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Understanding How Sea Ice Influences Arctic Deep-Water Food Webs across a Latitudinal Gradient

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INTRODUCTION

GLOBAL MARINE ECOSYSTEMS ARE FACING numerous stressors, including the opening of new shipping pathways, invasive species, and climate change. In the Arctic Ocean, the ongoing loss of sea ice is predicted to increase surface water temperatures to 10˚C by the year 2300 (Carton et al., 2015). This increase is concerning because the Arctic Ocean plays an important role in regulating the temperature, biogeochemical cycles, and the dynamics of global food webs (Harada, 2016). In combination, these stressors on Arctic ecosystems have the potential to influence the diversity, structure, and energy dynamics of food webs (Kortsch et al., 2015), which vary both spatially (with latitude) and temporally (within time) (McMeans et al., 2015).

To understand food webs and their response to change, the ecological niche of an individual can be defined as a hypervolume of *n* dimensions in relation to resource use (Colwell and Rangel, 2009). Using a multidimensional approach to niche, it is possible to identify the relationship between diet composition (trophic level and resource availability) and habitat use (foraging behaviour) (Newsome et al., 2007). Niche characterization consequently provides a tool for understanding the role of species within an ecosystem and the interspecies interactions that influence species' ecological traits and energy transfer, as well as how an ecosystem responds to stressors and food web structure (Newsome et al., 2007; Bison et al., 2015).

Deep-water food webs are defined as assemblages of organisms below 200 m from the surface (Rogers, 2015; Priede, 2017). Despite being collectively the largest ecosystem on earth (99% by volume; Norse et al., 2012), these food webs are little understood; they are difficult and expensive to access and study, particularly in the Arctic. Stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) provide a cost-effective tool for understanding averaged diet history (Post, 2002), trophic level (Turner et al., 2010; Zimmo et al., 2012), and habitat connectivity (Inger and Bearhop, 2008), as well as for making inferences about an organism's niche and understanding the proportional contribution of basal carbon sources to species' diets (e.g., through Bayesian mixing models; Jackson et al., 2011; Phillips et al., 2014). Previous global work on $\delta^{13}C$ and $\delta^{15}N$ values in species found in Arctic (Iken et al., 2005; Bergmann et al., 2009), canyon (Demopoulos et al., 2017), and seamount habitats (Preciado et al., 2017) indicates that deep-water food webs comprise approximately four to five trophic levels, ranging from primary producer to predators, with most species occupying trophic positions 2 to 4 (Iken et al., 2005; Valls et al., 2014; Preciado et al., 2017). However, only limited niche research has been done to provide a baseline for monitoring future human and climate change impacts as temperate species move farther north. In order to understand species' niches in deep-water communities and how these change over a latitudinal gradient, more work is needed.

Highly branched isoprenoid (HBI) biomarkers can form an index known as the H-Print (Brown et al., 2014a), which provides an approach complementary to the stable isotope method for examining the contributions of carbon derived from pelagic and sympagic (sea ice) sources (Brown and Belt, 2017). This biomarker tool provides a relative measure of the importance and transfer rate of sea ice–derived carbon to Arctic deep-water food webs (Brown and Belt, 2017). While studies have examined proportional origins of carbon across entire shallow-water Arctic food webs (Brown, 2018; Brown et al., 2018), as well as in zooplankton (Brown and Belt, 2012; Brown et al., 2017a), particulate organic matter (Brown et al., 2016), fishes (Brown and Belt, 2017; Brown et al., 2015, 2017b), beluga whales (Brown et al., 2017b), ringed seals (Brown et al., 2014b), and polar bears (Brown et al., 2018), researchers have yet to investigate the importance of sea-ice carbon to deep-water food webs that vary by latitude in ice cover and concentration. Within the Arctic, organismal samples usually contain six to seven HBIs, and primary productivity is mainly pelagic or sympagic (derived from sea ice) (Brown et al., 2014a). Dominant HBIs in Arctic tissue samples are often Ice Proxy 25, better known as "IP_{25}" (Belt et al., 2007), and HBI-II (Brown and Belt, 2017), which originate from within sea-ice algae; whereas HBI-III is found in phytoplankton, indicating pelagic sources (Belt et al., 2017; Brown and Belt, 2017; Brown et al., 2018). Applying the H-Print technique to deep-water species will provide information critical to understanding the role of sea ice and impacts of climate change to Arctic deep-water food webs under climate change predictions.

Specifically, the study will examine temporal variation (seasonal and inter-annual) and spatial variation (at three sites with varying sea-ice extent and timing) in niche dynamics of deep-water species that adopt different foraging strategies and feed at various trophic levels (from primary consumers to predators). In addition, it will quantify the energy pathways that support deep-water species by examining the proportional contributions of two principal basal carbon sources: sympagic and pelagic. The overall objective of the study is to examine the architecture of Arctic deep-water food webs by examining species' roles across the entire ecosystem, which will aid the development, conservation, and management of sustainable fisheries.

RESEARCH METHODS

Data Collection

To examine the structure of deep-water Arctic food webs, invertebrates and fishes were collected using an otter trawl (1200 Campelen Shrimp trawl) and longline surveys (size #12 circle hooks baited with squid; 200 hooks spaced 2 m apart followed by 800 m of weighted line as a spacer and then another 200 m of size #12 hooks spaced 2 m apart), as well as from Inuit subsistence hunts. We studied three sites along the east coast of Baffin Island that differ in the timing of sea-ice formation and breakup, collecting samples at Scott Inlet in 2013 and at Pond Inlet and Qikiqtarjuaq in 2017 and 2018 (Fig. 1). Fishes and invertebrate samples were sorted (Fig. 2), frozen immediately at −20˚C onboard the M.V. *Nuliajuk*, and transported to the University of Windsor.

Data on the morphometric characteristics of species sampled, such as total length, body mass, and condition (e.g., hepatosomatic index for fishes) was collected in addition to tissue samples (liver, muscle, fin clips) with various tissue turnover rates (slow versus fast; muscle versus liver) (Heady and Moore, 2013) (Fig. 3). Tissue turnover rates for slow-growing (Xia et al., 2013) deep-water species are not well known, but estimates can be derived from Vander Zanden et al. (2015), who systematically reviewed animal tissue isotopic turnover data to develop a model for predicting turnover rates, on the assumption that high and low metabolic tissues will follow similar trends in slow-growing species. The same study also reported that as body mass increases, so does isotopic half-life. By analyzing tissues (muscle and liver) with variable turnover rates for stable isotopes ($\delta^{13}C$ and $\delta^{15}N$), we can obtain snapshots of both recent diet (from the liver tissue) and average dietary interactions over a longer time period (from muscle tissue). This multi-tissue approach helps us understand seasonal and interannual variation in niche dynamics of deep-water species. The relationship between morphometric characteristics and chemical tracers (H-Print, $\delta^{13}C$ and $\delta^{15}N$ stable isotopes) of tissues is also considered for niche (e.g., whether or not larger species have larger niches and the impact of fitness on niche).

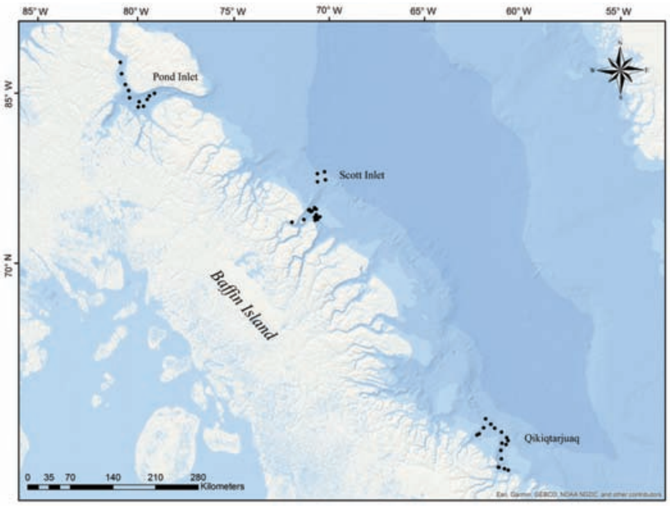

FIG. 1. Map of trawl locations from (north to south) Pond Inlet (2017), Scott Inlet (2013), and Qikiqtarjuaq (2017) on Baffin Island, Nunavut, Canada.

FIG. 2. Inuit science crew aboard the M.V. Nuliajuk *sorting fishes and invertebrates caught in an otter trawl.*

Benthic and pelagic primary productivity were quantified to determine the signatures of basal carbon sources by completing vertical zooplankton hauls (Fig. 4) and by grab sampling for benthic invertebrates.

Chemical Tracer and Niche Analysis

Tissue samples (muscle, liver, fin) will be analyzed for stable isotopes ($\delta^{13}C$ and $\delta^{15}N$). Samples were freeze dried (48 hours) at −53˚C using a Labconco freeze drier and then homogenized. Lipids will be removed using a 2:1 chloroform methanol solvent (performed once for muscle and twice for liver) and the remaining tissue will be weighed out in tin capsules using a Sartorius microgram balance. Stable isotope analysis will be completed at the Great Lakes Institute for Environmental Research

FIG. 3. Measuring morphometric characteristics of a Greenland halibut.

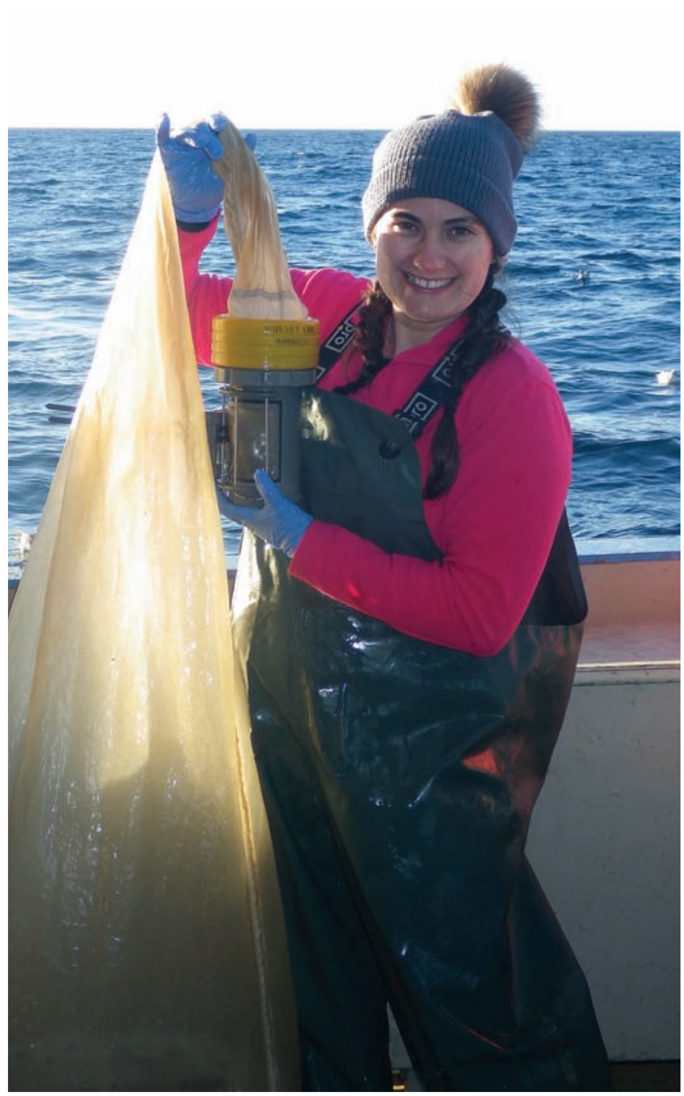

FIG. 4. Collecting zooplankton samples for baseline data to be analyzed for $\delta^{13}C$ and $\delta^{15}N$.

using a continuous flow Thermofinnigan Delta Plus mass spectrometer coupled with an elemental analyzer. Ratios of heavy to light nitrogen (^{15}N:^{14}N) and carbon (^{13}C:^{12}C) stable isotopes will be determined and compared to standard (Pee Dee Belemnite carbonate for $\delta^{13}C$; atmospheric nitrogen for $\delta^{15}N$) and internal references.

Liver will be analyzed for H-Print, given that ~70% of highly branched isoprenoid lipids are stored in this tissue (Brown et al., 2013). Liver tissue will be sent to the Scottish Association for Marine Science for extraction with analysis of HBI lipids and calculation of H-Print values using gas chromatography-mass spectrometry output. Mass spectral intensities of HBIs will be compared to authentic standards for identification and internal standards for quantification (Belt et al., 2012).

Environmental Data

Environmental factors such as water temperature, dissolved oxygen, salinity, and seasonal sea ice conditions were measured and will be compared to species niche and carbon contributions at the three sites (Fig. 1). Oceanographic data were collected from long-term fixed moorings with temperature loggers and shipborne conductivity-temperature-depth sensor casts, and sea-ice data was obtained from the Canadian Ice Service (which uses satellite data as well as ice observations from vessels, shores, and aircraft).

Sampling Conducted to Date

In fall 2013, longline and trawl surveys were completed in Scott Inlet using the M.V. *Nuliajuk*. In total, 21 trawls were completed spanning a depth range of 400 to 725 m. During the late summer of 2017, trawls were completed in Eclipse Sound (Pond Inlet) (11 trawls, depth range 165 to 728 m) and in the vicinity of Broughton Island (Qikiqtarjuaq) (17 trawls, depth range 185–653 m). Sampling in 2018 included trawling at Pond Inlet and Qikiqtarjuaq in August and September. Catches included Greenland halibut (*Reinhardtius hippoglossoides*), Arctic cod (*Boreogadus saida*), Polar cod (*Arctogadus glacialis*), sculpins (i.e., *Triglops pingelii*, *T. nybelini*, *Artediellus atlanticus*), Arctic skate (*Amblyraja hyperborea*), eelpouts (*Lycodes mcallisteri*, *L. rossi*, *L. eudipleurostictus*), shrimp (*Scleorcrangon* sp., *Eualus gaimardii*, *Pandalus borealis*), sea tadpoles (*Careproctus reinhardti*), snail fish (*Liparis fabricii*, *L. gibbus*), American plaice (*Hippoglossoides platessoides*), Atlantic poachers (*Leptagonus decagonus*), echinoderm species, and other fishes and invertebrates. Tissue samples (muscle, liver, fin) from all captured species are currently being processed for chemical tracer analyses.

SIGNIFICANCE

The Arctic marine environment is changing rapidly as a result of climate change and the ongoing and accelerating northward expansion of species from the south. It is critical that work be undertaken to help us understand how stressors are affecting the structure and stability of ecosystems, particularly deep-water food webs, to enable us to better predict how these communities will respond to changes, and to provide baseline data for future monitoring work on deep-water environments.

Deep-water food webs have received little attention from researchers. There are growing pressures to exploit and explore species in deep-waters (Hussey et al., 2017) with more than 300 exploitable deep-water species worldwide (Priede, 2017). These pressures are of concern because deep-water ecosystems are low-light (Drazon and Sutton, 2017; Priede, 2017), cold environments (approximately 4°C; Priede, 2017), where most species are highly *k*-selected with slow growth rates, longevity, late maturity (Norse et al., 2012; Victorero et al., 2018), low metabolism (Victorero et al., 2018), and a narrow dietary niche (Drazon and Sutton, 2017). Arctic deep-water ecosystems are particularly susceptible to climate change and acidification because carbon dioxide dissolves more quickly in cold water, ventilation is reduced, and organic material has increased residence time (Chen et al., 2017). Ongoing climate effects have the potential to alter conditions for deep-water species, with unknown ecological consequences (Levin and Le Bris, 2015).

In Nunavut, there is currently only one community-based commercial fishery for Greenland halibut (Hussey et al., 2017). The fishery started in 1986 (Coad and Reist, 2017) and is operated out of the community of Pangnirtung. Because of its success, other northern communities are interested in developing local fisheries (Barkley et al., 2018). An understanding of deep-water food webs and species interactions in the eastern Canadian Arctic will provide a baseline to assist the development of these community-based test fisheries. In addition, exploration of deep-water food webs is identifying new opportunities for subsistence fishing (e.g., shrimp fisheries, clam digging during low tide) to address food security issues in Arctic communities.

Throughout this project, local communities have participated in all aspects of research through co-planning of projects with Hunters and Trappers Organizations (community organizations involved in subsistence harvesting, sharing, and management of local research) and the employment and training of Inuit science staff in the use of fishing gear and sampling procedures. In addition, the incorporation of traditional knowledge (Inuit *Qaujimajatuqangit*) through community meetings and discussions is central to the success of research and its impact on northern communities (Riedlinger and Berkes, 2001). Hearing northern perspectives on how changes are influencing communities is crucial to incorporating this knowledge (Pearce et al., 2015) and to understanding the impacts of climate change (Riedlinger and Berkes, 2001). Deep-water species are not typically subjects of detailed traditional knowledge because historically these species were not commonly encountered (Idrobo and Berkes, 2012). For example, in the past Inuit *Qaujimajatuqangit* did not include deep-water species such as grenadiers (roughhead grenadier, *Macrourus berglax* and roundnose grenadier, *Coryphaenoides rupestris*; Devine et al., 2006), but the development of the Greenland halibut fishery in Pangnirtung has advanced knowledge of these species through direct experience. Grenadiers are a bycatch of the fishery, and community members have introduced them into their diet.

Overall, results from this study will be used to aid sustainable fishery development in the North, which will provide needed opportunities for economic growth, employment, and food security and will improve the well-being of Arctic communities. In addition, by completing an assessment at the ecosystem (multi-species) level rather than focusing on a single species, this research will foster an ecosystem-based approach to resource management and conservation.

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