	0.12 (±0.19)
Reinhardtius hippoglossoides	Greenland halibut	8 (±14)	0	0.41 (±0.57)	0
Lycodes mucosus	Saddled eelpout	<1 (±2)	0	0.34 (±1.2)	0
Lycodes sp.	Unid. eelpout	3 (±7)	0	0.34 (±0.96)	0
Liparis gibbus	Variegated snailfish	4 (±12)	0	0.31 (±1.09)	0
Lycodes rossi	Threespot eelpout	2 (±4)	<1 (±1)	0.28 (±0.59)	<0.01 (±0.02)
Liparis fabricii	Gelatinous seasnail	5 (±4)	0	0.16 (±0.35)	0
Myoxocephalus verrucosus	Warty sculpin	2 (±5)	<1 (±1)	0.04 (±0.13)	<0.01 (±0.002)
Triglops pingeli	Ribbed sculpin	8 (±22)	<1 (±1)	0.04 (±0.14)	<0.01 (±0.01)
Gadus macrocephalus	Pacific cod	<1 (±1)	0	0.03 (±0.13)	0
Careproctus sp. cf. *rastrinus* (Orr et al.)	Salmon snailfish	2 (±4)	<1 (±1)	0.03 (±0.07)	0.01 (±0.04)
Mallotus villosus	Capelin	<1 (±1)	0	0.03 (±0.12)	0
Gymnocanthus tricuspis	Arctic staghorn sculpin	3 (±7)	<1 (±1)	0.03 (±0.08)	<0.01 (±0.006)
Artediellus scaber	Hamecon	5 (±13)	3 (±4)	0.02 (±0.07)	0.01 (±0.03)
Lumpenus medius	Stout eelblenny	4 (±12)	0	0.01 (±0.05)	0
Liparis sp.	Unid. snailfish	1 (±3)	<1 (±1)	0.01 (±0.03)	<0.01 (±0.0005)
Aspidophoroides olriki	Arctic alligatorfish	5 (±11)	<1 (±1)	0.01 (±0.03)	<0.01 (±0.0002)
Cottidae	Sculpin family	3 (±10)	0	0.01 (±0.04)	0
Lumpenus maculatus	Daubed shanny	1 (±4)	0	0.01 (±0.03)	0
Triglops nybelini	Bigeye sculpin	2 (±8)	0	<0.01 (±0.03)	0
Lumpenus fabricii	Slender eelblenny	2 (±4)	0	<0.01 (±0.02)	0
Lumpenus sp.	Unid. eelblenny	<1 (±3)	0	<0.01 (±0.02)	0
Icelus spatula	Spatulate sculpin	<1 (±2)	<1 (±1)	<0.01 (±0.01)	<0.01 (±0.02)
Eumesogrammus praecisus	Fourline snakeblenny	<1 (±1)	<1 (±1)	<0.01 (±0.01)	<0.01 (±0.006)
Eleginus gracilis	Saffron cod	<1 (±1)	0	<0.01 (±0.01)	0
Liparis marmoratus	Festive snailfish	<1 (±1)	0	<0.01 (±0.001)	0
Nautichthys pribilovius	Eyeshade sculpin	<1 (±1)	0	<0.01 (±0.001)	0
Eumicrotremus derjugini	Leatherfin lumpsucker	0	<1 (±1)	0	0.01 (±0.02)
Gymnelus viridis	Fish doctor	0	<1 (±1)	0	<0.01 (±0.02)
Enophrys diceraus	Antlered sculpin	<1 (±1)	0	<0.01 (±0.001)	0

Table 3 Mean catch per unit effort, CPUE (No./ha) of fish caught in the paired demersal trawls during the 2008 Beaufort Sea survey

Scientific name	Common name	CPUE (No./ha) lined net, 10	CPUE (No./ha) unlined net, 22	CPUE (No./ha) lined net, 12	CPUE (No./ha) unlined net, 24
Boreogadus saida	Polar cod	825	234	556	8
Lycodes raridens	Marbled eelpout	0	0	0	0
Lycodes polaris	Canadian eelpout	58	1	4	0
Hippoglossoides robustus	Bering flounder	14	3	1	0
Theragra chalcogramma	Walleye pollock	0	0	84	41
Reinhardtius hippoglossoides	Greenland halibut	43	0	0	0
Lycodes mucosus	Saddled eelpout	0	0	1	0
Lycodes sp.	Unid. eelpout	0	0	0	0
Liparis gibbus	Variegated snailfish	0	0	0	0
Lycodes rossi	Threespot eelpout	0	0	0	0
Liparis fabricii	Gelatinous seasnail	0	0	0	0
Myoxocephalus verrucosus	Warty sculpin	14	0	1	0
Triglops pingeli	Ribbed sculpin	0	0	78	0
Gadus macrocephalus	Pacific cod	0	0	1	0
Careproctus sp. cf. *rastrinus* (Orr et al.)	Salmon snailfish	0	3	0	0
Mallotus villosus	Capelin	0	0	1	0
Gymnocanthus tricuspis	Arctic staghorn sculpin	0	0	13	1
Artediellus scaber	Hamecon	0	0	44	1
Lumpenus medius	Stout eelblenny	0	0	0	0
Liparis sp.	Unid. snailfish	0	0	0.04	0
Aspidophoroides olriki	Arctic alligatorfish	29	0	1	0
Cottidae	Sculpin family	0	0	36	0
Lumpenus maculatus	Daubed shanny	14	0	0	0
Triglops nybelini	Bigeye sculpin	29	0	0	0
Lumpenus fabricii	Slender eelblenny	0	0	0	0
Lumpenus sp.	Unid. eelblenny	0	0	9	0
Icelus spatula	Spatulate sculpin	0	0	0	0
Eumesogrammus praecisus	Fourline snakeblenny	0	0	0	0
Eleginus gracilis	Saffron cod	0	0	0	0
Liparis marmoratus	Festive snailfish	0	0	0	0
Nautichthys pribilovius	Eyeshade sculpin	0	0	0	0
Eumicrotremus derjugini	Leatherfin lumpsucker	0	1	0	0
Gymnelus viridis	Fish doctor	0	0	0	0
Enophrys diceraus	Antlered sculpin	0	0	0	0

The two pairs were trawls 10 and 22; and trawls 12 and 24. The trawl number is listed after net type

The largest catches (168–325 kg/ha) occurred in the western portion of the study area at those depths. In contrast, CPUE varied little by longitude in the 40- to 100-m depth range (0.01–14.8 kg/ha). Eighty-six snow crabs from three random trawls (2, 4, and 7) were weighed, measured, and preserved. Female snow crab carapace width ranged from 58 to 78 mm ($n = 16$), and male carapace width ranged from 55 to 119 mm ($n = 70$). The carapace width (mm) versus weight (kg) of snow crab (male and female combined) is shown in Fig. 6. The average weight of an individual crab was estimated for each trawl. Most crabs with a weight above 0.15 kg had a carapace width greater than 78 mm, the legal size limit for male snow crab commercially fished in the Bering Sea (Fig. 6). These crabs were found only in the 100- to 500-m depth range, specifically between 306 and 478 m. In the 40- to 100-m depth range, average crab weight ranged between 0.02 and 0.10 kg.

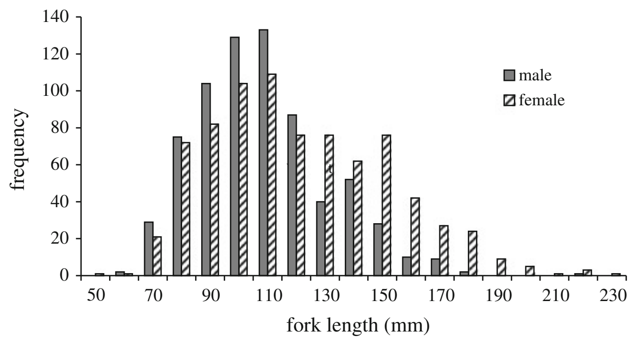

Fig. 2 Length frequencies for male and female polar cod (*Boreogadus saida*) captured during the 2008 Beaufort Sea survey. Data from lined and unlined nets are combined

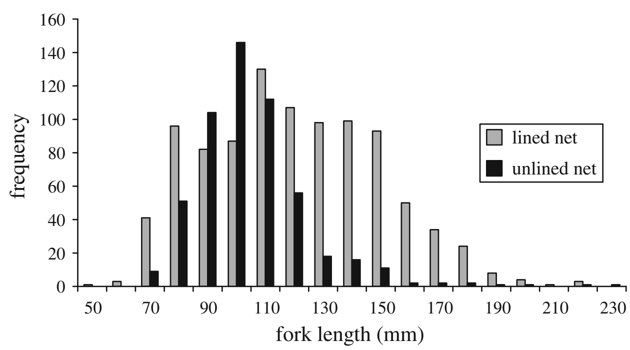

Fig. 3 Length frequencies for polar cod (*Boreogadus saida*) captured during the 2008 Beaufort Sea survey. Data are shown for lined and unlined nets separately

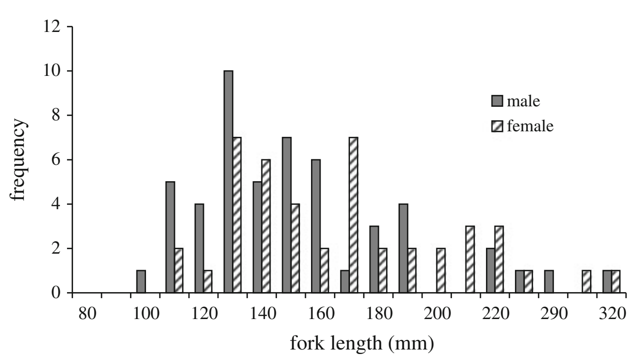

Fig. 4 Length frequencies of male and female walleye pollock (*Theragra chalcogramma*) captured in the 2008 Beaufort Sea survey. Data from lined and unlined nets are combined

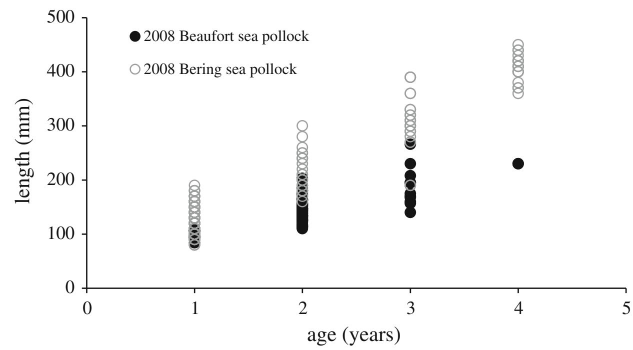

Fig. 5 Length-at-age for walleye pollock (*Theragra chalcogramma*) captured in the 2008 Beaufort Sea survey and 2008 Bering Sea survey

Discussion

Marine fishes

Polar cod (*Boreogadus saida*) were the most abundant fish caught during this survey, both numerically and by weight. Polar cod are known to be a major component of the Beaufort Sea fish community and important prey for higher trophic levels such as seabirds (Hobson 1993) and marine mammals (Bradstreet and Cross 1982; Bradstreet et al. 1986; Welch et al. 1992). They are also the dominant consumer of zooplankton (Atkinson and Percy 1992) and are thus an important conduit for secondary production (Welch et al. 1992). One of the earliest documented records of polar cod in the Alaskan Beaufort Sea is from 1951 (unpublished data, University of British Columbia, N. J. Wilimovsky, H. A. Fehlmann). Previous studies in near-shore, often brackish waters, have also documented the distribution of polar cod (Craig et al. 1982; Craig 1984; Moulton and Tarbox 1987; Jarvela and Thorsteinson 1999), but this study is the first to quantify the abundance of polar cod in offshore marine waters of the Beaufort Sea.

The polar cod caught in this survey were primarily sub-adults, ages 1 and 2, although some age-3 and -4 fish were found. Large polar cod were distributed primarily in the deeper depths (100–500 m) while small cod were found primarily in the shallower depths (40–100 m). This difference in size by depth is likely not driven by net type, because the larger cod in the deeper depths were caught with the lined net, and the smaller cod in shallower depths were caught with the unlined net. Frost and Lowry (1983) documented a similar distribution pattern from their 1977 survey. They report that polar cod were larger in water deeper than 100 m, whereas cod in water less than 100 m were on average, smaller. Similarly, in the northeast Chukchi Sea, polar cod greater than age 3 found offshore were significantly larger than the same age fish found inshore (Gillispie et al. 1997).

We documented or confirmed extensions to the known ranges of four species of fishes: walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), festive snailfish (*Liparis marmoratus*), and eyeshade sculpin (*Nautichthys pribilovius*). The Chukchi Sea survey in 1990 (Barber et al. 1997) reported Pacific cod at three stations located between 68°N and 69°N. Festive snailfish are a relatively rare species; only one specimen has been recorded in the northeast Bering Sea near St. Lawrence Island at

Table 4 Mean CPUE by numbers and weight for the top 24 invertebrate taxa caught in lined versus unlined nets during the 2008 Beaufort Sea survey

Species name	Common name	Mean CPUE (No./ha) lined net	Mean CPUE (No./ha) unlined net	Mean CPUE (kg/ha) lined net	Mean CPUE (kg/ha) unlined net
Ophiura sarsi	Notched brittle star	286,277	61	337.61	0.16
Chionoecetes opilio	Snow crab	996	8	86.54	0.47
Musculus spp.	Mussel	8,718	<1	50.12	<0.01
Ctenodiscus crispatus	Mud star	4,122	454	34.73	2.7
Actiniaria	Sea anemones	112	0	15.76	0
Strongylocentrotus sp.	Sea urchin	281	122	12.23	4.95
Psolus fabricii	Sea cucumber	526	118	11.97	4.0
Buccinum polare	Polar whelk	872	6	7.36	0.06
Pyrulofusus spp.	Whelk	144	2	6.28	0.07
Neptunea spp.	Whelk	178	9	5.32	0.40
Gorgonocephalus arcticus	Basket starfish	26	<1	5.28	<0.01
Golfingia margaritacea	Worm	3,706	<1	4.78	<0.01
Gersemia rubiformis	Soft coral	*	*	4.66	0.04
Psolus phantapus	Sea cucumber	69	0	3.88	0
Stomphia sp.	Anemone	125	26	3.25	1.13
Pagurus rathbuni	Hermit crab	800	8	2.92	0.07
Naticidae	Moon snails	432	1	2.50	0.01
Margarites spp.	Snails	1,254	<1	2.36	<0.01
Buccinum glaciale	Glacial whelk	115	3	2.20	0.06
Buccinum spp.	Whelk	241	<1	2.08	<0.01
Brada spp.	Polychaete	699	<1	1.83	<0.01
Hyas coarctatus	Lyre crab	155	37	1.69	1.52
Pagurus trigonocheirus	Hermit crab	255	83	1.32	1.57
Halocynthia aurantium	Ascidian	*	*	0.56	10.69

An *asterisk* indicates species not enumerated

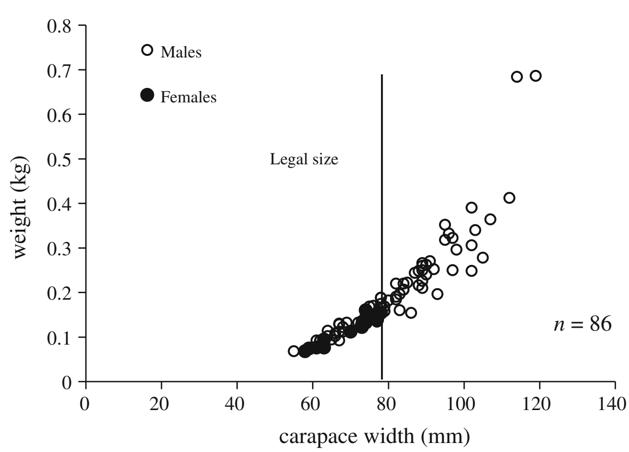

Fig. 6 Snow crab (*Chionoecetes opilio*) weight (kg) versus carapace width (mm). Legal crab size is 78 mm (*solid line*)

63°00′N, 169°20′W (Busby and Chernova 2001). Previous to this record, the species had only been documented in the Sea of Okhotsk. The northernmost record of the eyeshade sculpin previous to our survey was in the northern Chukchi Sea, west of Point Barrow (Barber et al. 1997). In addition to the range extensions of pollock and Pacific cod, Bering flounder (*Hippoglossoides robustus*) were caught in the present 2008 survey, but not in the 1977 survey (Frost and Lowry 1983). All three of these species are abundant in the Bering Sea and are commercially valuable.

We caught walleye pollock as far north as 71°59′N (154°25′W). The domestic groundfish fishery off Alaska is the largest US fishery by volume and walleye pollock make up the dominant portion of that catch (Hiatt et al. 2008). Pollock were recorded as far north as 71°23′N during a 2004 survey of the Chukchi Sea (Mecklenburg et al. 2007), and a specimen was collected at 69°26′N, during a 1990 survey of the Chukchi Sea on the *Ocean Hope III* (unpublished data; NMFS-AFSC-Resource Assessment and Conservation Engineering (RACE) Division, cruise 90–2). Two specimens were collected in the Beaufort Sea near the mouth of Elson Lagoon, east of Point Barrow at approximately 71°31′N, 156°32′W in 1951 and 1954 (unpublished data, University of British Columbia: N. J. Wilimovsky, J. E. Bohlke; D. Wohlschlag, and W. C. Freihofer). However, the specimens are missing and identification as walleye pollock is uncertain (K. Mecklenburg, pers. comm.). We found pollock in moderate densities throughout the survey area, so if the Elson Lagoon samples collected in 1954 were correctly identified as pollock, our results confirm the range extension and document that the species may be widespread in the Beaufort Sea.

Analysis of pollock otoliths showed that most of the fish caught in the present 2008 survey were sub-adults (age-2). In 1990, an ichthyoplankton survey in the Chukchi Sea (Echeverria 1995) found juvenile walleye pollock northwest of Point Barrow. During the Russian-American Long-Term Census of the Arctic (RUSALCA) survey of the Chukchi Sea in 2004, Mecklenburg et al. (2007) recorded pollock ranging from 102 to 168 mm total length, indicating that these fish were likely sub-adults. So, although pollock are occurring in Arctic seas, fish of spawning age or size have not yet been documented, and the origins of the juvenile fish are not known. The fact that the pollock we caught in the Beaufort Sea were smaller at age than pollock in the Bering Sea may provide evidence that the fish were spawned in cold Arctic waters or were transported into such waters shortly after spawning. The size difference is manifested first at age-2; age-1 pollock from the Bering and Beaufort seas were similar in size. This lends support to the latter hypothesis that fish were spawned in north Pacific waters and transported into the Arctic sometime during their first year of life. Despite the potential northward shift in the distribution of some species, the fish communities of the Beaufort and Chukchi seas are still distinct from the Bering Sea. Polar cod are a dominant component of the Beaufort and Chukchi Sea fish communities, whereas pollock, Pacific cod, and flatfish dominate the Bering Sea. Although we document the presence of pollock and commercial-sized snow crab in the Beaufort Sea, their densities are far lower than in the Bering Sea and Chukchi seas.

Benthic invertebrates

Invertebrates dominated the demersal trawl catches both in terms of abundance and species diversity. The notched brittle star (*Ophiura sarsi*) dominated all of the trawls in the present 2008 survey. The 1977 survey reported that notched brittle stars were also the most abundant invertebrate captured and dominated the catch west of longitude 154°W (Frost and Lowry 1983). Several studies have documented the prevalence of notched brittle stars in the North Pacific and Arctic ecosystems. Dense carpets of notched brittle star were reported off the coast of Japan (Fujita and Ohta 1989) and were also reported as one of the most dominant epibenthic invertebrates in many parts of the Chukchi Sea (Grebmeier et al. 2006a, b). Both the notched brittle star and snow crab (*Chionoecetes opilio*) were the most abundant epibenthic invertebrates encountered in the Chuckchi sea during the RUSLCA cruises in 2004, 2007, and 2008 (Bluhm et al. 2009). The size and depth distribution of snow crab during the 2008 survey were unexpected based on previous studies in the Bering and Chukchi Seas. In 1990 and 1991, 48 stations were sampled in the northeast Chukchi Sea to examine the distribution and abundance of snow crab (Paul et al. 1997). Snow crabs were found at all stations, with the highest abundance and mean crab weight occurring in the stations directly west of Point Barrow (Paul et al. 1997). However, carapace width of the male crabs ranged from 20 to 74 mm (Paul et al. 1997), compared with the measured snow crab in the present Beaufort survey that ranged from 55 to 119 mm. In the 1977 Beaufort Sea survey, the maximum carapace width for a male snow crab was 75 mm (Frost and Lowry 1983).

Recently, snow crab has also been observed in the northeast Atlantic's Barents Sea (Alvsvåg et al. 2008). Evidence of juveniles below 50 mm carapace width confirms that the population is established and reproductive with adult crabs ranging in size from 50 to 136 mm (Alvsvåg et al. 2008). The presence of female crabs with eggs during the 2008 Beaufort Sea survey is further evidence that this population is reproductive. Our survey found the highest CPUE and the largest crabs by carapace width and weight in water depths greater than 300 m and temperatures around 0.6°C. This result was also unexpected, as surveys in the Bering and Chukchi Seas indicate that snow crabs are found predominantly in waters less than 200 m in depth. However, the main population of crab found in the Barents Sea survey was located in depth ranges from 80 to 350 m and in waters less than 2°C (Alvsvåg et al. 2008). Also, the fact that Frost and Lowry (1983) only caught small snow crab (less than 80 mm) may be due to the fact that only one tow was made in water deeper than 200 m. The legal minimum carapace width for the commercial snow crab fishery in the Bering Sea is 78 mm; therefore, the 2008 survey is the first to document snow crab of commercial size in the North American Arctic.

Ecosystems comparisons and historical observations

The comparisons of the Arctic ecosystems (Chukchi and Beaufort seas) to the North Pacific ecosystem (Bering Sea) show differences in both species presence/absence and overall abundance. In general, the mean CPUE for species caught in the Beaufort Sea and in the Chukchi Sea fell

Table 5 Mean CPUE (kg/ha) of common species found in the Beaufort, Chukchi, and Bering Seas, with 95% confidence intervals shown for the Bering sea (in parenthesis)

Species common name	Beaufort Sea 2008[a] CPUE (kg/ha)	Chukchi Sea 1990[b] CPUE (kg/ha)	Bering Sea 2008[c] CPUE (kg/ha)
Polar cod	6.12	3.02	1.04 (0–2.65)
Arrowtooth flounder	*	*	10.7 (8.88–12.52)
Bering flounder	0.11	0.18	0.45 (0.30–0.60)
Cottidae (sculpin family)	0.03	0.76	4.22 (3.41–5.03)
Flathead sole	*	*	10.81 (8.18–14.33)
Greenland halibut	*	<0.01	0.27 (0.15–0.39)
Rock sole	*	*	41.03 (29.13–52.93)
Pacific cod	*	0.12	8.65 (7.54–9.76)
Saffron cod	*	0.39	0.003 (0.001–0.005)
Walleye pollock	0.13	0.02	61.16 (47.46–74.86)
Yellowfin sole	*	*	42.4 (32.28–52.46)
Zoarcidae (eelpout family)	0.03	0.21	0.79 (0.59–0.99)

The CPUE reported for the Beaufort Sea is from unlined demersal trawl nets only. An asterisk indicates that there was no catch of that species

[a] Beaufort Sea 2008 Survey

[b] Barber et al. (1997)

[c] Eastern Bering Sea 2008 survey

outside the confidence intervals of CPUE for the same species caught in the Bering Sea (Table 5). Polar cod was the most prevalent fish species in both the present 2008 Beaufort Sea survey and the 1990 Chukchi Sea survey (Table 5). In the Bering Sea, walleye pollock was the most abundant fish species, at 61.2 kg/ha compared with 0.13 kg/ha in the Beaufort Sea and 0.02 kg/ha in the Chukchi Sea (Table 5). In addition, the flatfish species that were dominant in the Bering Sea (arrowtooth flounder (*Atheresthes stomias*), Bering flounder (*Hippoglossoides robustus*), flathead sole (*Hippoglossoides elassodon*), Greenland halibut (*Reinhardtius hippoglossoides*), rock sole (*Lepidopsetta polyxystra* and *Lepidopsetta bilineata*), and yellowfin sole *(Limanda aspera)*) were absent or found in low densities in the Chukchi and Beaufort seas (Table 5). Saffron cod was more abundant in the Chukchi Sea than the Bering Sea, but was absent from the present 2008 Beaufort Sea survey (Table 5).

Of the 34 taxa captured and identified from the present 2008 Beaufort Sea survey, 17 of those had also been documented in the 1977 survey (Table 6). Although CPUE was not calculated during the 1977 survey, the number of fish caught was recorded at each station. Polar cod was the most numerous fish species found in both surveys. Bering flounder and walleye pollock were fairly abundant relative to other species in the 2008 survey but were not observed during the 1977 survey. Also, Pacific cod (*Gadus macrocephalus*), festive snailfish (*Liparis marmoratus*), eyeshade sculpin (*Nautichthys pribilovius*), and bigeye sculpin (*Triglops nybelini*) were caught during the 2008 survey (albeit in relatively small numbers), but were absent from the 1977 survey.

Eelpouts were common during both surveys, but different species were dominant; marbled eelpouts (*Lycodes raridens*) were the most abundant eelpout in the 2008 survey, whereas Canadian eelpouts (*Lycodes polaris*) and fish doctors (*Gymnelus viridis*) were most abundant in the 1977 survey. Snailfish were fairly common during both surveys. Variegated snailfish (*Liparis gibbus*) and gelatinous seasnail (*Liparis fabricii*) were the most abundant snailfish species in the 2008 survey, but snailfish were not identified to species in the 1977 survey. Sculpins were caught during both surveys, but they ranked higher in abundance during the 1977 survey. In addition, different species were caught: warty (*Myoxocephalus verrucosus*) and ribbed sculpin (*Triglops pingeli*) were most common during the 2008 survey while spatulate (*Icelus spatula*) and twohorn sculpin (*Icelus bicornis*) were the dominant species during the 1977 survey. The twohorn sculpin was the third most prevalent species in the 1977 survey and did not occur in the 2008 survey. These differences in the fish species composition between 1977 and 2008 are suggestive of changes in the marine fish community of the Beaufort Sea since the late 1970s. Nonetheless, without more extensive surveys, it is difficult to conclude that changes in species communities have occurred.

Future monitoring

Assessment of the impacts of climate change, northerly expansion of marine species, future offshore oil and gas exploitation, and potential fisheries development will require monitoring of the distribution and abundance of marine offshore fishes. Net mensuration and gear standardization are recommended for future monitoring studies and would provide quantitative estimates to compare with the present 2008 survey, and with future fishery surveys. Standardized, comparable surveys can serve as an index of change without bias due to changes in gear type and survey methods.

Table 6 Fish species from the 2008 Beaufort Sea survey (data from all demersal trawls combined) compared with the previous Beaufort Sea survey in 1977 by Frost and Lowry (1983)

Scientific name	Common name	2008 survey mean CPUE (No./ha)	1977 survey no. individuals
Boreogadus saida	Polar cod	1,303	194
Lycodes raridens	Marbled eelpout	24	7
Theragra chalcogramma	Walleye pollock	23	–
Lycodes polaris	Canadian eelpout	12	81
Triglops pingeli	Ribbed sculpin	8	2
Artediellus scaber	Hamecon	6	30
Hippoglossoides robustus	Bering flounder	4	–
Cottidae	Sculpin family	3	–
Gymnocanthus tricuspis	Arctic staghorn sculpin	3	2
Reinhardtius hippoglossoides	Greenland halibut	3	–
Aspidophoroides olriki	Arctic alligatorfish	2	19
Liparis fabricii	Gelatinous seasnail	2	–
Liparis gibbus	Variegated snailfish	2	–
Lumpenus medius	Stout eelblenny	2	1
Lycodes sp.	Unid. eelpout	2	–
Myoxocephalus verrucosus	Warty sculpin	2	–
Careproctus sp. cf. *rastrinus* (Orr et al.)	Salmon snailfish	1	–
Eleginus gracilis	Saffron cod	1	–
Enophrys diceraus	Antlered sculpin	1	–
Eumesogrammus praecisus	Fourline snakeblenny	1	4
Eumicrotremus derjugini	Leatherfin lumpsucker	1	29
Gadus macrocephalus	PACIFIC cod	1	–
Gymnelus viridis	Fish doctor	1	23
Icelus spatula	Spatulate sculpin	1	14
Liparis marmoratus	Festive snailfish	1	–
Liparis sp.	Unid. snailfish	1	29
Lumpenus fabricii	Slender eelblenny	1	11
Lumpenus maculatus	Daubed shanny	1	1
Lumpenus sp.	Unid. eelblenny	1	–
Lycodes mucosus	Saddled eelpout	1	2
Lycodes rossi	Threespot eelpout	1	2
Mallotus villosus	Capelin	1	–
Nautichthys pribilovius	Eyeshade sculpin	1	–
Icelus bicornis	Twohorn sculpin	–	74
Arctogadus glacialis	Polar cod	–	1
Triglops nybelini	Bigeye sculpin	1	–

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