Arctic Ocean Isoscapes

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1. Introduction

Arctic Ocean fisheries are a critical food source to indigenous people living along the Arctic coast. These fisheries are thought to be sensitive to recent climate warming in the Arctic, which has caused increased coastal erosion and freshwater inputs from land (Peterson et al. 2006) over the past 50 years. These changes alter the marine food webs by potentially increasing the delivery of allochthonous terrestrial organic matter to the Arctic Ocean. Whether this results in stimulating benthic and pelagic productivity or suppressing it remains unclear and so understanding the patterns, controls, and feedbacks in Arctic marine food webs is a central outstanding problem. Long-term changes of this nature are difficult to assess but can be done by monitoring faunal diets, either by direct stomach content analysis or by using a stable isotope approach.

Not all seas in the Arctic will be affected by climate change to the same extent – where baseline conditions vary, so too should the response to perturbation. The Chukchi and Bering Seas have higher productivity and benthic biomass than the Beaufort Sea (Dunton et al., 2005). Unlike the Chukchi and Bering Sea, the Beaufort Sea is an estuarine environment, especially in summer, due to freshwater inputs from arctic rivers such as the Colville and the Mackenzie. These rivers transport dissolved and particulate organic matter of terrestrial origin into the coastal Arctic Ocean (Macdonald et al., 2004). This terrestrial carbon is greatly important to coastal Beaufort food webs because of the low *in-situ* production in the Beaufort Sea (Dunton et al., 2006). Because of the different characteristics of these Arctic Seas, different species assemblages and food web dynamics characterize their upper trophic levels.

One way of assessing food sources and feeding relationships among organisms is to examine their stable isotope signatures. Since the carbon isotopic signature ($\delta^{13}C$) of an organism experiences little fractionation between trophic levels (0-1.5‰), it is indicative of the basal carbon energy source (ex. marine microalgae vs. terrestrial organic matter) that supports that organism's growth. The nitrogen stable isotope signature ($\delta^{15}N$) of an organism, on the other hand, is enriched by roughly 3.4‰ with each transfer up the trophic ladder, thus providing information on the trophic level of that organism (Hobson and Welsh, 1992). These two measures can be combined to outline food webs and trace the flow of energy through ecosystems (Fry and Sherr, 1984; Peterson, 1999).

Terrestrial organic matter can be distinguished from marine *in-situ* production based on their stable carbon and nitrogen isotope signature, both carbon and nitrogen stable isotope analysis has been used to determine the incorporation of terrestrial matter into food webs in the Arctic Ocean (i.e. Dunton et al., 2006). Terrestrial nitrogen sources have $\delta^{15}N$ signals ranging from 0-1.5‰ whereas marine phytoplankton are typically much heavier and range from 5-7‰. Similarly, the $\delta^{13}C$ signal of terrestrial organic matter is typically more depleted (-27‰) than that marine organic matter (-32‰) (O'Leary, 1988).

Previous isotopic studies have noted that $\delta^{13}C$ values of sediments (Dunton et al., 2006), zooplankton (Saupe et al., 1989), and many benthic invertebrates (Dunton et al., 1989), follow the same pattern as the benthic productivity rates along the coast. $\delta^{13}C$ values are more enriched in Bering (an area of high benthic production), decline in the Chukchi and the Western Beaufort, and are the most depleted in the Eastern Beaufort (an area of low production). This is attributed to the Beaufort Undercurrent, which flows from the Bering Sea, through the Bering Strait, into the Chukchi Sea during the summer ice-free months (Dunton et al., 2006). The Beaufort Undercurrent carries organic matter, enriched in ^{13}C, from the Bering Sea northward.

The purpose of this study is to examine spatial and temporal trends of stable C and N isotopic signature of basal carbon energy sources and of benthic consumers in the Arctic Ocean in order to make inferences about food web structure and energy flow.

2. Methods

2.1 Study Area

The study area in the Arctic Ocean extends Northward from the Bering Sea through the Bering Strait and into the Chukchi and the Beaufort seas (Figure 1). Major currents in this area include the Bering Strait through flow and the Beaufort Undercurrent. Major freshwater inputs include the Colville and Mackenzie rivers.

2.2 Study Species

I selected sediment, particulate organic matter (POM), and phytoplankton as carbon sources to examine both because they are important food sources to benthic fauna and because a lot of data was available for these species over the last 12 years. These carbon sources are expected to have similar stable isotope values because when phytoplankton die, they become part of the particulates in the water column, which eventually settle out and contribute to the OM pool in the sediments. All three of these carbon sources will also reflect terrestrial inputs.

I selected two bivalves (*Macoma* spp and *Ennucula tenuis*), a predatory polychaete worm (*Nephtys ciliata*), and Arctic Cod (*Boreogadus saida*) as benthic consumers.

I selected these bivalves, both commonly found in the Arctic, because they are deposit feeders, which consume sediment organic matter directly. I expect the stable isotope signature of these bivalves to reflect the signature of sediment OM, which contains a lot of detritus and may show signs of terrestrial influence in certain areas. I combined data for *Macoma calcarea*, *Macoma moestra*, and bivalves that had only been identified to the *Macoma* family in order to have enough data for this bivalve group.

Nephtys, a predatory polychaete, was selected because these worms burrow in the sediments but prey on meiofauna, so their isotope values should reflect a sediment OM source but an elevated trophic position relative to the benthic bivalves. Similarly, *Boreogadus*, which feeds on benthic invertebrates, was expected to show carbon stable isotope values indicative of sediment OM and nitrogen values more enriched than *Nephtys*, which may be part of *Boreogadus*'s diet.

2.3 PacMARS Data Set

An Isotope synthesis database comprised of >4,000 stable carbon and nitrogen values from several studies in the Arctic Ocean was compiled by Dr. Ken Dunton from the Marine Science Institute, University of Texas at Austin as part of the Pacific Marine Arctic Regional Synthesis (pacMARS) project (Figure 2). These data were added to a GIS feature class by Mr. Tim Whiteacre from the University of Texas at Austin. All data used in this project originated from this PacMARS isotope synthesis file, provided to me by Mr. Whiteacre. Although the isotope synthesis contained data from 1985-2011 from over 30 taxa, this project only used data from 2000-2011 from 3 carbon sources and 4 benthic consumers (Tables 1-7).

2.4 GIS Methods

2.4.1 Basics

The PacMARS stable isotope synthesis layer created by Mr. Tim Whiteaker was projected in the GCS_WGS_1984 Geographic coordinate system using the D_WGS_1984 datum. The Projected coordinate system is the North_Pole_Stereographic. The Topographic basemap available on arcMap 10.2 was used in some maps. In other maps, Natural Earth 50m resolution shapefiles (ocean, land, lakes, rivers, and glaciated areas) were added to create a visually pleasing background for maps. Rivers were also added at the 10m resolution so that smaller rivers could be seen on the Arctic coast. The state of Alaska is outlined in black in all maps.

2.4.2 Determining Spatial Interpolation Method

I created a query filter on the larger PacMARS dataset to begin making isoscapes for the $\delta^{13}C$ values of each food web component. Sample points were color-coded by their $\delta^{13}C$ value to get a sense for what spatial pattern should be expected. Next, I spatially interpolated the data to convert the vector points to a raster, which I restricted to the outermost geographical boundary of the data points. I tested several spatial interpolation methods (spline, natural neighbor, kriging, and inverse distance weighting) appropriate for continuous data to determine which method was most fitting for the stable isotope data (Figure 3). Because of previous knowledge suggesting that the Beaufort Sea has more $\delta^{13}C$-depleted POM than the Bering and Chukchi Seas, I eliminated using the spline method, which did not show this expected trend. The natural neighbor method interpolated over a small distance, which was not favorable given the small sample size for some food web components. The kriging method emphasized the maximum and minimum $\delta^{13}C$ values more than I thought was biologically likely. The inverse distance weighting interpolation method provided a realistic spatial pattern that fit with previous conceptions of isotopic trends in the region, and so I chose this method for generating isoscapes.

2.4.3 Generating Isoscapes and Identifying Patterns

I used the inverse-distance weighting interpolation method to create isoscapes of $\delta^{13}C$ and $\delta^{15}N$ data for three carbon sources in the Arctic Ocean—sediment, POM, and phytoplankton. First, I pooled data from all years available to generate an isoscape for $\delta^{13}C$ and $\delta^{15}N$ for each carbon source. Isotope values were binned such that I could apply the same color scale to each map. I chose to restrict isotope data to 6 bins because I only wanted to assess broad trends through space, and was not interested in differences smaller than 1-2‰. Next, I made a separate isoscape for each year with available data for each isotope and each carbon source (figures not shown). However, because of the paucity of data collected each year and the small spatial range of data from several years, robust conclusions about changes to $\delta^{13}C$ and $\delta^{15}N$ values of carbon sources from year to year is not possible at this time.

Finally, I created isoscapes for four benthic consumers common to the Arctic Ocean: *Macoma* spp., *Ennucula tenuis, Nephtys ciliata*, and *Boreogadus saida*. There was not enough data avialable to assess annual differences in spatial distribution of isotope values, so all data for each consumer was included to create a single $\delta^{13}C$ isoscape and a single $\delta^{15}N$ isoscape.

The isoscapes for benthic consumers were visually compared to the carbon source isoscapes to make inferences about these organisms feeding habits and position in Arctic Ocean food webs. I compared the implications from this study with previous studies about the feeding ecology of these benthic organisms.

3. Results and Discussion

3.1 Patterns through Time

Ignoring the spatial distribution, the average sediment organic matter became approximately 2‰ more enriched in ^{13}C from 2003 to 2010 (Figure 4). Neither POM nor phytoplankton showed significant linear trends, although there is high interannual variability in $\delta^{13}C$ in both of these carbon pools. POM ranges from -23‰ in 2004 to -31‰ in 2006. Phytoplankton ranges from -19‰ in 2002 and -25‰ in 2010.

The carbon sources also vary in $\delta^{15}N$ concentration through time (Figure 5). The $\delta^{15}N$ concentration is more variable in a given year than the $\delta^{13}C$ values, indicated by larger standard error bars. Sediment becomes approximately 3‰ more enriched from 2003 to 2010. POM values show the opposite trend, decreasing from 7‰ in 2002 to 5.5‰ in 2010.

The stable isotope signatures of benthic consumers are similarly variable through time between 2000 and 2012 (Figures 6 and 7). *Macoma* spp. and *Ennucula*, both bivalve species, have similar $\delta^{13}C$ and $\delta^{15}N$ values each year. *Nephtys* ranges widely in $\delta^{13}C$ values, from -23‰ in 2008 to -19‰ in 2009. *Boreogadus* becomes significantly more enriched in ^{13}C over time, from -23‰ in 2004 to -20‰ in 2010.

The $\delta^{15}N$ of the benthic consumers through time is indicative of their feeding style. The bivalve species are the more depleted in ^{15}N relative to *Nephtys* and *Boreogadus*, which are both secondary consumers. No significant relationships were apparent through time in the $\delta^{15}N$ data.

These analyses only consider changes to isotopic composition through time and do not consider the influence of spatial variability. The isotopic data summarized in these tables and graphs spans a huge spatial range—from the Bering Strait North into the Chukchi and Beaufort Seas. Because of this large spatial range it is neccesary to also examine changes over space.

3.2 Patterns through Space

There is insufficient data to generate isoscapes for each year of sampling for these food web components. Pooling data from multiple years, however, allows us to examine the broad geographic patterns of food webs in the region. These patterns are more likely related to ultimate source of carbon and nitrogen rather than trophic position or species differences.

Sediment, POM, and phytoplankton all show the same general trend of more enriched $\delta^{13}C$ values in the Bering Sea and in the Chukchi Sea (Figure 8). $\delta^{13}C$ values for each species become more depleted Eastward in the Beaufort Sea. Also notable is the large plume of depleted phytoplankton in the Beaufort Sea. This plume occurs near the mouth of the Colville River and is likely the result of terrestrially-derived carbon (~-27‰) being incorporated into the body tissues of phytoplankton. These findings agree with previous research that suggests the depleted $\delta^{13}C$ values of sediment and POM in the Eastern Beaufort are be due to terrestrial inputs from rivers (Dunton et al., 2012).

The three carbon sources also vary widely in $\delta^{15}N$ values though space (Figure 9). Sediment and POM range from less than 2‰ to over 10‰. Phytoplankton are more enriched and less variable in $\delta^{15}N$, although the lack of variability might be due to the small sample size of the phytoplankton dataset. Sediment $\delta^{15}N$ values are more enriched in the Western Beaufort and more depleted in the Eastern Beaufort, which also reflects the increasing importance of terrestrial organic matter in the Eastern Beaufort.

Similar spatial trends are evident in the isoscapes for the four benthic consumer species examined. In all four species, $\delta^{13}C$ values are more enriched in the Bering and in the Chukchi, and become more depleted in the Beaufort Sea (Figure 10). This pattern is to be expected because the benthic consumers are generating new body tissue from the carbon sources available to them—primarily utilizing OM in the sediment. This agrees with the recent findings of Dunton et al. (2012) which conclude that terrestrial organic matter is incorportated into benthic food webs. The $\delta^{13}C$ values of the consumer species are more enriched relative to the carbon sources in most areas of the Arctic Ocean. This consumer enrichment results from the 0-1.5 ‰ fractionation that occurs in $\delta^{13}C$ values between trophic levels during biomass incorporation.

The $\delta^{15}N$ isoscapes of benthic consumer reflect the same trophic positions as the spatially-averaged data (Figure 11), whereby *Macoma* and *Ennucula* are more depleted relative to the secondary consumers, *Nephtys* and *Boreogadus*. *Boreogadus* is most enriched in ^{15}N, reflecting the position of Arctic Cod as a top consumer in Arctic food webs Arctic (Craig et al., 1984). Additionally, the benthic consumer $\delta^{15}N$ isoscapes show the same trend as the sediment $\delta^{15}N$ isoscapes—$\delta^{15}N$ values for all consumers are more enriched in the Western Beaufort and more depleted in the Eastern Beaufort Sea. The *Macoma* and *Ennucula* isoscapes show this trend continues into the Chukchi sea.

3.3 Food webs

The isotope biplot provides a visualization of the carbon and nitrogen range of all carbon sources and consumers analyzed (Figure 12). The carbon sources regions all overlap in $\delta^{13}C$ values, which is to be expected since the particulate organic matter in the water column (POM) and on the ocean floor (sediment) contain a lot of recently dead phytoplankton. The organic matter on the sediment will also include POM that has settled out of the water column. The POM and sediment may be more depleted in ^{15}N than the phytoplankton because they incorporate organic matter of terrestrial origin. The benthic consumers are all more enriched in $\delta^{13}C$ than the carbon sources examined. Because they are more than 1.5‰ more enriched than the carbon sources, this must be due to more than the small trophic enrichment factor. This may be due to the importance of another carbon source that was not examined in this study, such as macroalgae.

The $\delta^{15}N$ values of consumers reflects their expected trophic positions. Bivalves are ~3‰ higher than sediment and POM, but only 1‰ higher than phytoplankton, indicating sediment and POM are more important carbon sources (assuming the trophic fractionation factor is accurate for this region). Also, cod is 5‰ higher than the bivalve species and 2‰ higher than Nephtys, indicated there are probably other intermediate consumer trophic levels present in the Arctic Ocean that are not examined in this paper.

3.4 Suggested Future Work

Previous isotopic studies in the Arctic Ocean have shown that stable isotope values of carbon sources and of consumers may vary seasonally (Dunton et al., 2006 and Dunton et al., 2012). For example, Dunton et al. (2012) found that lagoon fauna are more enriched in the early summer, likely due to reliance on marine carbon sources, and more depleted during the late Summer, likely due to increased terrestrial inputs as Arctic rivers melt and carry dissolved and particulate organic matter into the coastal ocean. Previous studies have also shown that prey availability in the Arctic may vary seasonally (i.e. Craig et al., 1984 and Dunton et al., 2006). As a result, higher consumers, such as Arctic cod, may change their diets during different times of the year.

As such, it would be very interesting to see if there are seasonal differences in isoscapes for carbon sources and benthic consumers in the Arctic Ocean. Due to the difficulty of collecting samples from the Arctic during winter, it may only be feasible to compare data from the early summer (May-June) and late summer (July-August) seasons, when the ice cover allows research vessels easier access. Future work should also explore temporal trends on a regional basis—by dividing the Arctic Ocean up into sub regions and looking for temporal trends in each sub region separately.

4. Conclusions

1. Isoscapes for sediment, POM, and phytoplankton all indicate that terrestrial inputs are more important to the Eastern Beaufort Sea whereas marine primary production supports food webs in the Bering and Chukchi Seas.

2. Isoscapes for benthic consumers show that terrestrial matter in the Eastern Beaufort is likely assimilated by benthic fauna. Importantly, there remains an unknown carbon source, which is δ^{13}C-enriched that was not examined in this study but contributes significantly to the biomass of benthic consumers.

3. More samples from a wider spatial area for each year are needed to assess changes to stable isotopic composition of carbon sources and benthic consumers though time. Future work should examine the PacMARS stable isotope dataset to determine if seasonal trends in subregions are present.

Acknowledgements

Thanks to Dr. Ken Dunton and Mr. Tim Whiteaker for making the PacMARS dataset available to me and for answering questions throughout this project. Thanks also to Carlos Galdeano and Stephen Jackson for help with picking an appropriate projection and basemap in arcMap. Thanks to Dr. Maidment for teaching a great class!

References

Craig, P.C., W.B. Griffiths, S.R. Johnson, and D.M. Schell. 1984. Trophic dynamics in an arctic lagoon. In: Barnes, PW, DM Schell, E Reimnitz (eds.), The Alaskan Beaufort Sea: Ecosystems and Environments. Academic Press, Inc.pp 347-380.

Dunton, K.H., J.L. Goodall, S.V. Schoberg, J.M. Grebmeier, and D.R. Maidment. 2005. Multidecadal synthesis of benthic-pelagic coupling in the western arctic: a role of cross-shelf advective processes. Deep-Sea Research II 52, 3462-3477.

Dunton, K.H., S.M. Saupe, A.N. Golikov, S.M. Schell, and S.V. Schonberg. 1989. Trophic relationships and isotopic gradients among arctic and sub-arctic marine fauna. Marine Ecological Progress Series 56: 89-97.

Dunton, K.H., S.V. Schonberg, and L.W. Cooper. 2012. Food web structure of the Alaskan nearshore shelf and estuarine lagoons of the Beaufort Sea. Estuaries and Coasts 35(1): .

Dunton, K.H., T. Weingartner, and E.C. Carmack. 2006. The nearshore western Beaufort Sea ecosystem: Circulation and importance of terrestrial carbon in arctic coastal food webs. Progress in Oceanography 71: 362-378.

Fry, B. and E. Sherr. 1984. ^{13}C measurements as indicators of carbon flow in marine and freshwater ecosystems. Contributions in Marine Science 27: 13-47.

Hobson, K.A., and H.E. Welsh. 1992. Determinations of trophic relationships within Arctic marine food webs using $\delta^{13}C$ and $\delta^{15}N$ analysis. Marine Ecology Progress Series 84: 9-18.

Macdonald, R.W., E. Sakshaug, and R. Stein. 2004. The Arctic Ocean: modern status and recent climate change. In *The organic carbon cycle in the Arctic Ocean*, ed. R. Stein and RW Macdonald. 6-21. Berlin: Springer.

O'Leary, M. 1988. Carbon isotopes in photosynthesis. Bioscience 38(5): 328-335.

PacMARS "About Page" http://pacmars.eol.ucar.edu/about.html

Peterson, B. J. and B. Fry. 1987. Stable Isotopes In Ecosystem Studies. Annual Review of Ecology and Systematics 18: 293-320.

Peterson, B. J., McClelland, J., Curry, R., Holmes, R. M., Walsh, J. E., & Aagaard, K. (2006). Trajectory shifts in the Arctic and subarctic freshwater cycle. *Science*, *313* (5790), 1061-1066.

Tables

All tables show the average, standard deviation (SD) and sample size for $\delta^{13}C$ and $\delta^{15}N$ data for a particular carbon source or benthic consumer for each year that data was available, and all years combined. The average depth from which the samples were collected is also shown. n.d.= no data available.

Table 1. Particulate Organic Matter (POM)

POM	$\delta^{13}C$			$\delta^{15}N$			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2002	61	-26.21	2.05	61	7.52	1.62	10
2003	21	-24.43	1.95	21	7.90	2.34	21
2004	69	-23.71	2.17	69	5.14	1.20	30
2006	3	-30.65	0.51	3	6.64	0.73	n.d.
2008	24	-24.88	1.37	24	5.45	1.14	12
2009	56	-24.06	1.67	56	5.38	2.14	22
2010	6	-23.31	0.51	6	5.57	1.92	21
All years	241	-24.69	2.16	240	5.38	2.14	18

Table 2. Sediment

Sediment	$\delta^{13}C$			$\delta^{15}N$			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2003	2	-25.68	0.15	2	2.21	0.33	n.d.
2004	3	-25.16	1.27	3	6.53	5.11	n.d.
2008	46	-25.39	0.97	46	3.29	0.51	n.d.
2009	74	-23.10	1.60	74	7.07	0.72	n.d.
2010	73	-23.15	0.67	71	8.04	1.25	n.d.
All years	198	-23.71	1.53	196	6.48	2.16	n.d.

Table 3. Phytoplankton

Phyto	$\delta^{13}C$			$\delta^{15}N$			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2002	1	-19.02	n/a	1	9.37	n/a	n.d.
2003	2	-25.68	0.15	2	2.21	0.33	n.d.
2004	3	-25.16	1.27	3	6.53	5.11	n.d.
2008	46	-25.39	0.97	46	3.29	0.51	n.d.
2009	87	-23.22	1.60	87	7.17	0.84	n.d.
2010	86	-23.40	0.94	86	9.75	0.64	n.d.
All years	225	-23.76	1.55	225	8.87	1.39	n.d.

Table 4. Macoma species (includes *Macoma calcarea*, *Macoma moestra*, and bivalves identified to the *Macoma* family)

Macoma	**δ¹³C**			**δ¹⁵N**			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2000	16	-20.89	2.25	16	8.43	0.83	n.d
2002	22	-19.74	1.60	22	9.23	0.99	n.d
2004	24	-18.66	1.17	24	8.97	1.15	n.d
2008	12	-24.39	0.50	12	7.19	0.70	n.d
2009	12	-20.75	0.97	12	9.33	1.73	n.d
2010	19	-19.57	1.49	19	9.65	0.87	n.d
All years	105	-20.30	2.20	105	8.90	1.27	n.d

Table 5. *Ennucula tenuis*

Ennucula	**δ¹³C**			**δ¹⁵N**			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2000	13	-20.16	1.12	13	9.61	0.59	n.d
2002	24	-18.89	1.12	24	10.11	0.74	n.d
2004	26	-18.38	0.55	26	9.00	0.80	n.d
2008	8	-23.90	1.27	8	8.91	0.55	n.d
2009	40	-20.05	0.73	40	9.45	0.82	n.d
2010	9	-18.85	1.08	8	9.88	0.51	n.d
All years	120	-19.63	1.61	119	9.50	0.84	n.d

Table 6. *Boreogadus saida*

Boreogadus	**δ¹³C**			**δ¹⁵N**			
Year	**n**	**Ave (‰)**	**SD (‰)**	**n**	**Ave (‰)**	**SD (‰)**	**Ave Depth (m)**
2004	9	-22.52	3.31	9	13.00	1.88	n.d
2006	1	-21.24	n/a	1	13.99	n/a	n.d
2007	1	-21.92	n/a	1	12.33	n/a	n.d
2009	23	-20.04	0.91	23	15.62	**0.74**	n.d
2010	7	-20.30	1.38	7	14.79	0.55	n.d
All years	41	-20.71	2.02	40	14.76	1.54	n.d.

Table 7. *Nephtys ciliata*

Nephtys	δ^{13}C			δ^{15}N			
Year	n	Ave (‰)	SD (‰)	n	Ave (‰)	SD (‰)	Ave Depth (m)
2008	29	-22.34	1.18	29	12.50	1.33	n.d
2009	20	-17.98	1.17	20	15.28	1.22	n.d
2010	22	-19.57	1.29	22	12.84	1.85	n.d
All years	71	-20.25	2.20	71	13.39	1.89	n.d

Figures

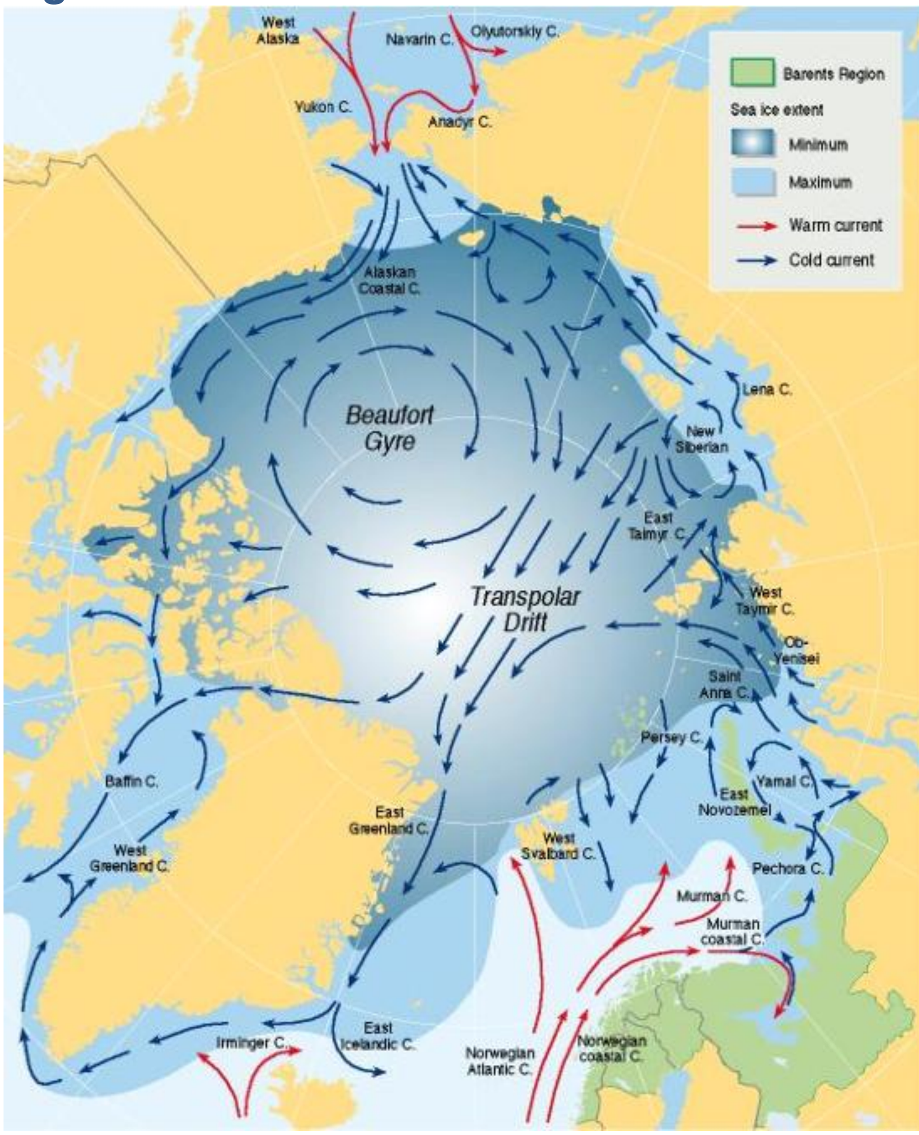

Figure 1. Map of the Arctic Ocean. Arrows indicate direction of water flow. The Arctic Ocean circulates in a clockwise pattern, called the Beaufort Gyre. Source: Philippe Rekacewicz, Barentswatch Atlas, 2005.

< http://www.grida.no/graphicslib/detail/ocean-currents-and-sea-ice-extent_4aa6>

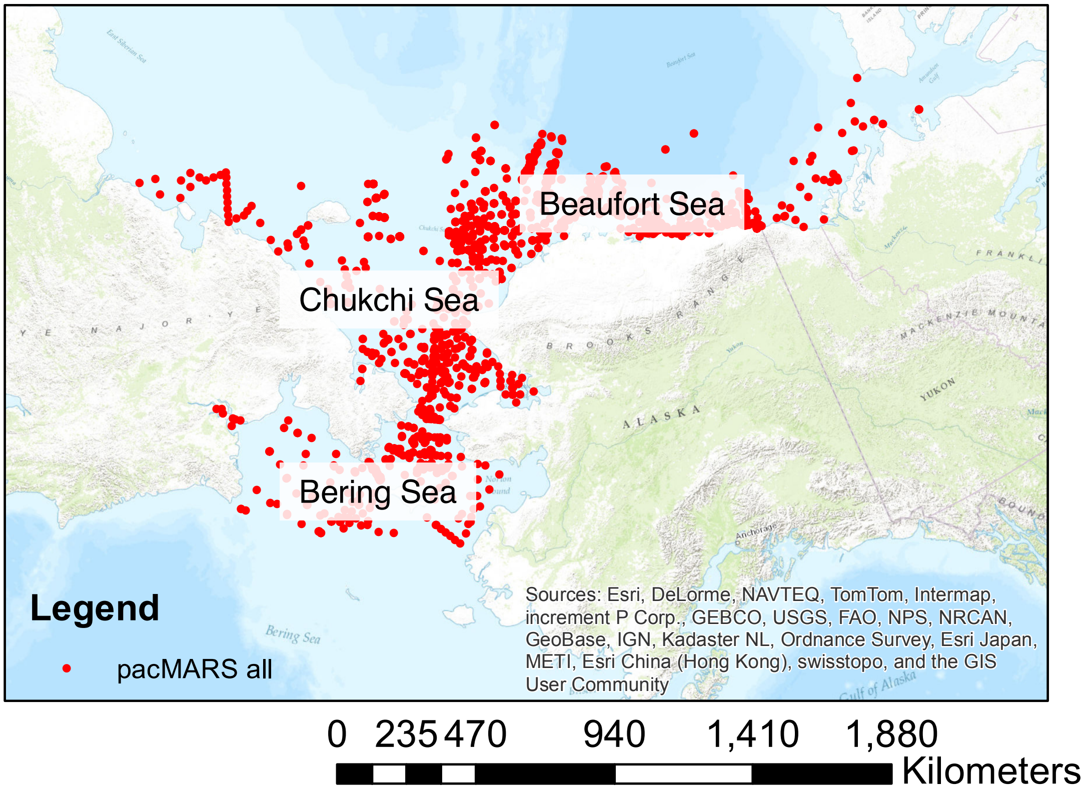

Figure 2. Locations of all data contained in the PacMARS stable isotope synthesis project. Each point represents a location with a $\delta^{13}C$ or $\delta^{15}N$ value for an organism (or type of organic matter) from 1985 to 2011.

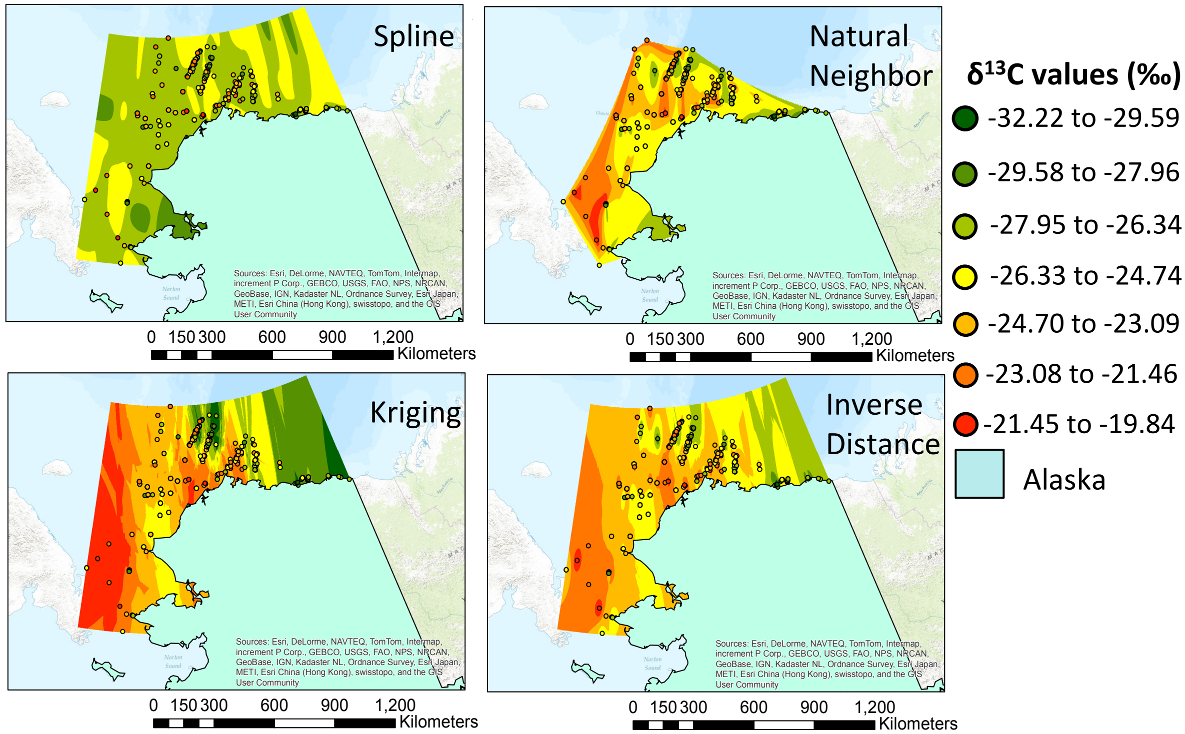

Figure 3. Rasters created from four spatial interpolation methods (spline, natural neighbor, kriging, and inverse distance) are shown. The original POM $\delta^{13}C$ values are displayed as points.

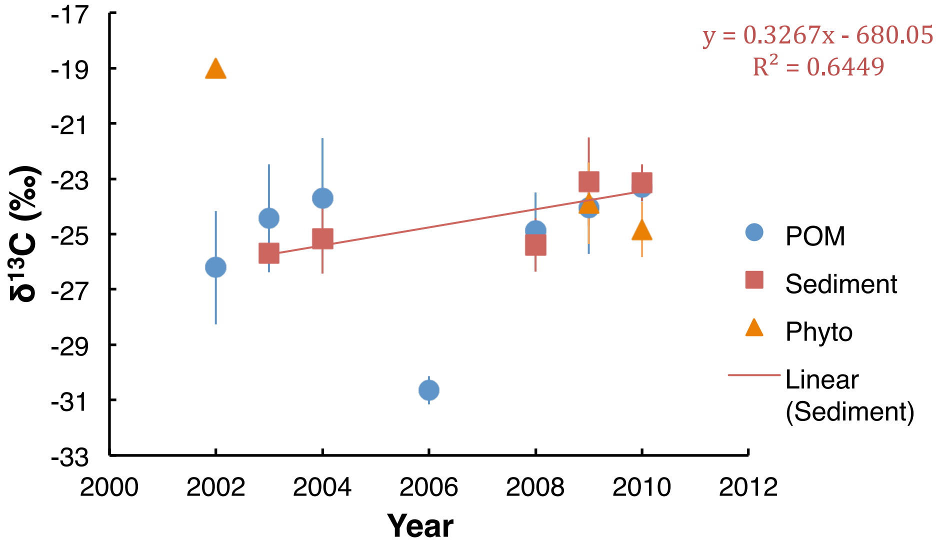

Figure 4. $\delta^{13}C$ values (mean ± SD) for three carbon sources (POM, sediment, and phytoplankton) from 2002 to 2011. Significant ($p<0.05$) linear regression lines are displayed. Data was not available for every year.

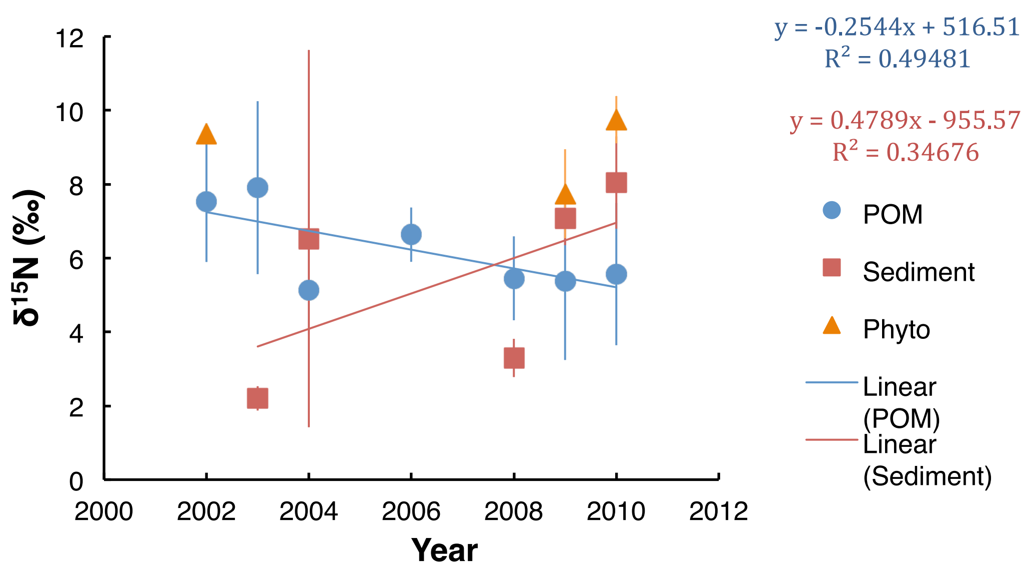

Figure 5. $\delta^{15}N$ values (mean ± SD) for three carbon sources (POM, sediment, and phytoplankton) from 2002 to 2011. Significant ($p<0.05$) linear regression lines are displayed. Data was not available for every year.

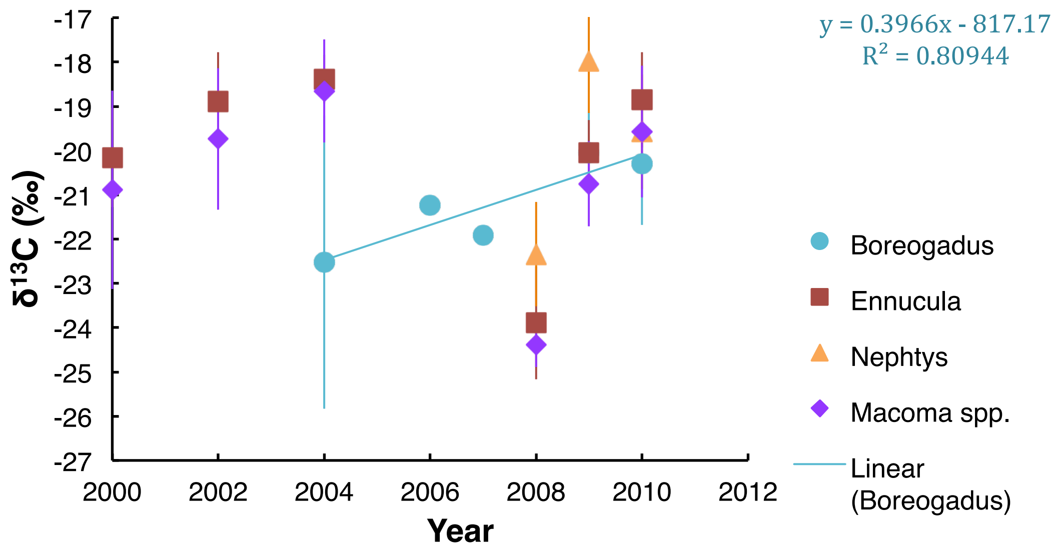

Figure 6. $\delta^{13}C$ values (mean ± SD) for four benthic consumers (Boreogadus, Ennucula, Nephtys, and Macoma) from 2000 to 2011. Significant ($p<0.05$) linear regression lines are displayed. Data for each species was not available for every year.

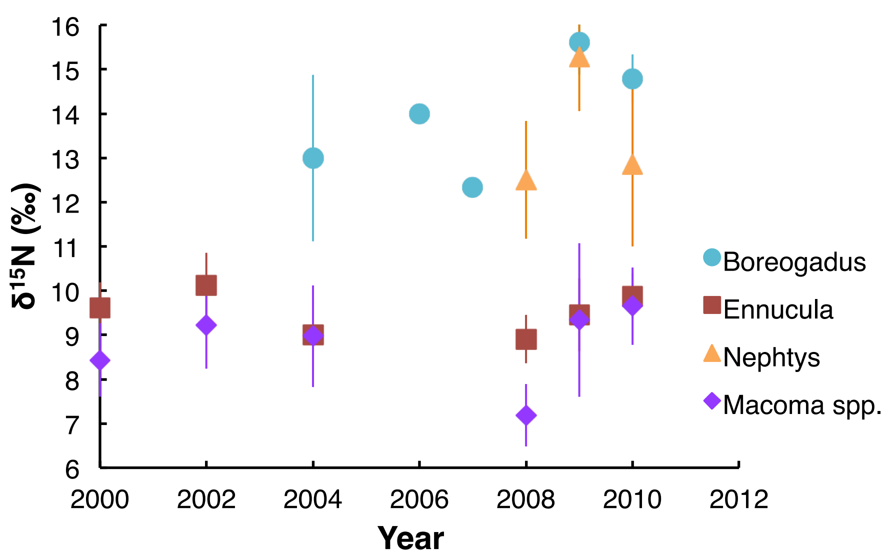

Figure 7. $\delta^{15}N$ values (mean ± SD) for four benthic consumers (Boreogadus, Ennucula, Nephtys, and Macoma) from 2000 to 2011. Data was for each species not available for every year.

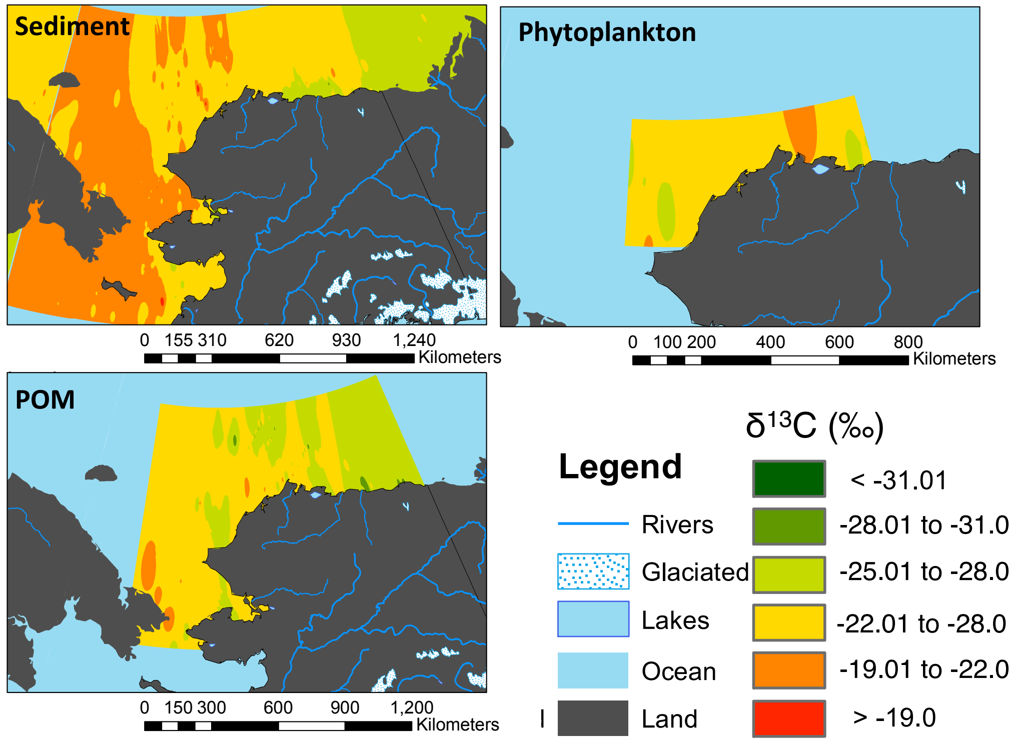

Figure 8. Carbon source $\delta^{13}C$ isoscapes. Data from all years are included.

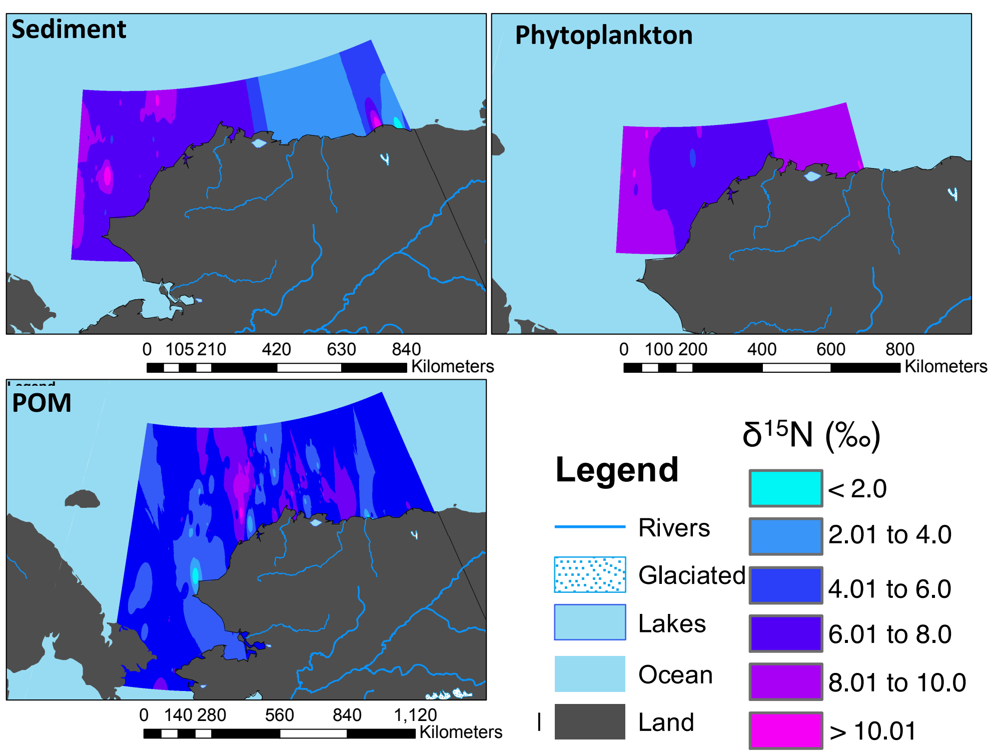

Figure 9. Carbon source $\delta^{15}N$ isoscapes. Data from all years are included.

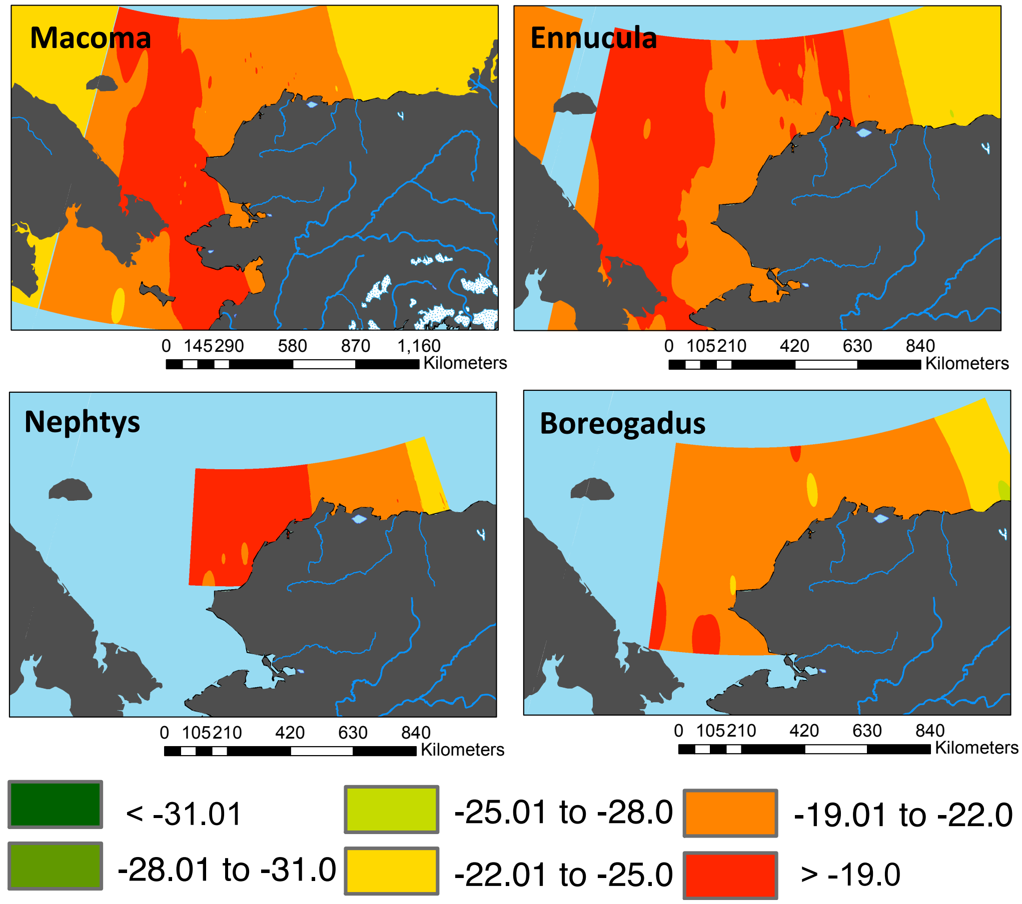

Figure 10. Benthic consumer $\delta^{13}C$ isoscapes. Data from all years are included.

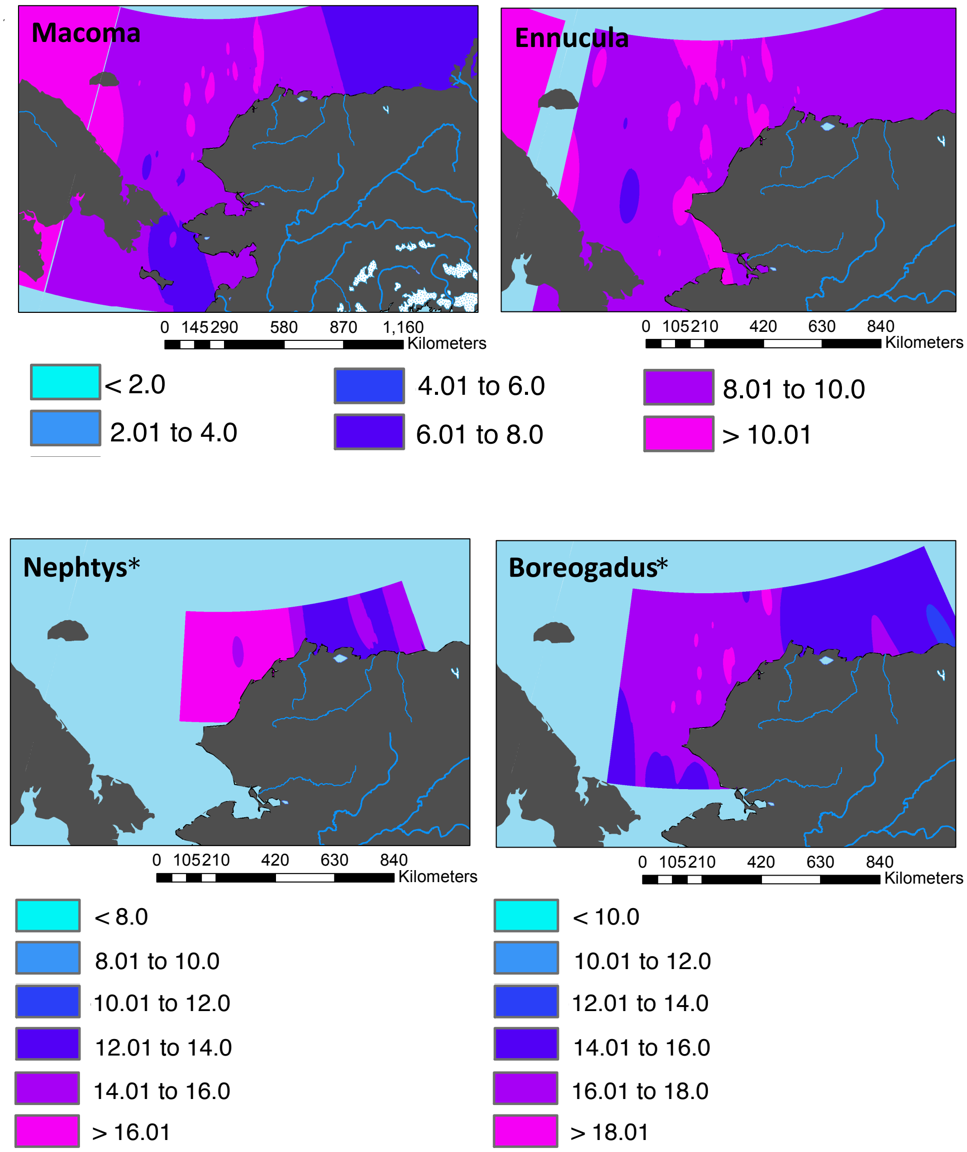

Figure 11. Benthic consumer $\delta^{15}N$ isoscapes. Data from all years are included. *Note that Nephtys and Boreogadus have different bin values than Macoma and Ennucla, which have the same bins as the carbon sources.

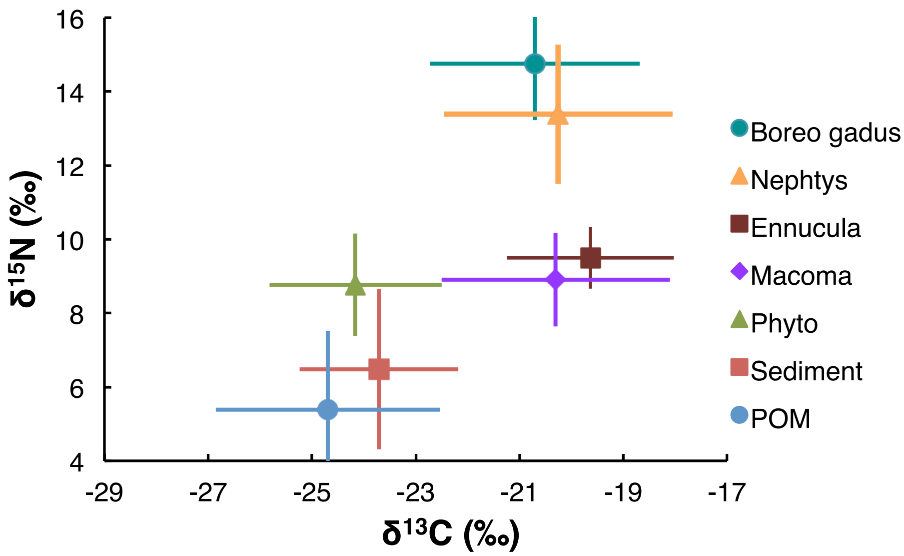

Figure 12. Biplot of $\delta^{13}C$ and $\delta^{15}N$ values (average over all years ± SD) for all carbon sources and benthic consumers examined.