Polar Biol (2013) 36:907–912
DOI 10.1007/s00300-013-1303-y

SHORT NOTE

The diets of polar cod (*Boreogadus saida*) from August 2008 in the US Beaufort Sea

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Received: 18 September 2012 / Revised: 29 January 2013 / Accepted: 31 January 2013 / Published online: 18 February 2013

Abstract Polar cod (*Boreogadus saida*) play an integral part in the Arctic ecosystems linking the upper and lower trophic levels. Though their estimated biomass is considerable, recent knowledge of their diets in the US Beaufort Sea is sparse. Collections of polar cod from the US Beaufort Sea were made during August 2008 using demersal and pelagic trawls. Polar cod diet composition was quantified as percent prey weight, percent prey count, and frequency of occurrence of prey. The diet composition between the demersal- and pelagic-captured cod showed differences in all these categories. Polar cod captured in the demersal nets primarily fed on fish (by weight), and pelagic cod primarily fed on copepods (frequency of occurrence) and euphausiids (by weight). In general, these dominant preys are different than what has been reported in other studies describing polar cod diets.

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Keywords Beaufort Sea · Polar cod diet · *Boreogadus saida*

Introduction

Polar cod (*Boreogadus saida*) are the most abundant marine fish in the US Beaufort Sea (Frost and Lowry 1983; Jarvela and Thorsteinson 1999; Parker-Stetter et al. 2011; Rand and Logerwell 2011) and occupy a central position in Arctic food webs. Previous trophic studies in the Beaufort Sea (Frost and Lowry 1984) and other Arctic systems (Bradstreet and Cross 1982; Welch et al. 1992; Whitehouse 2011) have shown polar cod to be the principal fish prey connecting production between lower and upper trophic levels. Their important role as prey throughout the Arctic is well documented among sea birds (Divoky 1984) and marine mammals (Frost and Lowry 1981; Bradstreet et al. 1986; Mehlum and Gabrielsen 1993; Weslawski et al. 1994); however, their role as predator in the US Beaufort Sea is less known. There are only a few published diet descriptions from the 1980s and thus are potentially out of date (Lowry and Frost 1981; Craig et al. 1982; Frost and Lowry 1983).

Because polar cod are a critical link in Arctic food webs, it is important to study their diet in order to inform ecological studies and modeling efforts to document and predict the impacts of climate change and other anthropogenic disturbances on Arctic ecosystems. For example, Arctic Sea ice coverage has declined (Stroeve et al. 2007; Comiso et al. 2008), and polar cod are known to rely on sea ice for foraging and refuge (Lønne and Gulliksen 1989; Gradinger and Bluhm 2004). Loss of sea ice due to Arctic warming may change the distribution and abundance of polar cod, thus altering their trophic relationships with predators (i.e., marine mammals) and their impact on lower trophic levels on which they prey (i.e., zooplankton). In addition, it has been predicted that warming waters may facilitate a northward expansion of several species of fishes, potentially increasing competition for food and habitat (Murawski 1993; Renaud et al. 2012). Ecosystem models can also be used to understand the impacts of climate change on predators (polar cod) through changes in primary and secondary production or "bottom-up" processes. Ecosystem models are capable of providing insight into community structure and resilience to human impacts such as fishing and oil spills (Gaichas et al. 2011; Whitehouse 2011). To date, a small number of food web models have been constructed to determine trophic relationships within Arctic systems (Bradstreet and Cross 1982; Frost and Lowry 1984; Hobson and Welch 1992). Therefore, this project can contribute directly to the foundation of a food web model for the US Beaufort Sea.

In this study, we describe the diets of polar cod collected in the US Beaufort Sea during August with pelagic and demersal trawls (Parker-Stetter et al. 2011; Rand and Logerwell 2011). Basic polar cod diet descriptions are sparse and potentially out of date for the US Beaufort Sea; therefore, this study is intended to add to the existing body of literature and provide current information on polar cod diets for this region.

Materials and methods

Polar cod (*Boreogadus saida*) were collected from the western Beaufort Sea in August 2008 from two different gear types, demersal and pelagic nets. 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 (Rand and Logerwell 2011). The pelagic net was a Marinovich net (fishing dimensions 3–4 m vertical by 6 m horizontal). Both the demersal and pelagic nets were fished with 1.83 × 2.75 m (6 × 9 ft) 816-kg steel V-doors (Parker-Stetter et al. 2011). All trawls were conducted between the hours of 7:00 AM and 7:00 PM Alaska Daylight Time (GMT–8). Fish were collected opportunistically at eleven demersal and seven pelagic trawl locations when time allowed. For example, most of the samples from the pelagic trawls were collected in the northwest part of the study area, whereas the demersal samples were collected throughout the study area (Fig. 1). Due to sampling bias and the nature of demersal and pelagic trawls (i.e., systematic versus unsystematic, different gears), statistical analysis between the demersal and pelagic trawls was not feasible. The demersal trawls ranged from 46 to 344 m bottom depth and pelagic trawls from 34 to 232 m depth. The demersal trawls sampled the bottom 2.5 m of the water column and did not vertically overlap with the pelagic trawls, which ranged from 6 to 150 m off bottom (Fig. 1). Approximately three to five whole polar cod were randomly selected from each trawl and preserved in 10 % formalin for laboratory analysis.

In the laboratory, each fish was measured to the nearest one millimeter (fork length) and a correction factor of 2 % for shrinkage due to preservation was applied to all lengths (Lowry and Frost 1981). Stomachs were removed from the

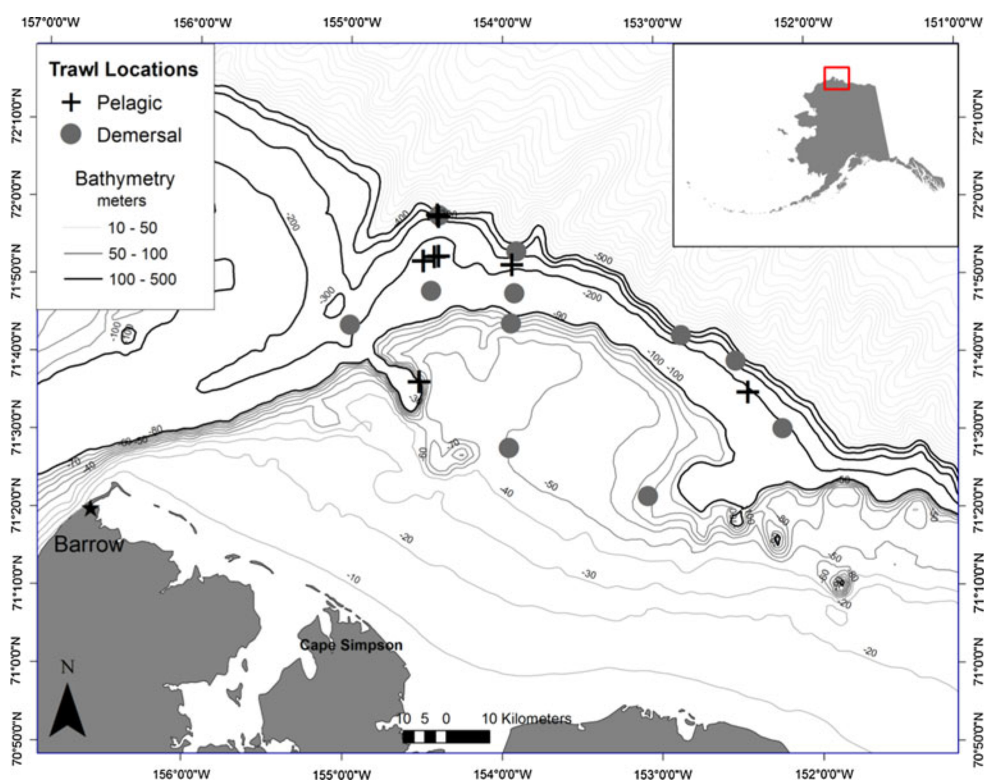

Fig. 1 Sampling locations for polar cod in the US Beaufort Sea in August 2008 that were used for stomach analysis. Locations sampled with pelagic and demersal trawls are indicated with *different symbols*

fish, and the formalin preserved prey items were weighed to the nearest one milligram (wet weight); empty stomachs were recorded. Prey items were sorted to the lowest taxonomic level, weighed, and counted. An assortment of literature sources, including primary literature, text books, field guides, gray literature, and unpublished reports, were used to identify prey to the lowest taxon. Due to digestion and other practical considerations, it was not possible to identify all prey to the species level. To simplify presentation of the data, we combined certain prey categories; for example, all copepod taxa were combined into the prey category "copepod." Other composite prey categories were euphausiids, amphipods, and "other" prey. The "other" prey category includes prey items identified during laboratory analysis as Mysida, Cumacea, Decapoda, Macrura Reptantia, Paguridae, Echiuroidea, Chaetognatha, Thaliacea, and Copelata.

When extensive digestion of stomach contents left only traces of prey parts (e.g., antenna, bone), precluding identification to a lower taxonomic level during laboratory analysis, prey were lumped into either "Crustacea" or "Teleostei" (all unidentifiable fish parts). These two prey categories were the lowest practical taxon for the remaining bits and pieces of nearly completely digested prey. As such, the prey items that comprise the contents of these prey categories may have come from any taxa known to be a potential prey item of polar cod within the region of study. When a fish was found in polar cod stomachs, length was measured to the nearest tenth of a millimeter. The prey categories reported are as recorded during laboratory analysis and do not overlap. For example, the prey category Decapoda includes only those stomach contents identified as Decapoda and does not include lower taxonomic levels (e.g., Macrura Reptantia). Polar cod diet composition was summarized for both demersal and pelagic trawls by percent prey weight (%WT), percent prey count (%N), and percent frequency of occurrence (%FO). To calculate %WT, the total weight of each prey category was averaged within each trawl (3–5 stomachs) and then averaged across all trawls within each gear type (demersal or pelagic). The total average weight for each prey category was then divided by the sum of all averaged prey categories and multiplied by 100 to give percentage. The %N is the total count of each prey category averaged for each trawl (3–5 stomachs) and then averaged by gear type. The %FO is the number of stomachs containing a particular prey item category divided by the total number of stomachs for that trawl and then averaged by gear type (demersal or pelagic).

Results

A total of 82 polar cod stomachs contained prey and were analyzed; 34 were from the pelagic trawls and 48 from the demersal trawls. In addition, there were 5 empty stomachs in the demersal trawls, and no empty stomachs were found in the pelagic trawls. The modal length for polar cod was 120 mm for fish caught in the demersal trawls and 110 mm for the pelagic trawls. The mean length for polar cod sampled from the demersal trawls is 118 mm and 104 mm for cod from the pelagic trawls. These measurements are consistent with mode and mean fork lengths previously reported for polar cod in this region (Frost and Lowry 1983; Rand and Logerwell 2011). The minimum observed length for polar cod in the demersal trawls was 84 mm, and the maximum was 181 mm. For the pelagic trawls, the minimum length sampled was 66 mm and the maximum length was 137 mm.

Diets varied between polar cod caught in the demersal and pelagic trawls. The %WT of the demersal trawl samples was dominated by a genus of sculpin, *Myoxocephalus,* (pers. comm. Morgan Busby, NOAA Fisheries, Alaska Fisheries Science Center), and other unidentified fishes (Teleostei and non-gadoid fishes) (Fig. 2). The *Myoxocephalus* were identified to be in the postflexion and transformation stage and ranged in length from 17 to 31.3 mm with a mean of 23.4 mm and a median of 23.8 mm. The fish prey category combined for the demersal trawls comprised over 75 %WT (Table 1). Of the 48 polar cod stomachs examined in the demersal trawls, 15 contained fishes (~30 %FO). Euphausiids were absent from the polar cod diets in the demersal trawls (Fig. 2; Table 1). Calanoid copepods and larvacea (Copelata) numerically (%N) dominated the diet of polar cod collected with demersal trawls (Fig. 2; Table 1).

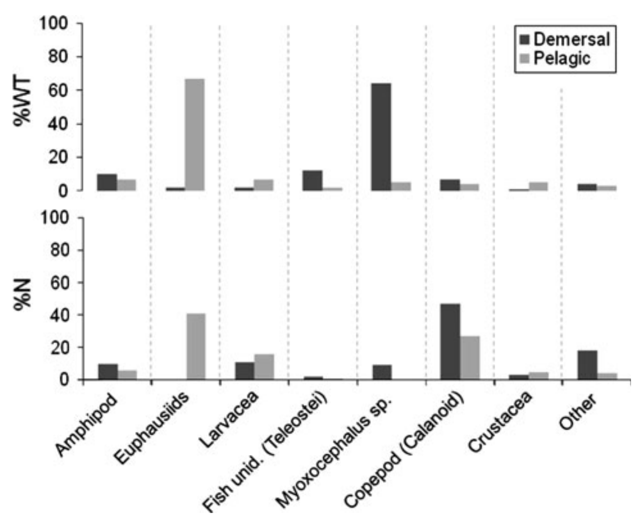

Fig. 2 Diet composition by percent weight (%WT) and percent count (%N) of polar cod collected from demersal and pelagic trawls. The category "other" includes the following: Mysidae, Cumacea, Decapoda, Macrura Reptantia, Paguridae, Echiuroidea, Chaetognatha, Thaliacea, and Copelata

Diets of polar cod sampled with pelagic trawls were dominated by euphausiids by %WT and %N. Larvacea (Copelata) and calanoid copepods had the highest %FO (53 and 64 %, respectively) in the diets of polar cod caught in pelagic trawls, but were less than 10 by %WT (Fig. 2; Table 1). Very little fish consumption occurred in polar cod collected with pelagic trawls (<8 %WT). Mysid consumption only occurred in the diets of polar cod from the demersal samples (Table 1).

Discussion

Previous food habit studies from this region have shown adult polar cod to primarily prey upon zooplankton, both by %FO and by %N; however, these studies did not report polar cod prey by %WT (e.g., Craig et al. 1982). In this study, fish consumption dominated the diets of demersal polar cod by %WT and demonstrates that fish consumption is not insignificant in polar cod diets during the summer months. Adult polar cod have previously been documented as consuming mostly copepods and amphipods in the offshore US Beaufort Sea waters, by frequency of occurrence (Frost and Lowry 1983) and mysids in the inshore waters (Craig et al. 1982). Similarly, other studies have shown that copepods were often the main prey in the diets of adult polar cod in the Canadian Beaufort Sea (Bradstreet and Cross 1982), in the Barents Sea (Lønne and Gulliksen 1989), and in NE Greenland (Christiansen et al. 2012). Hop et al. (1997) reported a high percentage of empty stomachs in adult cod (64 %) collected in the Canadian high Arctic, but when food was present, the most abundant food items in their stomachs were pelagic hyperiid amphipods (*Themisto* spp.) and *Calanus* spp. copepods. Consistent with previous studies, Walkusz et al. (2012) found that demersal polar cod diets were dominated by copepods, amphipods, and mysids and Cui et al. (2012) reported that pelagic copepods and ampeliscid amphipods dominated polar cod diets in the north Bering Sea. In this study, copepods had a high frequency of occurrence in polar cod stomachs captured in the pelagic trawls, but contributed little to the percent weight of their diet.

Fishes were an important component of polar cod diets in the Beaufort Sea during August 2008. Fish consumption by polar cod has previously been documented to occur during a winter offshore survey in the Beaufort Sea (Craig et al. 1982). Fishes comprised the majority of the diet by %WT; however, FO was low; only 3 of the 22 stomachs examined contained fishes (Craig et al. 1982). There were no fishes documented in polar cod diets during the summer inshore survey in the same area, and no offshore survey occurred during the summer months (Craig et al. 1982). Thus, our results, from our summer offshore collections,

Table 1 Diet composition of polar cod collected with demersal and pelagic trawls characterized by percent frequency of occurrence (% FO), mean percent of prey weight (% WT), and mean percent of prey count (% N)

Prey	Demersal			Pelagic		
	%FO	%WT	% N	%FO	%WT	% N
Polychaeta	1.82	0.09	0.16	–	–	–
Crustacea	12.73	0.85	NA	23.57	5.11	NA
Calanoida (copepods)	53.48	7.23	46.50	63.57	4.2	27.17
Mysidae	10.45	1.0	2.36	–	–	–
Cumacea	8.94	0.68	4.30	–	–	–
Amphipoda (amphipods)	12.73	0.12	1.72	2.86	0.12	0.24
Gammaridae	14.39	1.07	2.54	5.71	0.86	0.48
Hyperiidae	10.45	9.44	5.28	21.43	5.73	5.46
Euphausiacea (euphausiids)	–	–	–	5.71	25.40	17.52
Euphausiidae	–	–	–	11.43	41.97	23.76
Decapoda (crab and shrimps)	–	–	–	5.71	0.87	0.96
Macrura Reptantia (crab)	4.09	0.29	1.52	6.43	0.43	0.84
Paguridae (hermit crab)	–	–	–	2.86	1.13	0.24
Echiuroidea (marine worm)	2.27	0.02	0.20	–	–	–
Chaetognatha (arrow worm)	15.45	1.45	7.95	–	–	–
Thaliacea (salp)	4.09	0.01	0.52	2.86	0.01	0.96
Copelata	23.64	1.53	11.43	52.86	6.65	15.90
Teleostei (fish)	4.09	3.81	0.36	6.43	2.24	0.54
Cottidae (sculpins)	–	–	–	<0.01	5.23	0.24
Myoxocephalus (sculpin)	17.27	63.75	9.27	–	–	–
Non-gadoid fish	1.82	7.51	1.28	–	–	–
Unidentified organic material	11.66	1.13	1.29	5.71	0.03	0.48
Total number of stomachs		48			34	
Total number of hauls		11			7	
Total number of prey		573			291	
Total prey weight (g)		14.203			7.083	

The prey categories reported are as recorded during laboratory analysis and do not overlap. For example, the prey category Decapoda includes only those stomach contents identified as Decapoda and does not include lower taxonomic levels (e.g., Macrura Reptantia). The %WT column sums to approximately 1.0. Note: The %FO, %WT, and %N are averaged by haul and then averaged by gear type; the totals shown for stomachs, hauls, number of prey, and weight are absolute and do not reflect the averaging confirm the previous observations of Craig et al. (1982) from the winter, indicating that fishes may be a regular part of the polar cod diet in the offshore Beaufort Sea. The dominant fish species by weight found in stomach contents of polar cod caught in demersal trawls were postflexion and transformation-stage sculpins, genus *Myoxocephalus* (family Cottidae). *Myoxocephalus* are pelagic at these life-history stages. Interestingly, Parker-Stetter et al. (2011) reported pelagic trawl catches of age-0 fish from the Cottidae family during the August 2008 US Beaufort Sea survey. It is possible that age-0 Cottidae fish identified acoustically during pelagic trawling (Parker-Stetter et al. 2011) may be the *Myoxocephalus* identified in the demersal diets of polar cod from the same survey. This suggests that demersal polar cod are vertically migrating in the water column to feed. This is strengthened by the fact that pelagic-associated prey (e.g., Chaetognatha, Thaliacea, and Copelata) were found in demersal cod and benthic-associated prey (e.g., Gammaridae, Macrura Reptantia, and Paguridae) were found in pelagic hauls. These results are consistent with Benoit et al. (2010), who documented diurnal vertical migration (DVM) from demersal to pelagic habitats by polar cod less than 25 g.

In general, the diets of adult polar cod can vary spatially (Craig et al. 1982; Frost and Lowry 1983) and temporally (Craig et al. 1982). For example, in the US Chukchi Sea, humpy shrimp (*Pandalus goniurus*) were the dominant food item for polar cod; however, depending on sample location, copepods, epibenthic mysids, and fishes were also dominant (Coyle et al. 1997). In this study, there appears to be little overlap between the demersal and pelagic cod diets in the dominant prey species by %WT. Demersal cod fed primarily on fishes (%WT), and pelagic cod fed primarily on euphausiids, by weight. However, the %FO of occurrence was similar in that copepods seemed to be the most common diet item for cod from both gear types. There are other qualitative differences between the demersal and pelagic diets, although their contribution to %WT is small. For example, taxa from Polychaeta, Mysidae, Cumaceans, Echiuroidea, and Chaetognatha occur only in demersal diets, and taxa from Decapoda and Paguridae occur only in the pelagic trawls. These results suggest that within the water column, polar cod feeding ecology may be spatially different. The pelagic and demersal trawls did not, in general, overlap in space and time (Parker-Stetter et al. 2011; Rand and Logerwell 2011); however, this consistent difference in a significant portion of their diet (by weight) suggests different targeted prey or different feeding behaviors between polar cod caught by pelagic and demersal trawls. A limitation in this diet analysis is that the pelagic trawls from which polar cod stomachs were collected were concentrated in the western portion of the study area (Fig. 1). Future research efforts should seek to remedy this by spacing collections for the demersal and pelagic trawls throughout the study area. Another possible explanation for the observed differences in diet between the demersal and pelagic trawls is the size of the polar cod sampled by the two different gear types. The maximum size of a polar cod in the demersal trawls was 18.1 versus 13.7 cm in the pelagic trawls. The different size ranges of polar cod sampled may be an artifact of the gear or real differences based on depth. Regardless, size of the fish is often a very important factor influencing diet composition. These differences have been documented between larval and juvenile polar cod (Walkusz et al. 2011) and young-of-the-year (YOY) and juvenile/adult polar cod (Pirtle and Mueter 2011).

In summary, our results show that fishes are a more important part of polar cod diet than previously understood and this information should be used to update Arctic food web models. In addition, our results showed possible differences in the diet of polar cod in pelagic versus benthic habitats, and this suggests that diet research for polar cod should incorporate sampling from both the demersal and pelagic environments, especially if using the data to inform ecosystem models.

Acknowledgments We would like to thank Troy Buckley and Christina Jump of the Alaska Fisheries Science Center (AFSC) and two anonymous reviewers for their very helpful reviews.

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