NITROGEN ISOTOPE ANALYSIS IN THE ARCTIC: IDENTIFYING FISH PROCESSING AND MARINE RESOURCE USE THROUGH ETHNOARCHAEOLOGICAL SOIL ANALYSIS ON NELSON ISLAND, ALASKA

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ABSTRACT

Despite the importance of marine resources and seasonal fish processing in the past, their ephemeral natures hamper archaeological study. However, nitrogen isotope analysis of soils provides a new, minimally invasive method to identify marine resource procurement and processing in the archaeological record, and has potential for use in the Arctic and beyond. To aid researchers utilizing nitrogen isotope analysis in the Arctic, we first present a comprehensive overview of published nitrogen isotope data in the Arctic. We then present nitrogen isotope data ($\delta^{15}N$) from ethnoarchaeological soils from known fish processing areas and a historic semisubterranean structure in Tununak, Nelson Island, Alaska. In addition to presenting isotopic floral and faunal baseline data, we demonstrate that, compared to offsite samples [mean $\delta^{15}N_{(AIR)}$ = 2.2‰ ± 0.4‰ (1σ, n = 35)], soils from fish processing areas were significantly more enriched in ^{15}N [mean $\delta^{15}N_{(AIR)}$ = 13.4‰ ± 0.4‰ (1σ, n = 49)]. Soil samples collected from an abandoned semisubterranean structure where marine products were processed and stored [mean $\delta^{15}N_{(AIR)}$ = 6.8‰ ± 0.2‰ (1σ, n = 105)] were also significantly enriched in ^{15}N.

INTRODUCTION

Despite the importance of marine resources in the Arctic, the ephemeral nature of fish and marine resource processing areas can make them difficult to identify. However, biogeochemical analyses of archaeological soils have become important tools to identify archaeological sites and activities (see overviews in Holliday et al. 2010; Lopez Varela and Dore 2010; Walkington 2010). For example, multi-elemental characterizations of archaeological soils have been used to identify past activities, including fish processing (e.g., Entwistle et al. 2007; Knudson and Frink 2010a; Knudson et al. 2004; Middleton and Price 1996; Misarti et al. 2011; Terry et al. 2004; Wells 2004; Wilson et al. 2008). However, the behavior and concentrations of anthropogenically deposited metals will fluctuate depending on the chemical, biological and physical characteristics of the site and soil (Haslam and Tibbett 2004). In addition, many regions do not have modern sites that can provide ethnoarchaeological soil samples from known activity areas for comparison with archaeological samples.

We argue that soil nitrogen isotope analysis can identify past use of marine products, which in turn may help elucidate subsistence behaviors at ephemeral sites, particularly in areas where large excavations are not possible. In archaeology, the application of nitrogen isotope analysis has a long history. Nitrogen isotopes vary according to trophic level and, in marine ecosystems, $\delta^{15}N$ values increase by approximately 3‰ with each trophic level (Post 2002; Schoeninger and DeNiro 1984; Wada 1980). We argue that this innovative application of a well-established technique in archaeology provides a minimally invasive way to examine marine resource use in the past and is applicable at a variety of archaeological sites.

In this article, we present an overview of published nitrogen isotope values in the Arctic and Subarctic as well as new isotopic data from ethnoarchaeological soil samples collected from known herring processing areas and a historic semisubterranean structure at Tununak, a contemporary Yup'ik community located on Nelson Island in southwestern Alaska (Figs. 1, 2). First, we discuss nitrogen isotope analysis in soils, followed by a discussion of observed and expected nitrogen isotope values in arctic ecosystems. We then introduce our case study from the site of Tununak and the Yukon-Kuskokwim Delta of southwestern Alaska, followed by our field and laboratory methods and results. We conclude with a discussion of the utility of nitrogen isotope analysis of archaeological soils to elucidate past subsistence behaviors.

NITROGEN ISOTOPE ANALYSIS OF ETHNOARCHAEOLOGICAL AND ARCHAEOLOGIAL SOILS

Since $\delta^{15}N$ values vary with trophic level, archaeologists have used nitrogen isotope values to investigate paleodiet in archaeological human remains (DeNiro and Epstein 1981; Schoeninger and DeNiro 1984; Schoeninger et al. 1983; Walker and DeNiro 1986). Nitrogen isotopes of bone collagen (Commisso and Nelson 2010; Drucker and Bocherens 2004; Jay and Richards 2006), hair keratin (Fernández et al. 1999; Knudson et al. 2007; Macko et al. 1999), and tooth dentine (Balasse et al. 2001; Fuller et al. 2003; Wright and Schwarcz 1999) are widely used

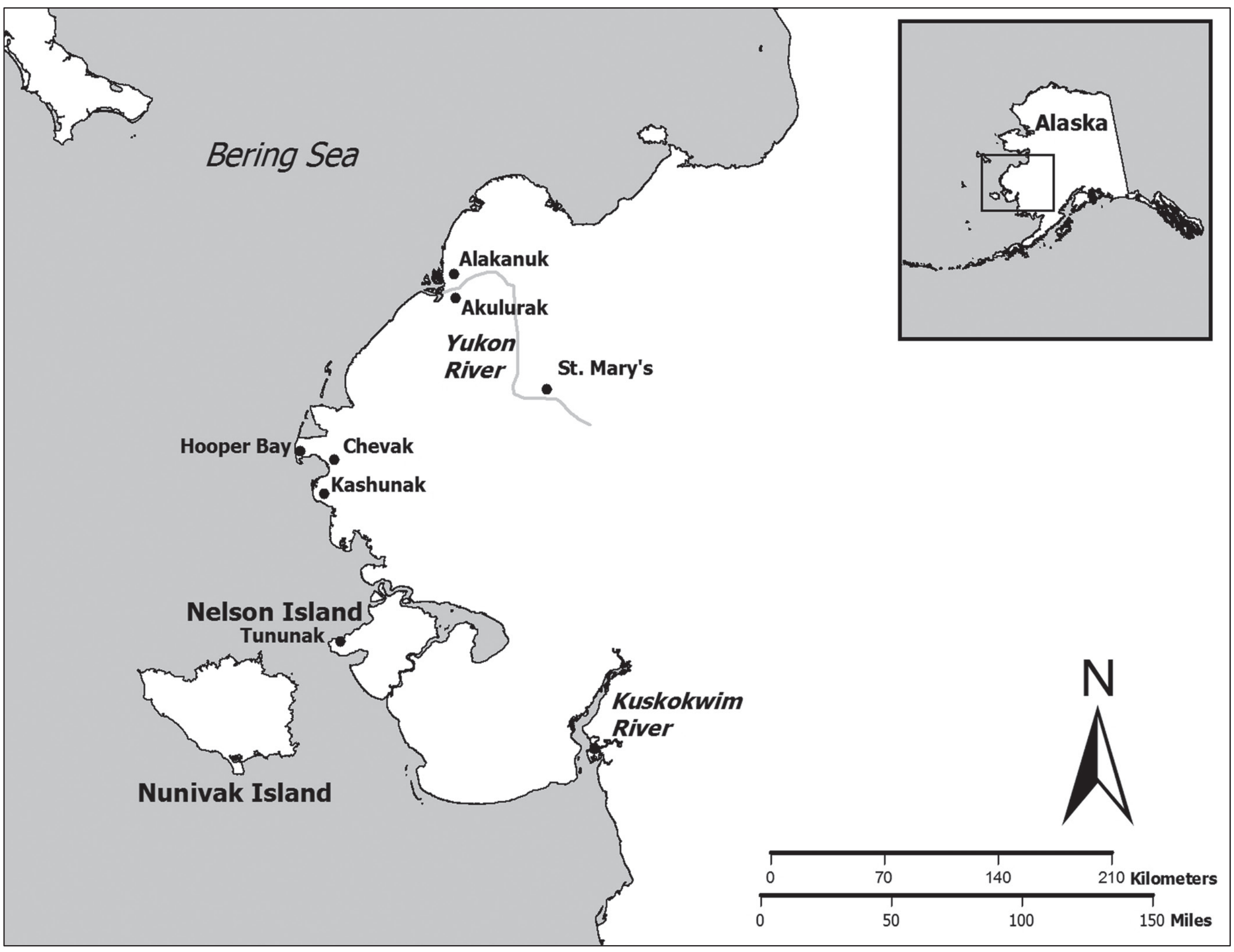

Figure 1. Location of the study site of Tununak in western Alaska.

cal soils can therefore be used to identify and better understand pastoralism in the archaeological record. Despite a number of studies using nitrogen isotope analyses of soils in other parts of the world, little work has been done in arctic and subarctic environments.

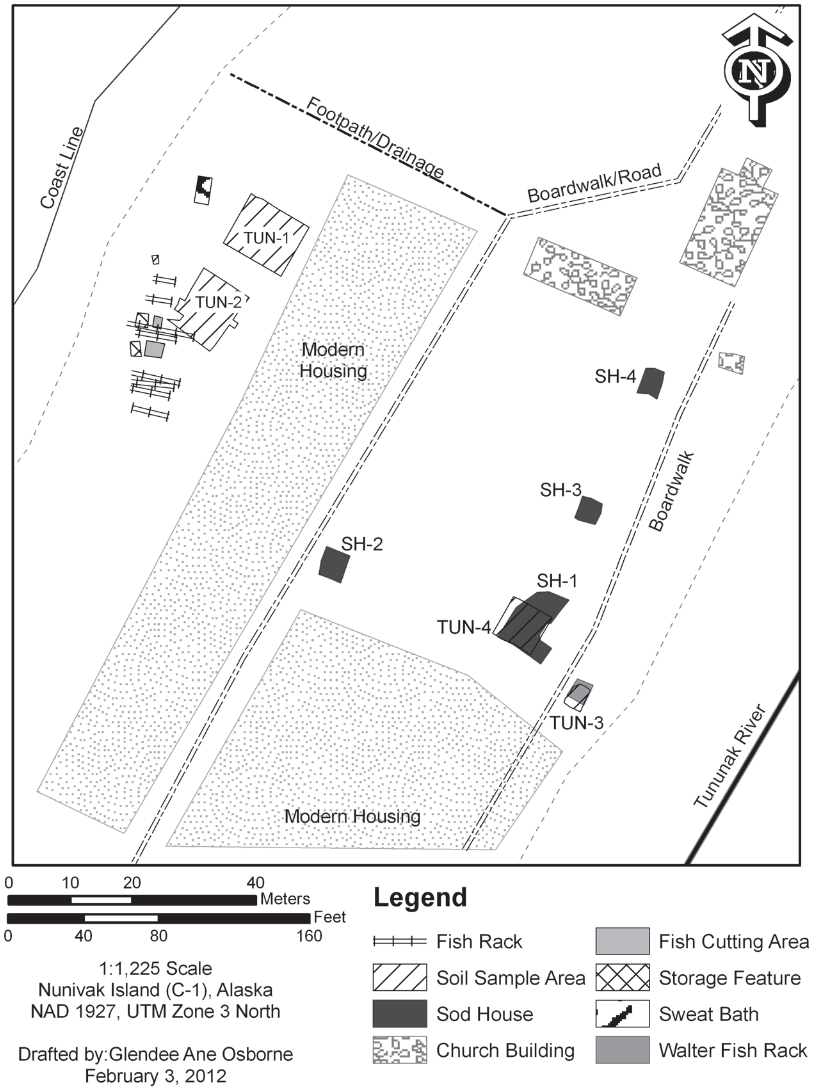

Figure 2. Site map of Tununak with location of the fish processing areas and semisubterranean dwelling.

to investigate paleodiet. In addition, the role of climatic effects, manuring, and trophic level differences continue to be investigated (Ambrose 1991; Ambrose and DeNiro 1987; Bogaard et al. 2007; Hedges and Reynard 2007).

The majority of these studies focused on the elucidation of paleodiet through light stable isotope analyses of bone collagen (see overviews in Katzenberg 2000; Katzenberg and Harrison 1997; Schoeninger and Moore 1992; Tykot 2006). However, archaeologists have recently applied nitrogen isotope analysis to ethnoarchaeological and archaeological soil samples. For example, analysis of ethnoarchaeological soil samples from Maasai sites in Kenya demonstrated that the soils in abandoned livestock enclosures were substantially enriched in ^{15}N (Shahack-Gross et al. 2008). Enrichment of ^{15}N in archaeologi-

NITROGEN ISOTOPE ENRICHMENT AND MARINE RESOURCE USE: A NOVEL APPLICATION IN ETHNOARCHAEOLOGICAL AND ARCHAEOLOGICAL SOILS

There is a long history of research into the complex behavior of nitrogen in soils (see overviews in Cheng et al. 1964; Evans 2007; Hart and Myrold 1996; Hedin et al. 1998; Högberg 1997; Hübner 1986). Briefly, a simplified nitrogen cycle involves nitrogen fixation, in which microorganisms such as *Rhizobium* sp. remove nitrogen (N_2) from the air and convert nitrogen gas (N_2) to ammonia (NH_3). The ammonium ion (NH_4+) can be converted into nitrite (NO_2–) and nitrate (NO_3–) through nitrification. The incorporation of ammonium (NH_4+) or nitrate (NO_3–) into living tissue is called assimilation or immobilization, while the degradation of organic matter and release of ammonium (NH_4+) is called mineralization or ammonification. Finally, denitrification is the conversion of nitrate (NO_3–) and nitrite (NO_2–) to nitrogen gas (N_2) by anaerobic bacteria, some fungi, and aerobic bacteria.

At different stages of the nitrogen cycle, the two stable isotopes of nitrogen, ^{15}N and ^{14}N, are fractionated, resulting in different $\delta^{15}N$ values. In soil, $\delta^{15}N$ values are determined by the initial isotopic composition and subsequent fractionation during nitrogen inputs, transformations, and loss (see overviews in Evans 2007; Sharp 2007; Yoneyama 1996). Nitrogen inputs in soils include nitrogen fixation, atmospheric deposition, and fertilizers. Nitrogen transformations include mineralization. Finally, nitrogen loss in soils generally results from volatilization, nitrification, and denitrifiction (e.g., Bergstrom et al. 2002; Erskine et al. 1998). At each of these stages, isotopic fractionation effects can vary from $\delta^{15}N(_{AIR})$ = 0–3‰ during nitrogen fixation to $\delta^{15}N_{(AIR)}$ = 20‰ during nitrification (Evans 2007; Sharp 2007; Yoneyama 1996). While there can be very large changes in $\delta^{15}N$ values at different stages in the nitrogen cycle, the $\delta^{15}N$ value of soil total nitrogen is largely determined by the isotopic composition of stable nitrogen in the soil (Högberg 1997); this value is unlikely to change quickly and ensures that the $\delta^{15}N$ value of soil total nitrogen exhibits much less variability compared to the variability seen in marine ecosystems, as discussed below.

Therefore, we argue that the variability of nitrogen isotope values in soils that is based on soil functions and speciation will be much smaller than the variability based on the incorporation of marine-derived nitrogen into soils in a particular area. For example, when marine-derived nitrogen from salmon carcasses was incorporated into terrestrial soils, vegetation, and invertebrates in six different sites in British Columbia, there was statistically significant ^{15}N enrichment in the terrestrial ecosystem (Reimchen et al. 2002). In fact, there was a direct correlation between salmon spawning density and ^{15}N enrichment in the associated soils (Reimchen et al. 2002). For example, salmon carcass density was highest at Warn Bay Creek in British Columbia and nitrogen isotope values were highest in soil humus samples [mean $\delta^{15}N_{(AIR)}$ = 1.5‰ ± 1.3‰ (1σ, n = 35)], huckleberry (*Vaccinium parvifolium*) vegetation samples [mean $\delta^{15}N_{(AIR)}$ = 1.6‰ ± 2.9‰ (1σ, n = 13)], and salmonberry (*Rubus spectabilis*) vegetation samples [mean $\delta^{15}N_{(AIR)}$ = 3.2‰ ± 2.5‰ (1σ, n = 18)] (Reimchen et al. 2002). In comparison, nitrogen isotope values from Bulson River, where salmon were not present, were lower [soil humus sample mean $\delta^{15}N_{(AIR)}$ = 0.9‰ ± 1.3‰ (1σ, n = 30); huckleberry (*Vaccinium parvifolium*) vegetation sample mean $\delta^{15}N_{(AIR)}$ = –0.9‰ ± 1.9‰ (1σ, n = 16); and salmonberry (*Rubus spectabilis*) vegetation sample mean $\delta^{15}N_{(AIR)}$ = –0.1‰ ± 2.5‰ (1σ, n = 15)] (Reimchen et al. 2002). Similarly, marine-derived nitrogen from spawning salmon and seabirds also resulted in ^{15}N enrichment in Alaskan and Canadian ecosystems (Ben-David et al. 1998a, 1998b; Bilby et al. 1996; Finney et al. 2000; Griffiths et al. 2010; Hilderbrand et al. 1999; Holtham et al. 2004; Keatley et al. 2011; Krummel et al. 2009; Selbie et al. 2007), while the introduction of predators such as Arctic foxes (*Alopex lagopus*) reduced the sea bird population on fox-infested islands in the Aleutian archipelago, and therefore reduced the nitrogen isotope values found in soils (Croll et al. 2005; Maron et al. 2006).

However, we also note that the agricultural practice of manuring or soil microbial processes could result in elevated $\delta^{15}N$ values in soils. For example, manuring results in elevated $\delta^{15}N$ values in plants grown in these agricultural fields (Bogaard et al. 2007; Choi et al. 2002, 2003; Commisso and Nelson 2010; Koerner et al. 1999; Meharg et al. 2006), and in the bone collagen of individuals who consume those crops (Bogaard et al. 2007; Finucane 2007). We recommend using additional lines of evidence, including site location, to eliminate the possibility that intentional manuring resulted in elevated $\delta^{15}N$ values at a particular archaeological site.

Given the clear evidence for ^{15}N-enrichment from marine resources in terrestrial ecosystems in the ecological literature, we hypothesize that terrestrial soils from archaeological sites where marine resources were processed will exhibit higher $\delta^{15}N$ values than soils that do not contain marine-derived ^{15}N. Important questions, however, involve the residence time of marine-derived ^{15}N-enrichment in soils and the age of the archaeological sites that can be analyzed using this technique. Elevated $\delta^{15}N$ values have been identified in former agricultural sites (Bogaard et al. 2007; Choi et al. 2002, 2003; Commisso and Nelson 2010; Koerner et al. 1999; Meharg et al. 2006). For example, ^{15}N-enriched plants growing on abandoned medieval farms in Greenland demonstrate that enrichment is present at least 500 years after deposition (Commisso and Nelson 2006, 2007, 2008, 2010); ^{15}N enrichment in former agricultural lands have been identified 200 years after deposition in France (Koerner et al. 1999). Therefore, we hypothesize that this technique will be useful at archaeological sites, although we note that soil nitrogen turnover rates will vary and must be quantified for each study region. We now turn to a discussion of nitrogen isotope baseline values from our study region in order to generate expectations of marine-derived nitrogen in archaeological and ethnoarchaeological soils.

NITROGEN ISOTOPE VALUES IN THE ARCTIC: AN OVERVIEW

Trophic-level variability in $\delta^{15}N$ values has been well-established in a number of different ecosystems and, in general, $\delta^{15}N$ values increase by 3–4‰ for each successive trophic level (see overviews in Ambrose 1991; DeNiro and Epstein 1981; Kelly 2000; Koch 1998, 2007; Schoeninger 1985; Schoeninger and Moore 1992; Schwarcz and

Schoeninger 1991). However, there is also evidence that climatic variability, particularly aridity, and nutritional stress can also affect nitrogen isotope composition in vertebrates (Ambrose 1991; Fuller et al. 2004, 2005; Hatch et al. 2006; Mekota et al. 2006). Therefore, here we reconstruct nitrogen isotope values in different trophic levels in both marine and terrestrial ecosystems in the Arctic and Subarctic and use these values as our study baseline (Table 1, Fig. 3, Appendix 1).

In arctic and subarctic marine ecosystems, there are clear trophic level differences in $\delta^{15}N$ values (Table 1, Fig. 3, Appendix 1) (Michener and Kaufman 2007). While benthic algae exhibits a mean $\delta^{15}N$ value of 1.4‰ ± 2.0‰ (Kline et al. 1990), primary consumers and animals that consumed a mixture of primary producers and primary consumers exhibit higher $\delta^{15}N$ values; these include anadromous fish such as salmon (*Oncorhynchus* spp.), squid (*Berryteuthis magister* and *Gonatopsis borealis*), and walruses (*Odobenus rosmarus*). Largely secondary consumers, such as humpback whales (*Megaptera novaeangliae*), Pacific herring (*Clupea pallasi*), and Pacific cod (*Gadus macrocephalus*), exhibited higher $\delta^{15}N$ values than largely primary consumers. Finally, tertiary consumers in the marine ecosystem exhibit very high $\delta^{15}N$ values; these animals include Steller sea lions (*Eumetopias jubatus*), killer whales (*Orcinus orca*), and polar bears (*Ursus maritimus*).

However, we note that $\delta^{15}N$ values do vary within an organism, based on sample and tissue type (Ambrose 1991; DeNiro and Epstein 1981; Minagawa and Wada 1984). Therefore, we also present mean bone collagen $\delta^{15}N$ values to remove variability in sample type. There are clear trophic level differences in bone collagen samples from the arctic marine ecosystem. For example,

Table 1. Mean nitrogen isotope values and standard deviation (σ) of baseline samples from the Arctic listed in ascending order.

Species*	mean $\delta^{15}N$ (‰)	σ	References
Primary Consumers			
Zooplankton	10.6	1.7	Atwell et al. 1998; Hobson et al. 1997; Hoekstra et al. 2002; Kline 1997, 1999; Lee et al. 2005; Schell et al. 1998
Anadromous fish [Salmon (*Oncorhynchus* spp.) and Dolly varden trout (*Salvelinus malma*)]	11.1	2.1	Hoekstra et al. 2002; Kaeriyama et al. 2004; Kline et al. 1990; Misarti 2007; Satterfield and Finney 2002; Uchiyama et al. 2008
Crustaceans*	11.9	1.4	Dunton et al. 1989; Kline 1999
Squid (*Berryteuthis magister* and *Gonatopsis borealis*)	11.7	2.4	Hobson et al. 1997; Kurle and Worthy 2001
Walrus (*Odobenus rosmarus*)	12.9	0.5	Atwell et al. 1998; Dehn et al. 2006; Hobson and Welch 1992
Secondary Consumers			
Humpback whale (*Megaptera novaeangliae*)	13.0	1.0	Witteveen et al. 2009
Pacific herring (*Clupea pallasi*)	13.7	1.1	Kline 1999; Kurle and Worthy 2001
Sea birds*	14.7	1.7	Atwell et al. 1998; Hobson et al. 1994, 2004a, 2004b; Hobson and Montevecchi 1991
Sea otter (*Enhydra lutris*)	15.3	2.1	Worthy 2008
Harbor porpoise (*Phocoena phocoena*)	15.6	0.4	Toperoff 2002
Pacific cod (*Gadus macrocephalus*)	16.1	2.0	Dunton et al. 1989; Hobson et al. 1997; Misarti 2007
Tertiary Consumers			
Northern fur seal (*Callorhinus ursinus*)	16.9	1.1	Burton and Koch 1999; Hirons 2001; Hobson et al. 1997; Kurle and Worthy 2001, 2002; Newsome et al. 2007
Steller sea lion (*Eumetopias jubatus*)	17.8	0.9	Hirons 2001; Hobson et al. 1997, 2004a, 2004b; Kurle and Gudmundson 2007; Misarti 2007
Killer whale (*Orcinus orca*)	17.9	1.6	Herman et al. 2005; Worthy 2008
Polar bear (*Ursus maritimus*)	20.4	0.8	Atwell et al. 1998; Dehn et al. 2006; Hobson and Welch 1992

* See individual species listed in Appendix 1.

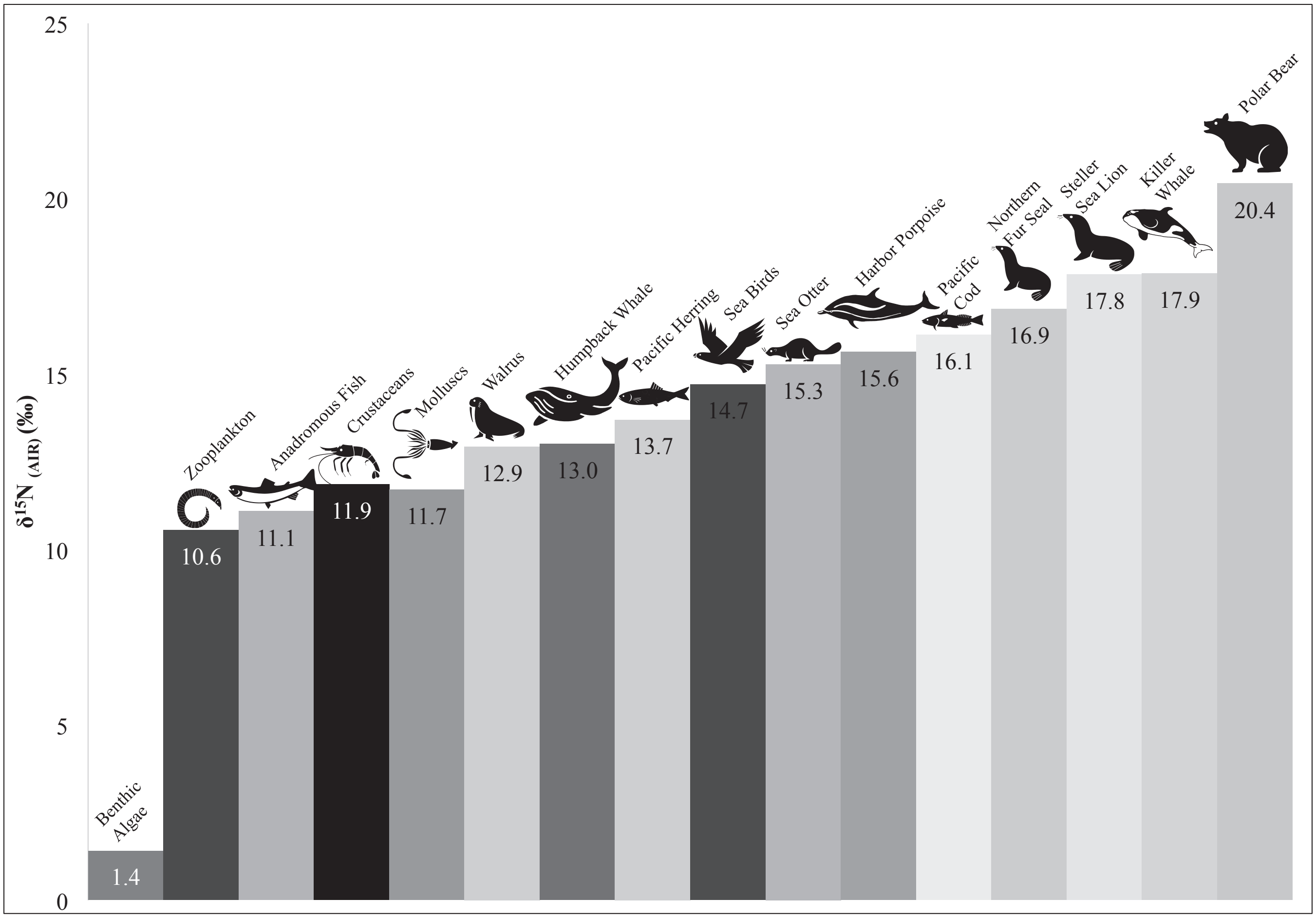

Figure 3. Mean nitrogen isotope values of baseline samples from the Arctic (mean data in Table 1 from Atwell et al. 1998; Burton and Koch 1999; Dehn et al. 2006; Dunton et al. 1989; Herman et al. 2005; Hirons 2001; Hobson et al. 1994, 1997; Hobson, Bowen et al. 2004; Hobson and Montevecchi 1991; Hobson, Sinclair, et al. 2004; Hobson and Welch 1992; Hoekstra et al. 2002; Kaeriyama et al. 2004; Kline 1997, 1999; Kline et al. 1990, 1993; Kurle and Gudmundson 2007; Kurle and Worthy 2001, 2002; Lee et al. 2005; Misarti 2007; Newsome et al. 2007; Satterfield and Finney 2002; Schell 2001; Schell et al. 1998, Toperoff 2002; Uchiyama et al. 2008; Witteveen et al. 2009; Worthy 2008).

when only bone collagen samples are included, mean $\delta^{15}N$ values are as follows:

- anadromous fish (*Oncorhynchus* spp.) 10.5‰ ± 1.6‰ Misarti 2007
- Tufted puffin (*Fratercula cirrhata*) 16.1‰ ± 2.3‰ Hobson and Montevecchi 1991; Hobson et al. 1994
- Pacific cod (*Gadus macrocephalus*) 16.4‰ ± 0.4‰ Misarti 2007
- Northern fur seals (*Callorhinus ursinus*) 17.1‰ ± 1.5‰ Burton and Koch 1999; Hirons 2001; Misarti 2007; Newsome et al. 2007
- Steller sea lions (*Eumetopias jubatus*) 18.0‰ ± 0.6‰ Hirons 2001; Hobson, Bowen et al. 2004; Misarti 2007

In arctic and subarctic terrestrial ecosystems, nitrogen isotope values in O and B horizons of forest soils and sediment cores from lakes have a mean $\delta^{15}N$ of 1.3‰ ± 1.8‰ (Hobbie et al. 1998; 2000; Misarti 2007). Terrestrial vegetation from areas without piscivorous predator activity exhibited a mean $\delta^{15}N$ of 1.1‰ ± 3.6‰ in Chichagof Island (Ben-David et al. 1998b), while small mammals from areas away from ^{15}N-enriched vegetation ranged from values from –0.1‰ to 4.0‰ (Ben-David et al. 1998b). Arctic fox (*Alopex lagopus*) exhibited a mean value of 10.3‰ ± 1.4‰ (Dehn et al. 2006). As previously discussed, we note that terrestrial ecosystems can exhibit nonanthropogenic ^{15}N enrichment (Ben-David et al. 1998a, 1998b; Bilby et al. 1996; Hilderbrand et al. 1999; Reimchen et al. 2002). In addition, nitrogen cycles in arctic terrestrial ecosystems are very complex (Binkley et al. 1985; Blackmer and Bremner 1977; Chapin et al. 1988; Chapin et al. 1993; Chapin and Shaver 1981; Hu et al. 2001; Kaye et al. 2003; Rhoades et al. 2001). However, we hypothesize that the anthropogenic inputs from processing marine resources will result in ^{15}N enrichment in soils that is significantly greater than the variability in soil values discussed here. Finally, we note that climatic variability and changes in animal behavior and prey species availability over time can result in δ^{15}N variability (Misarti 2007; Misarti et al. 2009); however, these temporal changes are smaller than the expected ^{15}N enrichment in anthropogenically altered soils.

CASE STUDY: NITROGEN ISOTOPE ANALYSIS OF ETHNOARCHAEOLOGICAL SOILS ON NELSON ISLAND

SUBSISTENCE PRACTICES AT THE YUP'IK COMMUNITY OF TUNUNAK

Nelson Island lies just off the mainland coast of southwestern Alaska and is geologically part of the Yukon-Kuskokwim Delta (Fig. 1). The Yup'ik community of Tununak, on the northwestern coast of the island, has approximately 300 inhabitants. Its location on the Bering Sea coast enables residents to take advantage of spring, summer, and fall resources (Barker 1993; Frink 2009), since they depend on subsistence foods for a large part of their diet. Residents still harvest large numbers of migrating waterfowl such as Canada goose (*Branta canadensis*) and collect flora from the land including berries (*Rubus* spp.) (Ager and Ager 1980).

Although terrestrial resources are utilized at Tununak, fish is arguably the most important subsistence food for coastal Yup'ik people (e.g., Nash et al. 2009, 2012; O'Brien et al. 2009; Wilkinson et al. 2007). Herring (*Clupea* spp.) is particularly significant, and Tununak is located near herring spawning grounds. Every year, men, as the primary subsistence harvesters, fish for herring while the women of Tununak, the primary subsistence producers, spend weeks processing and drying the fish for the winter months (Figs. 2, 3) (Barker 1993; Fienup-Riordan 1983, 1986; Frink and Knudson 2010; Frink 2002, 2007, 2009; Frink et al. 2003; Pete et al. 1987). Although herring is vital to the inhabitants of Tununak, Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*Oncorhynchus kisutch*), Pacific halibut (*Hippoglossus stenolepis*), and Pacific cod (*Gadus macrocephalus*) are also important marine resources (Pete et al. 1987). People also rely on several sea mammal taxa, including five species of seal [ringed (*Pusa hispida*), harbor (*Phoca vitulina*), spotted (*Phoca largha*), ribbon (*Histriophoca fasciata*), and bearded (*Erignathus barbatus*)], as well as beluga whale (*Delphinapterus leucas*). As discussed in more detail elsewhere (Frink and Knudson 2010; Knudson and Frink 2010a), as fish and other marine products are processed and dried at Tununak, discarded flesh and whole fish are incorporated into the soils of the processing and storage areas, creating anthropogenically altered soils.

PHYSICAL ENVIRONMENT AND SOILS AT TUNUNAK

Most of the Yukon-Kuskokwim Delta is composed of Quaternary sands and silts, underlain by Cenozoic sedimentary rocks; delta soils are generally mapped as Histic Pergelic Cryaquepts and Pergelic Cryofibrists (Gough et al. 1988; Lyle et al. 1982; MacManus et al. 1974). Because of the large numbers of lakes and rivers and a discontinuous permafrost layer, delta soils are poorly drained and minimally weathered. The physical characteristics of the soils collected at Tununak are described in detail in the following sections.

FIELD METHODS: SAMPLE COLLECTION AT TUNUNAK

In May 2007, we collected ethnoarchaeological soil samples at Tununak from current fish processing areas during herring procurement and processing[1] (Figs. 4, 5). In these areas, approximately 10 grams of soil (wet weight) were collected in a 1 x 1 meter grid; this point sampling strategy was designed to assess the isotopic variability (Entwistle et al. 2000; Haslam and Tibbett 2004; Wells 2010) and to compare the isotopic signatures of the soils in the fish processing areas and drying racks with the isotopic signatures in the soils from unused spaces between the racks and along the edges of the processing areas.

We also collected ethnoarchaeological soil samples from an abandoned semisubterranean structure in Tununak in order to understand the isotopic signatures of areas where marine products were stored and processed, although less intensively than at the fish processing sites[2] (Fig. 6). The construction, use and attributes of the semisubterranean structure are discussed in detail elsewhere (Knudson and Frink 2010b). Within and outside of the turf walls of the structure, a point sampling strategy was used (Entwistle et al. 2000; Haslam and Tibbett 2004). Samples were collected in a 1 x 1 meter grid. At each sampling location, a galvanized steel soil sampler was used to take soil cores and to collect samples at depths of five centimeters at each point (Caldwell et al. 2005; Feek et al. 2006). Therefore, at each point on our one-meter grid within and around the semisubterranean structure, we collected samples from the surface soil, including roof fall in some areas, from the house floors, and from underneath the floors. Interviews with former inhabitants of the sod house that was sampled allowed us to reconstruct the life history of the structure, including length of occupation, time of abandonment, and identification of activity areas in and around the house (Knudson and Frink 2010b).

Figure 4. Herring braids on racks at Tununak, Nelson Island, Alaska. Photo by Kelly Knudson.

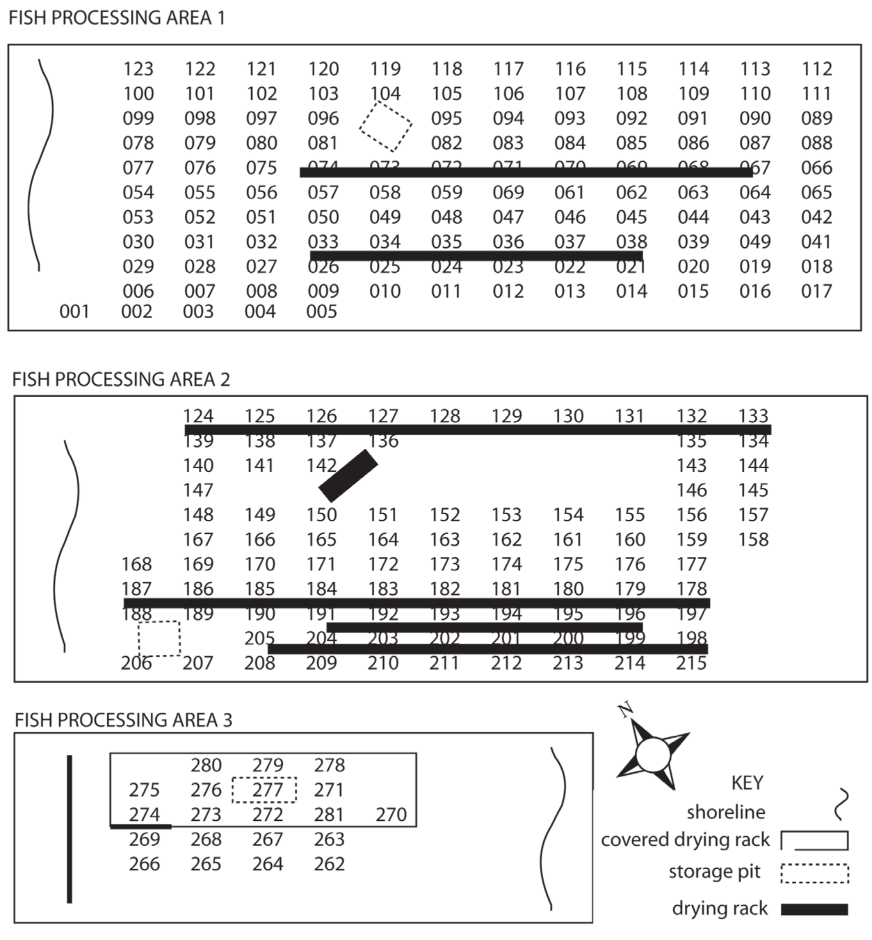

Figure 5. Fish processing areas sampled at Tununak with sample locations identified. Not to scale.

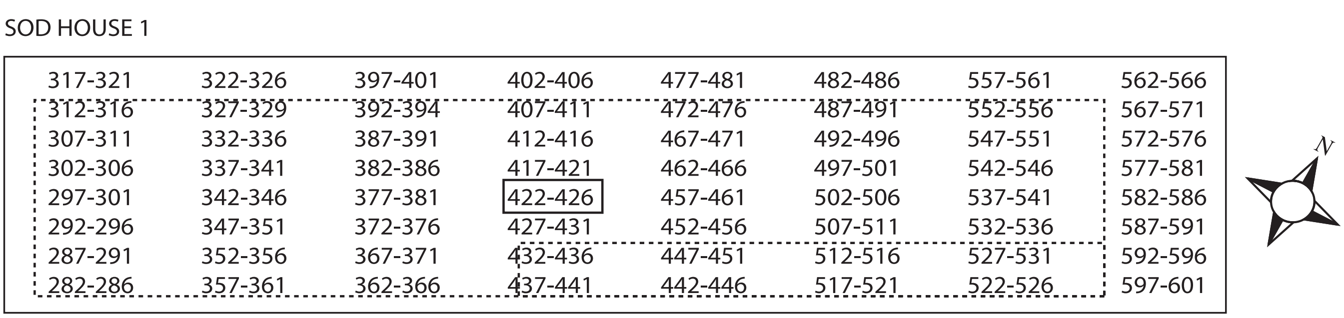

Figure 6. Abandoned semisubterranean dwelling sampled at Tununak with sample locations identified. Not to scale.

All soil samples were collected to ensure that variability in $\delta^{15}N$ values in the Tununak soils was due to the incorporation of marine products into the soils, rather than non-anthropogenic soil processes. More specifically, denitrification can have very large fractionation effects (Sharp 2007). Since denitrification often occurs in poorly-aerated, saturated soils as well as in deeper layers of soil, samples were collected from areas that were similarly saturated throughout the year. With the exception of the semi-subterranean structure samples, which were collected at a number of different depths and will be discussed in detail below, all offsite and fish processing area samples were collected at the same depth to control for depth-related variability in $\delta^{15}N$ values.

In addition to the fish processing area and semi-subterranean structure samples, we collected soil samples from three offsite areas to examine the isotopic signatures of soils not affected by anthropogenic processes[3] (Fig. 7). Offsite soil samples were collected using a nested sampling regime to examine the spatial variability in the soils with fewer samples (Andronikov et al. 2000; Lark 2005; Youden and Mehlich 1937). Samples were also collected from a fourth offsite sampling area to examine the isotopic effects of bird waste and fecal material on soil. Finally, baseline samples from both the marine and terrestrial ecosystems were collected in October of 2009 and July of 2010. Vegetation, shell, and fish samples were collected opportunistically and are listed in Table 2; all vertebrate samples were collected from carcasses with the permission of the subsistence hunters who obtained the fish.

LABORATORY METHODS: SAMPLE ANALYSIS AT ARIZONA STATE UNIVERSITY

All samples were prepared in the Archaeological Chemistry Laboratory at Arizona State University. Each soil or plant sample was first dried at 60°C for forty-eight hours, pulverized with a Coors porcelain mortar and pestle and screened with a 2 mm screen to remove all particles larger than sand-sized, and then pulverized using a ball mill (Choi et al. 2002; Gebauer and Schulze 1991; Shahack-Gross et al. 2008). Bone samples were chemically cleaned using 95% and 100% ethanol (C_3H_5OH) and acetone ($(CH_3)_2CO$) and demineralized using 0.25 M hydrochloric acid (HCl). Modern bone samples were then treated with a 1:2:0.8 solution of chloroform ($CHCl_3$), methanol (CH_3OH), and water (H_2O) to remove any lipids present and then treated with 0.125 M sodium hydroxide (NaOH) to remove any humic acids present before solubilizing and freeze-drying the samples (Ambrose 1990; Jørkov et al. 2007).

Samples were analyzed at the W. M. Keck Foundation Laboratory for Environmental Biogeochemistry using a Delta Plus Advantage Isotope Ratio Mass Spectrometer (IRMS) coupled with a Costech Elemental Analyzer (EA). Accuracy and precision were determined using the external and internal standards of NIST-1646 (estuarine sediment), USGS SDO-1 (Devonian Ohio Shale), glycine, acetanilide, and ACL-1119 (TUN-0250). When possible, samples were analyzed in triplicate on the same day and during subsequent sample runs (Pye et al. 2006). Maximum standard error on soil, plant and bone collagen sample replicates was $\delta^{15}N_{(AIR)}$ = 0.3‰. Nitrogen isotope ratios are reported relative to the AIR (atmospheric nitrogen) standard and are expressed in parts per mil (‰) using the following formula: $\delta^{15}N = (((^{15}N/^{14}N_{sample})/(^{15}N/^{14}N_{standard})) - 1) \times 1{,}000$ (Mariotti 1983).

RESULTS OF THE CASE STUDY

Terrestrial plants collected from Tununak exhibit mean $\delta^{15}N_{(AIR)}$ = 2.7‰ ± 0.5‰ (1σ, n = 3) (Table 2). In contrast, marine plants collected from Tununak exhibit mean $\delta^{15}N_{(AIR)}$ = 22.1‰ ± 2.6‰ (1σ, n = 9). All fish samples exhibit mean $\delta^{15}N_{(AIR)}$ = 13.6‰ ± 0.9‰ (1σ, n = 13); more specifically, anadromous fish exhibit a range of $\delta^{15}N_{(AIR)}$ = 10.8‰ to $\delta^{15}N_{(AIR)}$ = 12.4‰ and marine fish exhibit mean $\delta^{15}N_{(AIR)}$ = 13.5‰ ± 1.0‰ (1σ, n = 11). These nitrogen isotope values are similar to expected values based on light stable nitrogen isotope data from published sources, as previously discussed (Fig. 3, Appendix 1).

Nitrogen isotope data from all ethnoarchaeological samples collected at Tununak are presented in Tables 3 and 4. Nitrogen isotope values from the offsite areas exhibit mean $\delta^{15}N_{(AIR)}$ = 2.2‰ ± 0.4‰ (1σ, n = 35). The fish processing areas exhibit mean $\delta^{15}N_{(AIR)}$ = 13.4‰ ± 0.4‰ (1σ, n = 49). The nitrogen isotopes values from all samples collected from the sod house exhibit mean $\delta^{15}N_{(AIR)}$ = 6.8‰ ± 0.2‰ (1σ, n = 105) (Table 4).

DISCUSSION OF NITROGEN ISOTOPE VALUES IN ETHNOARCHAEOLOGICAL SOILS FROM TUNUNAK

An examination of the nitrogen isotope values from the offsite areas [mean $\delta^{15}N_{(AIR)}$ = 2.2‰ ± 0.4‰ (1σ, n = 35)]

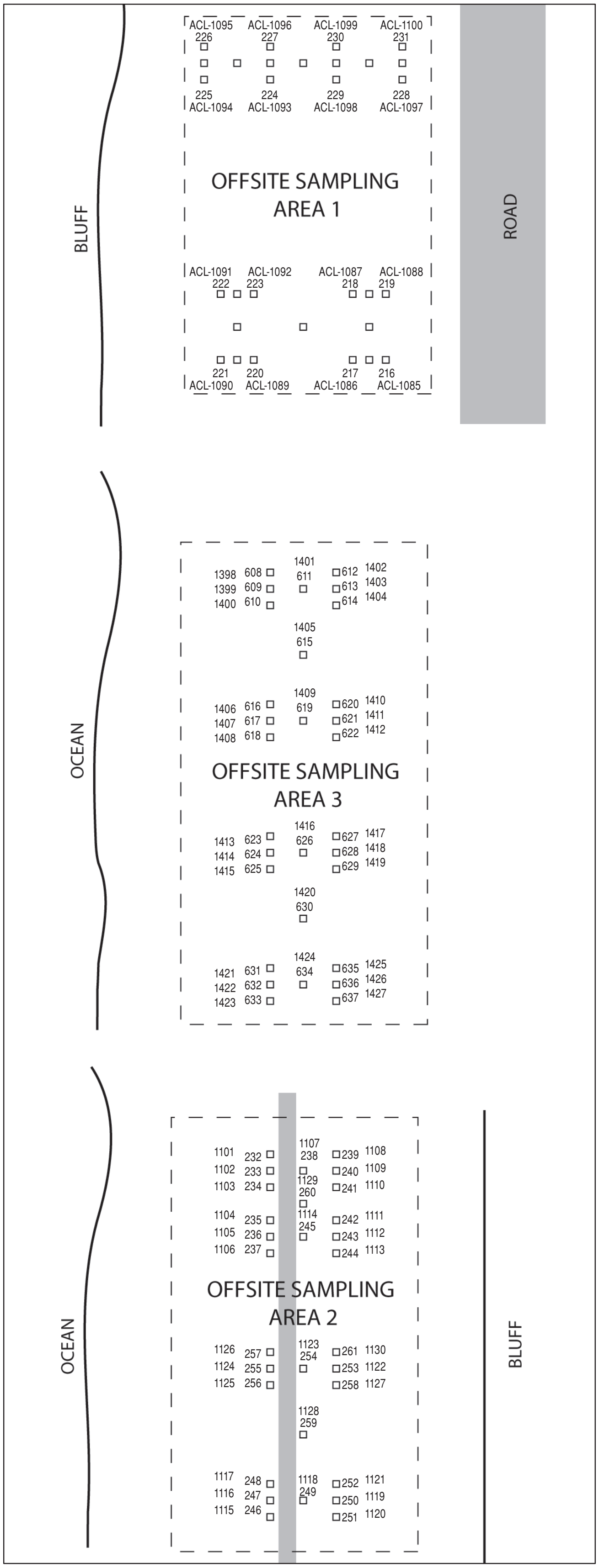

Figure 7. Offsite areas sampled at Tununak with sample locations identified. Not to scale.

and the fish processing areas [mean $\delta^{15}N_{(AIR)}$ = 13.4‰ ± 0.4‰ (1σ, n = 49)] shows that the fish processing area soil are enriched in ^{15}N (Table 4). The difference in $\delta^{15}N_{(AIR)}$ values between fish processing area samples and offsite area samples is statistically significant (t = 19.5, df = 82, $p < 0.001$). We interpret these data as reflecting the incorporation of marine-derived nitrogen from fish and marine mammals into the soils in the fish processing areas.

The nitrogen isotope values from the offsite areas [mean $\delta^{15}N_{(AIR)}$ = 2.2‰ ± 0.4‰ (1σ, n = 35)] and all samples collected from the sod house [mean $\delta^{15}N_{(AIR)}$ = 6.8‰ ± 0.2‰ (1σ, n = 105)] are also distinct. The difference between all sod house samples and the offsite samples is also statistically significant (t = 11.3, df = 138, $p < 0.001$). Although processing marine products was less intensive in the semisubterranean structures compared to the fish processing areas, the sod house soils are enriched in ^{15}N, although less enriched than the fish processing soils. We interpret these data as indicating the incorporation of marine-derived nitrogen from fish and marine mammals into the floors of the sod house during processing, storing, consuming, and/or discarding marine products in and around the semisubterranean structures.

The enrichment in ^{15}N varies by soil depth, as demonstrated by soil samples collected at different depths at and below the hypothesized floor surface. The sod house soil samples were obtained from twenty-six different sampling locations within the house with different depths collected at the surface as well as every five centimeters below the surface. Out of the twenty-six sampling locations, eleven had soil samples from five depths, eleven had samples from four depths, one had samples from three depths, and three had a surface soil sample. Soils collected from the surface of the sod house floor exhibited mean $\delta^{15}N_{(AIR)}$ = 8.7‰ ± 1.7‰ (1σ, n = 26). Soils collected below the surface exhibited the following nitrogen isotope values: mean $\delta^{15}N_{(AIR)}$ = 6.4‰ ± 1.4‰ (5 cm below surface, 1σ, n = 23); mean $\delta^{15}N_{(AIR)}$ = 5.9‰ ± 1.6‰ (10 cm below surface, 1σ, n = 23); mean $\delta^{15}N_{(AIR)}$ = 6.0‰ ± 1.8‰ (15 cm below surface, 1σ, n = 22); and mean $\delta^{15}N_{(AIR)}$ = 6.4‰ ± 1.7‰ (20 cm below surface, 1σ, n = 11).

However, the variability of $\delta^{15}N_{(AIR)}$ values by depth does not follow the pattern one would expect if it was due solely to soil formation processes. In general and across many different ecosystems, soil $\delta^{15}N_{(AIR)}$ values increase with soil depth due to fractionation during mineralization, nitrification and loss of nitrogen gas (N_2)

Table 2. Nitrogen isotope data from all baseline samples collected from Nelson Island. Fish samples were collected opportunistically from carcasses obtained by subsistence hunters.

Laboratory Number	Field Sample Number	Species	Sample Type	Percentage of N in sample by weight	$\delta^{15}N_{(AIR)}$ (‰)
ACL-2702	TUN-0663	cf. *Halosaccion* spp.	Sea sac (pod)	8.6	20.9
ACL-2706	TUN-0667	cf. *Halosaccion* spp.	Sea sac (pod)	14.5	20.0
ACL-2712	TUN-0673	cf. *Halosaccion* spp.	Sea sac (pod)	13.9	20.6
ACL-2713	TUN-0674	cf. *Codium fragile* spp.	Seaweed (blades)	5.2	24.5
ACL-2720	TUN-0679	*Plantago maritima*	Goose-tongue (rosette)	7.2	19.6
ACL-2723	TUN-0682	cf. *Callophyllis* spp.	Seaweed (blades)	4.5	18.6
ACL-2724	TUN-0683	cf. *Codium fragile* spp.	Seaweed (blades)	3.3	25.3
ACL-2728	TUN-0686	cf. *Codium fragile* spp.	Seaweed (blades)	4.4	25.6
ACL-2761	TUN-0690	unidentified plant	unidentified plant	3.2	23.4
ACL-2700	TUN-0661	*Hippoglossus stenolepis*	Pacific halibut bone collagen	14.4	19.4
ACL-2701	TUN-0662	*Hippoglossus stenolepis*	Pacific halibut bone collagen	14.2	19.1
ACL-2722	TUN-0681	*Hippoglossus stenolepis*	Pacific halibut bone collagen	13.3	20.3
ACL-2715	TUN-0675	*Hippoglossus stenolepis*	Pacific halibut bone collagen	14.3	18.9
ACL-2721	TUN-0680	*Hippoglossus stenolepis*	Pacific halibut bone collagen	12.1	18.7
ACL-2936	TUN-0715	*Hippoglossus stenolepis*	Pacific halibut bone collagen	12.9	18.6
ACL-2940	TUN-0719	*Hippoglossus stenolepis*	Pacific halibut bone collagen	12.1	18.5
ACL-2703	TUN-0664	unidentified fish bone	unidentified fish bone collagen	13.5	14.6
ACL-2930	TUN-0709	*Anarrhichthys ocellatus*	Wolf eel bone collagen	13.3	19.7
ACL-2949	TUN-0721	*Prosopium cylindraceum*	Whitefish bone collagen	15.1	15.7
ACL-2950	TUN-0722	*Paralichthys* sp.	Flounder bone collagen	12.8	14.6
ACL-2920	TUN-0699	cf. *Oncorynchus keta*	Chum salmon bone collagen	14.1	10.8
ACL-2717	TUN-0677	*Oncorhynchus keta*	Chum salmon bone collagen	14.2	12.4
ACL-2688	TUN-0649	*Calamagrostis canadensis*	Bluejoint grass (stalk and glumes)	2.1	6.2
ACL-2730	TUN-0688	*Eriophorum angustifolium*	Cottongrass (stalk and flowers)	2.9	9.6
ACL-2731	TUN-0689	unidentified plant	unidentified plant	3.2	8.8

(Evans 2007; Fry 1991; Högberg 1997; Natelhoffer and Fry 1988). Therefore, since some of the highest $\delta^{15}N_{(AIR)}$ values in the semisubterranean structure soils are from the first 10 cm of soil beneath the surface, we argue that this enrichment is at least partially due to ^{15}N enrichment from anthropogenic activities, such as processing and storing marine products.

CONCLUSIONS

In conclusion, we have presented an overview of published nitrogen isotope values in the Arctic and Subarctic. These data demonstrate the trophic level variability in these ecosystems. We believe that this variability indicates that the Arctic, in particular, is an excellent region in which to use nitrogen isotope analysis to examine marine resource consumption, particularly in ethnoarchaeological and archaeological soils.

We have also presented new light stable isotope data from arctic baseline samples as well as ethnoarchaeological soil samples from known fish processing areas and a historic semisubterranean house. While terrestrial plants collected from Tununak exhibit mean $\delta^{15}N_{(AIR)}$ = 2.7‰ ± 0.5‰ (1σ, n = 3), marine plants collected from Tununak exhibit mean $\delta^{15}N_{(AIR)}$ = 22.1‰ ± 2.6‰ (1σ, n = 9). Anadromous fish exhibit a range of $\delta^{15}N_{(AIR)}$ = 10.8‰ to $\delta^{15}N_{(AIR)}$ = 12.4‰ and marine fish exhibit mean $\delta^{15}N_{(AIR)}$ = 13.5‰ ± 1.0‰ (1σ, n = 11). Soils in offsite areas exhibited

Table 3. Nitrogen isotope data from all ethnoarchaeological samples collected from Nelson Island.

Laboratory Number	Field Sample Number	Percentage of N in sample by weight	$\delta^{15}N_{(AIR)}$ (‰)	Sample Origin
Offsite Areas				
Offsite Area 1				
ACL-1085	TUN-0216	1.2	2.9	
ACL-1086	TUN-0217	1.3	–0.5	
ACL-1087	TUN-0218	1.1	2.7	
ACL-1090	TUN-0221	1.0	0.0	
ACL-1091	TUN-0222	0.9	0.8	
ACL-1095	TUN-0226	0.5	0.2	
ACL-1096	TUN-0227	0.7	–0.6	
ACL-1097	TUN-0228	0.8	–0.5	
Offsite Area 2				
ACL-1103	TUN-0234	0.5	2.8	
ACL-1108	TUN-0239	0.3	3.6	
ACL-1109	TUN-0240	0.3	4.0	
ACL-1112	TUN-0243	0.2	3.4	
ACL-1113	TUN-0244	0.3	3.7	
ACL-1118	TUN-0249	0.8	2.4	
ACL-1121	TUN-0252	0.3	1.6	
ACL-1127	TUN-0258	0.2	3.8	
ACL-1129	TUN-0260	0.5	2.9	
ACL-1130	TUN-0261	0.2	4.4	
Offsite Area 3				
ACL-1399	TUN-0609	0.3	13.7	
ACL-1400	TUN-0610	0.1	2.1	
ACL-1401	TUN-0611	0.0	2.5	
ACL-1405	TUN-0615	0.2	2.0	
ACL-1407	TUN-0617	0.1	1.5	
ACL-1408	TUN-0618	0.2	1.7	
ACL-1409	TUN-0619	0.1	1.9	
ACL-1411	TUN-0621	0.1	2.1	
ACL-1412	TUN-0622	0.3	1.0	
ACL-1414	TUN-0624	0.1	0.8	
ACL-1415	TUN-0625	0.0	1.2	
ACL-1417	TUN-0627	0.4	0.7	
ACL-1418	TUN-0628	0.3	1.7	
ACL-1420	TUN-0630	0.1	1.4	
ACL-1421	TUN-0631	0.3	2.0	
ACL-1423	TUN-0633	0.1	1.4	
ACL-1426	TUN-0636	0.2	1.1	
Fish Processing Area 1				
ACL-0886	TUN-0017	0.2	12.2	peripheral
ACL-0892	TUN-0023	0.2	14.2	rack
ACL-0894	TUN-0025	0.2	16.3	rack
ACL-0904	TUN-0035	0.1	11.3	rack
ACL-0907	TUN-0038	0.1	13.3	rack
ACL-0927	TUN-0058	0.2	17.2	rack
ACL-0928	TUN-0059	0.1	14.5	rack
ACL-0930	TUN-0061	0.1	13.1	rack
ACL-0936	TUN-0067	0.5	14.3	rack
ACL-0939	TUN-0070	0.2	13.2	rack
ACL-0942	TUN-0073	0.1	11.3	rack
ACL-0950	TUN-0081	0.1	12.0	near storage pit
ACL-0951	TUN-0082	0.1	15.5	rack
ACL-0965	TUN-0096	0.3	16.0	rack
ACL-0974	TUN-0105	0.1	14.0	peripheral, near storage pit

Table 3. (continued)

Laboratory Number	Field Sample Number	Percentage of N in sample by weight	$\delta^{15}N_{(AIR)}$ (‰)	Sample Origin
ACL-0980	TUN-0111	0.7	12.9	peripheral
ACL-0982	TUN-0113	1.1	14.6	peripheral
ACL-0983	TUN-0114	0.2	13.2	peripheral
ACL-0988	TUN-0119	0.1	12.6	peripheral
ACL-0991	TUN-0122	0.0	7.2	peripheral, "walk area"
Fish Processing Area 2				
ACL-0941	TUN-0072	0.1	11.3	rack
ACL-0994	TUN-0125	0.2	14.0	rack
ACL-0999	TUN-0130	0.2	14.3	rack
ACL-1001	TUN-0132	0.5	16.5	rack
ACL-1005	TUN-0136	0.5	14.5	rack
ACL-1008	TUN-0139	0.1	12.5	rack
ACL-1011	TUN-0142	0.2	14.7	rack
ACL-1017	TUN-0148	0.1	14.3	peripheral
ACL-1019	TUN-0150	0.1	19.5	rack
ACL-1021	TUN-0152	0.2	13.4	peripheral, near tent
ACL-1022	TUN-0153	0.2	10.8	peripheral, near tent
ACL-1024	TUN-0155	0.1	11.1	peripheral, near tent
ACL-1047	TUN-0178	0.4	15.3	rack
ACL-1049	TUN-0180	0.3	14.3	rack
ACL-1052	TUN-0183	0.2	14.4	rack
ACL-1054	TUN-0185	0.2	15.7	rack
ACL-1060	TUN-0191	0.5	17.5	rack
ACL-1062	TUN-0193	0.3	11.3	rack
ACL-1065	TUN-0196	0.3	14.5	rack
ACL-1070	TUN-0201	0.3	15.9	rack
ACL-1071	TUN-0202	0.3	16.5	rack
Fish Processing Area 3				
ACL-1132	TUN-0263	0.2	11.1	peripheral
ACL-1134	TUN-0265	0.3	12.4	outside covered rack
ACL-1135	TUN-0266	0.4	10.4	peripheral, near doorway
ACL-1142	TUN-0273	0.5	11.8	covered rack
ACL-1143	TUN-0274	0.1	2.9	covered rack near door
ACL-1144	TUN-0275	0.4	9.1	covered rack near door
ACL-1147	TUN-0278	0.4	11.5	covered rack
ACL-1149	TUN-0280	0.2	15.1	covered rack
Sod House				
ACL-1151	TUN-0282	0.3	11.8	
ACL-1152	TUN-0283	0.4	8.8	
ACL-1153	TUN-0284	0.2	7.2	
ACL-1154	TUN-0285	0.1	6.5	
ACL-1155	TUN-0286	0.1	5.6	
ACL-1161	TUN-0292	0.3	7.0	
ACL-1162	TUN-0293	0.1	6.8	
ACL-1163	TUN-0294	0.1	7.2	
ACL-1164	TUN-0295	0.2	6.5	
ACL-1165	TUN-0296	0.1	6.5	
ACL-1168	TUN-0302	0.3	9.7	
ACL-1169	TUN-0303	0.4	10.0	
ACL-1170	TUN-0304	0.1	9.8	
ACL-1171	TUN-0305	0.1	8.0	
ACL-1172	TUN-0306	0.2	7.7	
ACL-1193	TUN-0332	0.4	7.7	
ACL-1194	TUN-0333	0.3	5.7	
ACL-1195	TUN-0334	0.1	4.7	

Table 3. (continued)

Laboratory Number	Field Sample Number	Percentage of N in sample by weight	$\delta^{15}N_{(AIR)}$ (‰)	Sample Origin
ACL-1196	TUN-0335	0.1	3.9	
ACL-1197	TUN-0336	0.3	8.1	
ACL-1203	TUN-0342	0.4	8.2	
ACL-1204	TUN-0343	0.2	5.2	
ACL-1205	TUN-0344	0.2	7.3	
ACL-1206	TUN-0345	0.1	8.4	
ACL-1207	TUN-0346	0.0	4.8	
ACL-1213	TUN-0352	0.2	9.6	
ACL-1214	TUN-0353	0.3	6.4	
ACL-1215	TUN-0354	0.1	5.1	
ACL-1216	TUN-0355	0.1	4.9	
ACL-1217	TUN-0356	0.1	4.4	
ACL-1226	TUN-0367	0.3	14.9	
ACL-1227	TUN-0368	0.1	4.7	
ACL-1228	TUN-0369	0.2	4.7	
ACL-1229	TUN-0370	0.1	4.8	
ACL-1230	TUN-0371	0.1	7.0	
ACL-1239	TUN-0382	0.4	8.6	
ACL-1240	TUN-0383	0.4	6.7	
ACL-1241	TUN-0384	0.2	7.0	
ACL-1242	TUN-0385	0.1	6.0	
ACL-1243	TUN-0386	0.1	5.3	
ACL-1244	TUN-0387	0.4	8.3	
ACL-1245	TUN-0388	0.3	7.2	
ACL-1246	TUN-0389	0.2	6.2	
ACL-1247	TUN-0390	0.2	5.1	
ACL-1248	TUN-0391	0.3	4.5	
ACL-1257	TUN-0402	0.5	8.7	
ACL-1258	TUN-0403	0.3	6.7	
ACL-1259	TUN-0404	0.3	7.7	
ACL-1260	TUN-0405	0.2	6.8	
ACL-1273	TUN-0422	0.2	10.8	
ACL-1274	TUN-0423	0.4	6.0	
ACL-1275	TUN-0424	0.2	5.4	
ACL-1276	TUN-0425	0.2	6.8	
ACL-1277	TUN-0426	0.3	6.5	
ACL-1278	TUN-0427	0.4	8.7	
ACL-1279	TUN-0428	0.3	6.8	
ACL-1280	TUN-0429	0.4	4.8	
ACL-1281	TUN-0430	0.1	8.8	
ACL-1282	TUN-0431	0.2	9.7	
ACL-1290	TUN-0442	0.3	9.2	
ACL-1291	TUN-0443	0.5	6.6	
ACL-1292	TUN-0444	0.3	3.5	
ACL-1295	TUN-0445	0.1	4.4	
ACL-1301	TUN-0462	0.2	6.8	
ACL-1302	TUN-0463	0.2	5.1	
ACL-1303	TUN-0464	0.3	4.1	
ACL-1304	TUN-0465	4.6	4.4	
ACL-1305	TUN-0467	0.6	7.5	
ACL-1306	TUN-0468	0.3	6.3	
ACL-1307	TUN-0469	0.3	4.7	
ACL-1308	TUN-0470	0.2	5.6	
ACL-1321	TUN-0487	0.4	7.5	
ACL-1322	TUN-0488	0.3	8.4	

Table 3. (continued)

Laboratory Number	Field Sample Number	Percentage of N in sample by weight	$\delta^{15}N_{(AIR)}$ (‰)	Sample Origin
ACL-1323	TUN-0489	0.4	6.0	
ACL-1324	TUN-0490	0.2	8.2	
ACL-1326	TUN-0492	0.2	8.4	
ACL-1327	TUN-0493	0.3	5.4	
ACL-1328	TUN-0494	0.2	5.1	
ACL-1329	TUN-0495	0.2	3.8	
ACL-1330	TUN-0497	0.3	7.4	
ACL-1331	TUN-0498	0.2	4.8	
ACL-1332	TUN-0499	0.2	6.0	
ACL-1333	TUN-0502	0.4	7.9	
ACL-1334	TUN-0507	0.1	8.8	
ACL-1335	TUN-0512	0.4	9.2	
ACL-1348	TUN-0537	0.1	9.1	
ACL-1349	TUN-0538	0.1	7.3	
ACL-1350	TUN-0539	0.1	9.3	
ACL-1351	TUN-0540	0.3	9.1	
ACL-1352	TUN-0542	0.3	7.5	
ACL-1353	TUN-0543	0.2	4.9	
ACL-1354	TUN-0544	0.2	4.2	
ACL-1355	TUN-0545	0.2	4.4	
ACL-1359	TUN-0552	0.3	7.7	
ACL-1360	TUN-0553	0.2	5.5	
ACL-1361	TUN-0554	0.4	4.3	
ACL-1362	TUN-0555	0.7	3.8	
ACL-1371	TUN-0572	0.4	9.7	
ACL-1372	TUN-0573	0.3	8.0	
ACL-1373	TUN-0574	0.2	6.5	
ACL-1374	TUN-0575	0.2	7.1	
ACL-1384	TUN-0592	0.1	6.8	
ACL-1385	TUN-0593	0.0	4.6	
ACL-1386	TUN-0594	0.1	5.1	
ACL-1387	TUN-0595	0.1	3.6	

mean $\delta^{15}N_{(AIR)}$ = 2.2‰ ± 0.4‰ (1σ, n = 35). However, ethnoarchaeological soil samples collected from known fish processing areas exhibit mean $\delta^{15}N_{(AIR)}$ = 13.4‰ ± 0.4‰ (1σ, n = 49); we interpret the much higher nitrogen isotope values from the fish processing areas as evidence of marine-derived ^{15}N. Ethnoarchaeological soil samples from a historic semisubterranean structure in Tununak exhibited nitrogen isotope values that were intermediate between the offsite and fish processing areas, and samples from the sod house exhibited mean $\delta^{15}N_{(AIR)}$ = 6.8‰ ± 0.2‰ (1σ, n = 105).

There is a statistically significant difference in $\delta^{15}N$ values from the fish processing areas and the semisubterranean structures and the $\delta^{15}N$ values from offsite areas. We interpret this difference as the result of enrichment in ^{15}N as marine-derived nitrogen from fish and marine mammals is incorporated into the soil during processing, storing, and discarding these products. Importantly, high $\delta^{15}N$ values are present in ethnoarchaeological soils in areas currently used for fish processing as well as in soils collected from a historic semisubterranean house that has been abandoned for more than fifty years. The use of nitrogen isotope analysis of archaeological soils to identify marine resource use is a novel application of a well-established technique in archaeology. We argue that this new method could be particularly useful for a minimally invasive examination of archaeological sites and activity areas, including processing and storing marine and anadromous fish resources as well as animals that consume these products. Finally, nitrogen isotope analysis of anthropogenically modified soils could also be used to examine long-term human impacts on arctic ecosystems.

Table 4. Descriptive statistics from nitrogen isotope data from all ethnoarchaeological samples collected from Nelson Island.

	$\delta^{15}N_{(AIR)}$ (‰)
Offsite Area	
Mean	2.2
Standard Error	0.4
Median	1.9
Standard Deviation	2.4
Sample Variance	5.7
Range	14.2
Minimum	–0.6
Maximum	13.7
Count	35
Fish Processing Area	
Mean	13.4
Standard Error	0.4
Median	14.0
Standard Deviation	2.7
Sample Variance	7.5
Range	16.6
Minimum	2.9
Maximum	19.5
Count	49
Sod House	
Mean	6.8
Standard Error	0.2
Median	6.8
Standard Deviation	2.0
Sample Variance	3.9
Range	11.4
Minimum	3.5
Maximum	14.9
Count	105

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NOTES

1. In fish processing area 1, the sand, silty sand, clayey sand and loam soils were characterized as 10YR 2/2 (Munsell color chart "very dark brown"), 10YR 3/1 ("very dark gray"), 10YR 3/2 ("very dark grayish brown"), and 10YR 2/1 ("black"). In fish processing area 2, the silty sand and loamy sand soils were characterized as 10YR 2/1 ("black"), 10YR 2/2 ("very dark brown"), 10YR 3/1 ("very dark gray"), and 10YR 3/2 ("very dark grayish brown"). Finally, in fish processing area 3, the silty loam and silty clay loam soils were characterized as 10YR 3/1 ("very dark gray"), and 10YR 4/2 ("dark grayish brown").
2. The sandy clay, silty loam, and sandy loam soils from the semisubterranean structure were characterized as 10YR 2/2 and 4/3 (Munsell color chart "very dark brown" and "brown") and 10YR 3/2 ("very dark grayish brown").
3. In offsite area 1, clay loam soils were characterized as 7.5YR 3/2 and 4/2 (Munsell color chart "dark brown" and "brown") and 5Y 3/2 ("dark olive gray"). In offsite area 2, loamy clay and clay soils ranged between 10YR 2/1("black") and 10YR 4/3 ("brown"). Finally, offsite area 3 soils ranged between 10YR 2/1 ("black")

and10YR 3/1 ("very dark gray") and were sandy silty loam soils with a loose and friable texture.

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APPENDIX 1. ARCTIC NITROGEN ISOTOPE DATA FROM PUBLISHED SOURCES

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Benthic Algae						
Periphyton (benthic algae)	algae	0.2	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	–0.1	1.0	2	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	–2.0	0.2	5	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.8	0.3	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.5	0.5	4	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.5	0.1	2	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.2	0.3	2	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.5	0.1	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.0	0.1	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.5	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.5	0.1	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.1	0.6	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	–0.5	0.2	2	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.9	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	2.2	0.1	4	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	1.4	0.2	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	6.2	0.4	3	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	6.3	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	0.6	0.2	4	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	2.4	0.1	2	Sashin Creek (AK, USA)	Kline et al. 1990
Periphyton (benthic algae)	algae	3.3	0.1	4	Sashin Creek (AK, USA)	Kline et al. 1990
Invertebrates						
Zooplankton	whole body	8.3	0.9	116	Prince William Sound (AK, USA)	Kline 1999
Zooplankton (Copepods)	whole body	9.8	0.2	10	Barrow (AK, USA)	Hoekstra et al. 2002
Zooplankton (Copepods)	whole body	10.4	0.5	20	Kaktovik (AK, USA)	Hoekstra et al. 2002
Zooplankton (Copepods)	whole body	10.4	0.4	10	Holman (NW Territories, Canada)	Hoekstra et al. 2002
Zooplankton (Chaetognaths)	whole body	11.1	0.5	11	Arctic Ocean	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	11.9	0.6	15	Beaufort Sea (Canada)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	12.7	0.2	64	Central Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	12.9	0.3	35	East Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	12.3	0.3	27	East Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	12.3	0.8	4	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Chaetognaths)	whole body	12.8	0.8	11	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Chaetognaths)	whole body	13.5	0.6	5	Eastern Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	13.3	0.2	40	North Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	8.5	0.3	27	South Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	14.2	0.3	5	Western Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	11.6	0.3	27	West Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Chaetognaths)	whole body	12.2	0.3	26	West Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	9.0	1.1	36	Arctic Ocean	Schell et al. 1998
Zooplankton (Copepods)	whole body	10.0	0.2	14	Beaufort Sea (Canada)	Schell et al. 1998
Zooplankton (Copepods)	whole body	9.6	0.2	132	Central Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	9.8	0.2	64	East Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	10.5	0.2	54	East Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	10.3	0.6	33	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Copepods)	whole body	10.8	1.0	30	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Copepods)	whole body	10.8	0.2	45	Eastern Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	11.3	0.1	54	North Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	5.8	0.2	87	South Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	11.6	0.4	6	Western Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	8.7	0.2	64	West Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	whole body	10.3	0.3	54	West Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Copepods)	muscle	8.5	NA	1	Gulf of Alaska (AK, USA)	Hobson et al. 1997

Species	Sample type	δ15N (‰)	standard error / standard deviation	*n*	Location	Reference
Zooplankton (Copepods; *Euchaeta elongata* or *Neocalanus* spp.)	whole body	12.0	0.2	6	Prince William Sound (AK, USA)	Kline 1999
Zooplnakton (Copepods; *Euchaeta elongata* or *Neocalanus* spp.)	whole body	11.9	0.6	23	Prince William Sound (AK, USA)	Kline 1999
Zooplankton (Euphausiids)	whole body	9.3	0.2	47	Central Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	10.0	0.2	33	East Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	9.7	0.3	33	East Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	11.0	0.3	5	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Euphausiids)	whole body	11.2	0.7	5	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Zooplankton (Euphausiids)	whole body	11.0	0.2	36	North Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	7.2	0.3	34	South Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	9.1	0.2	32	West Bering Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	9.9	0.3	32	West Chukchi Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	9.2	0.6	18	Eastern Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids)	whole body	11.2	0.3	21	Western Beaufort Sea (AK, USA)	Schell et al. 1998
Zooplankton (Euphausiids; *Euphausia pacifica* and *Thysanoessa* spp.)	whole body	10.5	0.6	55	Prince William Sound (AK, USA)	Kline 1999
Zooplankton (Euphausiids; *Euphausia pacifica*, *Thysanoessa* spp.)	whole body	9.4	0.3	20	Prince William Sound (AK, USA)	Kline 1999
Zooplankton (Euphausiids; *Euphausia pacifica*, *Thysanoessa* spp.)	whole body	10.7	1.9	95	Prince William Sound (AK, USA)	Kline 1999
Zooplankton (*Neocalanus cristatus*)	whole body	8.0	1.8	938	Prince William Sound (AK, USA)	Kline et al. 1997
Crustaceans						
Amphipods (principally *Cyphocaris challengeri*)	whole body	11.6	0.8	23	Prince William Sound (AK, USA)	Kline 1999
Amphipods (principally *Cyphocaris challengeri*)	whole body	10.6	2.0	85	Prince William Sound (AK, USA)	Kline 1999
Aquatic sowbug (*Saduria entomon*)	whole body	10.1	NA	1	Bering Sea (AK, USA)	Dunton et al. 1989
Aquatic sowbug (*Saduria entomon*)	whole body	14.4	NA	1	Chukchi Sea (AK, USA)	Dunton et al. 1989
Aquatic sowbug (*Saduria entomon*)	whole body	10.9	0.7	3	Eastern Beaufort Sea (AK, USA)	Dunton et al. 1989
Decapods	whole body	11.2	1.9	20	Prince William Sound (AK, USA)	Kline 1999
Decapods	whole body	11.4	1.5	38	Prince William Sound (AK, USA)	Kline 1999
Hermit crab (*Pagurus trigonocheirus*)	muscle	12.0	0.2	2	Bering Sea (AK, USA)	Dunton et al. 1989
Hermit crab (*Pagurus trigonocheirus*)	muscle	11.9	NA	1	Chukchi Sea (AK, USA)	Dunton et al. 1989
Hermit crab (*Pagurus trigonocheirus*)	muscle	12.0	NA	1	Western Beaufort Sea (AK, USA)	Dunton et al. 1989
Shrimp (*Crangon dalli*)	whole body	14.4	0.4	2	Bering Sea (AK, USA)	Dunton et al. 1989
Molluscs						
Mollusc (*Hiatella arctica*)	whole body	9.1	0.7	5	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Squid (*Berryteuthis magister*)	whole body	11.4	0.2	3	Bering Sea (AK, USA)	Kurle & Worthy 2001
Squid (*Berryteuthis magister*)	whole body	11.4	0.2	9	Bering Sea (AK, USA)	Kurle & Worthy 2001
Squid (*Berryteuthis magister*)	NA	12.3	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Squid (*Berryteuthis magister*)	NA	14.1	NA	NA	Shelikof Strait (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Squid (*Gonatopsis borealis*)	whole body	11.1	0.2	3	Bering Sea (AK, USA)	Kurle & Worthy 2001
Squid (*Gonatopsis borealis*)	NA	9.7	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Squid	muscle	16.7	NA	1	Gulf of Alaska (AK, USA)	Hobson et al. 1997
Squid	muscle	9.6	0.5	4	Gulf of Alaska (AK, USA)	Hobson et al. 1997

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Anadromous Fish						
Chinook salmon (*Oncorhynchus tshawytscha*)	NA	13.8	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Chinook salmon (*Oncorhynchus tshawytscha*)	muscle	14.0	0.6	6	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Chinook salmon (*Oncorhynchus tshawytscha*)	NA	14.9	NA	NA	Shelikof Strait (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Chinook salmon (*Oncorhynchus tshawytscha*)	bone	13.2	NA	1	Yukon River (AK, USA)	Misarti 2007
Chinook salmon (*Oncorhynchus tshawytscha*)	muscle	14.4	NA	1	Yukon River (AK, USA)	Misarti 2007
Chum salmon (*Oncorhynchus keta*)	muscle	11.8	0.2	3	Barrow (AK, USA)	Hoekstra et al. 2002
Chum salmon (*Oncorhynchus keta*)	whole body	10.5	NA	1	Bering Sea (AK, USA)	Kurle & Worthy 2001
Chum salmon (*Oncorhynchus keta*)	muscle	10.6	1.1	39	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Chum salmon (*Oncorhynchus keta*)	muscle	11.0	1.2	25	AK, USA	Satterfield & Finney 2002
Coho salmon (*Oncorhynchus kisutch*)	muscle	11.8	0.7	39	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Coho salmon (*Oncorhynchus kisutch*)	muscle	13.8	0.5	12	AK, USA	Satterfield & Finney 2002
Coho salmon (*Oncorhynchus kisutch*), spawning	whole body	9.0	NA	2	Sashin Creek (AK, USA)	Kline et al. 1990
Coho salmon (*Oncorhynchus kisutch*), spawning	whole body	12.0	NA	3	Sashin Creek (AK, USA)	Kline et al. 1990
Coho salmon (*Oncorhynchus kisutch*), spawning	whole body	11.4	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Coho salmon (*Oncorhynchus kisutch*), spawning	whole body	13.5	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Dolly Varden trout (*Salvelinus malma*), spawning	whole body	10.9	NA	2	Sashin Creek (AK, USA)	Kline et al. 1990
Dolly Varden trout (*Salvelinus malma*), spawning	whole body	13.5	NA	3	Sashin Creek (AK, USA)	Kline et al. 1990
Dolly Varden trout (*Salvelinus malma*), spawning	whole body	12.2	NA	1	Sashin Creek (AK, USA)	Kline et al. 1990
Dolly Varden trout (*Salvelinus malma*), spawning	whole body	12.9	NA	1	Sashin Creek(AK, USA)	Kline et al. 1990
King salmon (*Oncorhynchus tshawytscha*)	muscle	15.2	0.3	15	AK, USA	Satterfield & Finney 2002
Pink salmon (*Oncorhynchus gorbuscha*)	muscle	10.8	0.6	7	Barrow (AK, USA)	Hoekstra et al. 2002
Pink salmon (*Oncorhynchus gorbuscha*)	NA	8.5	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pink salmon (*Oncorhynchus gorbuscha*)	muscle	10.4	1.0	37	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Pink salmon (*Oncorhynchus gorbuscha*)	muscle	10.8	0.4	22	AK, USA	Satterfield & Finney 2002
Silver salmon (*Oncorhynchus kisutch*)	NA	15.0	NA	NA	Shelikof Strait (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Sockeye salmon (*Oncorhynchus nerka*)	bone	11.5	1.7	91	Sanak Islands (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	bone	9.5	0.3	3	Chitina River (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.2	0.5	3	Chitina River (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	muscle	11.4	0.7	40	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Sockeye salmon (*Oncorhynchus nerka*)	bone	9.0	NA	1	Kodiak (AK, USA)	Misarti 2007

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.3	NA	1	Kodiak (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	whole body	11.6	0.3	4	Kvichak River (AK, USA)	Kline et al. 1993
Sockeye salmon (*Oncorhynchus nerka*)	whole body	12.3	0.9	16	Tazimina River and Chinkelyes Creek (AK, USA)	Kline et al. 1993
Sockeye salmon (*Oncorhynchus nerka*)	bone	10.5	1.0	2	Unalaska (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.7	0.2	2	Unalaska (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	bone	9.2	NA	1	Yukon River (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.9	NA	1	Yukon River (AK, USA)	Misarti 2007
Sockeye salmon (*Oncorhynchus nerka*)	muscle	11.2	0.6	47	AK, USA	Satterfield & Finney 2002
Sockeye salmon (*Oncorhynchus nerka*)	muscle	11.0	0.6	29	AK, USA	Satterfield & Finney 2002
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.6	NA	32	Black Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.4	NA	34	Iliamna Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.7	NA	50	Iliamna Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.0	NA	60	Iliamna Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	13.7	NA	5	Akalura Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	12.6	NA	10	Auke Lake, Juneau (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.1	NA	15	Becharof Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.5	NA	24	Becharof Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	7.5	NA	19	Becharof Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.3	NA	68	Black Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.9	NA	6	Chignik Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.8	NA	50	Chignik Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.0	NA	29	Chignik Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.9	NA	20	Chignik Lake (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	13.0	NA	10	Chilkat Lake (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	13.4	NA	10	Chilkat Lake (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.5	NA	10	Chilkoot Lake (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.1	NA	20	Coghill Lake, Prince William Sound (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	12.6	NA	5	Frazer Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.1	NA	20	Frazer Lake, Kodiak (AK, USA)	Uchiyama et al. 2008

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Sockeye salmon (*Oncorhynchus nerka*)	muscle	10.8	NA	20	Hidden Lake, Cook Inlet (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.4	NA	10	Hugh Smith Lake (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.7	NA	5	Iliamna Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	12.8	NA	7	Karluk Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	15.7	NA	12	Karluk Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	14.0	NA	18	Karluk Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	13.2	NA	19	Karluk Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	11.0	NA	10	Lake McDonald (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	16.1	NA	20	Red Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	7.7	NA	10	Redoubt Lake, Southeast (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	7.1	NA	10	Speel Lake, Southeast (AK, USA)	Barto 2004; in Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	11.3	NA	10	Spiridon Lake, Kodiak (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.6	NA	19	Tustumena Lake, Cook Inlet (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.5	NA	16	Ugashik Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.6	NA	25	Ugashik Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	9.8	NA	20	Ugashik Lake, Bristol Bay (AK, USA)	Uchiyama et al. 2008
Sockeye salmon (*Oncorhynchus nerka*)	muscle	8.1	NA	20	Upper Russian Lake, Cook Inlet (AK, USA)	Uchiyama et al. 2008
Steelhead trout (*Oncorhynchus mykiss*)	muscle	12.5	1.0	35	Gulf of Alaska (AK, USA)	Kaeriyama et al. 2004
Marine Fish						
Pacific herring (*Clupea pallasi*)	whole body	15.3	0.2	5	Bering Sea (AK, USA)	Kurle & Worthy 2001
Pacific herring (*Clupea pallasi*)	whole body	13.5	0.1	8	Bering Sea (AK, USA)	Kurle & Worthy 2001
Pacific herring (Clupea pallasi)	NA	13.9	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pacific herring (Clupea pallasi)	NA	14.5	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pacific herring (*Clupea pallasi*)	whole body	12.3	0.9	110	Prince William Sound (AK, USA)	Kline 1999
Pacific herring (*Clupea pallasi*)	whole body	12.7	0.3	250	Prince William Sound (AK, USA)	Kline 1999
Pacific cod (*Gadus macrocephalus*)	bone	16.1	1.2	101	Sanak Islands (AK, USA)	Misarti 2007
Pacific cod (*Gadus macrocephalus*)	NA	17.9	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pacific cod (*Gadus macrocephalus*)	NA	14.8	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pacific cod (*Gadus macrocephalus*)	NA	17.1	NA	NA	Bering Sea (AK, USA)	Kurle et al. unpub. data in Worthy 2008
Pacific cod (*Gadus macrocephalus*)	muscle	16.2	1.3	3	Bering Sea (AK, USA)	Dunton et al. 1989
Pacific cod (*Gadus macrocephalus*)	muscle	11.4	0.2	19	Gulf of Alaska (AK, USA)	Hobson et al. 1997
Pacific cod (*Gadus macrocephalus*)	bone	16.6	NA	1	Pavlof (AK, USA)	Misarti 2007
Pacific cod (*Gadus macrocephalus*)	muscle	17.1	NA	1	Pavlof (AK, USA)	Misarti 2007
Pacific cod (*Gadus macrocephalus*)	NA	17.9	NA	NA	Shelikof Strait (AK, USA)	Kurle et al. unpub. data in Worthy 2008

Species	Sample type	δ^{15}N (‰)	standard error / standard deviation	*n*	Location	Reference
Sea birds						
Ancient murrelet (*Synthliboramphus antiquus*)	muscle	15.0	0.3	12	Oak Bay (BC, Canada)	Hobson et al. 1994
Ancient murrelet (*Synthliboramphus antiquus*)	muscle	12.8	0.6	5	Shumagin Islands, Alaska	Hobson et al. 1994
Black guillemot (*Cepphus grylle*)	muscle	15.0	0.4	6	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Black guillemot (*Cepphus grylle*)	bone	18.2	0.7	16	Lancaster Sound (Nunavut, Canada)	Hobson & Montevecchi 1991
Black-legged kittiwake (*Rissa tridactyla*)	muscle	15.8	0.3	6	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Black-legged kittiwake (*Rissa tridactyla*)	muscle	14.2	1.1	6	Shumagin Islands (AK, USA)	Hobson et al. 1994
Cassin's auklet (*Ptychoramphus aleuticus*)	muscle	14.5	0.2	6	Barkley Sound (BC, Canada)	Hobson et al. 1994
Cassin's auklet (*Ptychoramphus aleuticus*)	bone	16.4	0.2	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Cassin's auklet (*Ptychoramphus aleuticus*)	muscle	12.3	0.5	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Cassin's auklet (*Ptychoramphus aleuticus*)	muscle	13.5	0.4	6	Shumagin Islands (AK, USA)	Hobson et al. 1994
Common eider (*Somateria mollissima*)	muscle	13.5	0.0	3	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Common murre (*Uria aalge*)	bone	17.3	0.8	6	Masset Inlet (BC, Canada)	Hobson et al. 1994
Common murre (*Uria aalge*)	muscle	15.5	1.3	6	Masset Inlet (BC, Canada)	Hobson et al. 1994
Common murre (*Uria aalge*)	muscle	15.3	0.9	5	Shumagin Islands (AK, USA)	Hobson et al. 1994
Crested auklet (*Aethia cristatella*)	feathers	14.5	2.3	13	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Crested auklet (*Aethia cristatella*)	feathers	13.5	2.3	9	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Crested auklet (*Aethia cristatella*)	feathers	12.6	2.0	9	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Crested auklet (*Aethia cristatella*)	feathers	12.6	1.9	6	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Crested auklet (*Aethia cristatella*)	muscle	12.5	0.7	6	Shumagin Islands (AK, USA)	Hobson et al. 1994
Double-crested cormorant (*Phalacrocorax auritus*)	muscle	17.5	NA	1	Shumagin Islands (AK, USA)	Hobson et al. 1994
Fork-tailed storm-petrel (*Oceanodroma furcata*)	bone	17.9	0.4	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Fork-tailed storm-petrel (*Oceanodroma furcata*)	muscle	15.9	0.4	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Fork-tailed storm-petrel (*Oceanodroma furcata*)	muscle	14.0	NA	1	Semidi Islands (AK, USA)	Hobson et al. 1994
Glaucous gull (*Larus hyperboreus*)	muscle	16.7	0.2	4	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Glaucous-winged gull (*Larus canus*)	muscle	15.1	0.9	6	Shumagin Islands (AK, USA)	Hobson et al. 1994
Great auk (*Pinguinus impennis*)	bone	15.8	1.9	30	Funk Island (Newfoundland, Canada)	Hobson & Montevecchi 1991
Horned puffin (*Fratercula corniculata*)	muscle	13.3	0.8	4	Shumagin Islands (AK, USA)	Hobson et al. 1994
Kittlitz's murrelet (*Brachyramphus brevirostris*)	muscle	14.5	1.1	6	Kachemak Bay (AK, USA)	Hobson et al. 1994
Leach's storm-petrel (*Oceanodroma leucorhoa*)	bone	17.1	0.3	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Leach's storm-petrel (*Oceanodroma leucorhoa*)	muscle	13.5	0.9	6	Hippa Island (BC, Canada)	Hobson et al. 1994
Leach's storm-petrel (*Oceanodroma leucorhoa*)	muscle	13.8	0.7	5	Semidi Islands (AK, USA)	Hobson et al. 1994
Little auk or dovekie (*Alle alle*)	muscle	12.5	NA	1	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998

Species	Sample type	δ[15]N (‰)	standard error / standard deviation	*n*	Location	Reference
Marbled murrelet (*Brachyramphus marmoratus*)	muscle	15.3	0.2	19	Barkley Sound (BC, Canada)	Hobson et al. 1994
Marbled murrelet (*Brachyramphus marmoratus*)	muscle	14.7	0.6	10	Kachemak Bay (AK, USA)	Hobson et al. 1994
Mew gull (*Larus canus*)	muscle	15.3	0.4	3	Shumagin Islands (AK, USA)	Hobson et al. 1994
Northern fulmar (*Fulmarus glacialis*)	muscle	15.4	0.2	5	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Northern fulmar (*Fulmarus glacialis*)	muscle	15.7	1.0	5	Shumagin Islands (AK, USA)	Hobson et al. 1994
Parakeet auklet (*Aethia psittacula*)	muscle	13.8	0.4	5	Shumagin Islands (AK, USA)	Hobson et al. 1994
Pelagic cormorant (*Phalacrocorax pelagicus*)	muscle	15.8	1.1	3	Shumagin Islands (AK, USA)	Hobson et al. 1994
Pigeon guillemot (*Cepphus columba*)	muscle	16.5	0.2	5	Barkley Sound (BC, Canada)	Hobson et al. 1994
Pigeon guillemot (*Cepphus columba*)	muscle	15.1	0.7	4	Shumagin Islands (AK, USA)	Hobson et al. 1994
Rhinoceros auklet (*Cerorhinca monocerata*)	muscle	15.9	0.2	9	Barkley Sound (BC, Canada)	Hobson et al. 1994
Rhinoceros auklet (*Cerorhinca monocerata*)	bone	17.6	0.4	6	Lucy Island (BC, Canada)	Hobson et al. 1994
Rhinoceros auklet (*Cerorhinca monocerata*)	muscle	15.4	0.5	6	Lucy Island (BC, Canada)	Hobson et al. 1994
Rhinoceros auklet (*Cerorhinca monocerata*)	muscle	13.1	1.2	2	Semidi Islands (AK, USA)	Hobson et al. 1994
Sooty shearwater (*Puffinus griseus*)	bone	15.8	0.4	4	Hecate Strait (BC, Canada)	Hobson et al. 1994
Sooty shearwater (*Puffinus griseus*)	muscle	11.7	0.9	4	Hecate Strait (BC, Canada)	Hobson et al. 1994
Surf scoter (*Melanitta perspicillata*)	bone	11.8	1.0	5	Hecate Strait (BC, Canada)	Hobson et al. 1994
Thick-billed murre (*Uria lomvia*)	muscle	16.4	0.1	4	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Thick-billed murre (*Uria lomvia*)	bone	17.6	1.1	14	Lancaster Sound (Nunavut, Canada)	Hobson & Montevecchi 1991
Tufted puffin (*Fratercula cirrhata*)	muscle	12.9	0.5	4	Shumagin Islands (AK, USA)	Hobson et al. 1994
Tufted puffin (*Fratercula cirrhata*)	feathers	15.5	1.4	15	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	15.4	1.4	15	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	16.0	1.4	3	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	15.5	1.1	3	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	13.4	2.5	32	North Pacific	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	13.4	2.5	21	North Pacific	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	12.1	1.9	3	North Pacific	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	13.2	1.8	17	North Pacific	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	feathers	12.5	2.3	14	North Pacific	Hobson, Sinclair et al. 2004
Tufted puffin (*Fratercula cirrhata*)	muscle	14.7	0.5	5	Triangle Island (BC, Canada)	Hobson et al. 1994
White-winged scoter (*Melanitta fusca*)	bone	12.2	0.4	5	Hecate Strait (BC, Canada)	Hobson et al. 1994
Marine Mammals (Order: Cetacea)						
Blue whale (*Balaenoptera musculus*)	skin	12.9	0.3	2	Bahia de La Paz (Mexico)	Gendron et al. 2001
Bowhead whale (*Balaena mysticetus*)	muscle	13.3	0.6	110	AK, USA	Dehn et al. 2006
Bowhead whale (*Balaena mysticetus*)	skin	13.9	0.2	2	AK, USA	Schell et al. 2000
Bowhead whale (*Balaena mysticetus*)	muscle	13.3	0.3	21	Barrow (AK, USA)	Hoekstra et al. 2002

Species	Sample type	δ15N (‰)	standard error / standard deviation	*n*	Location	Reference
Bowhead whale (*Balaena mysticetus*)	muscle	13.5	0.4	9	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.1	0.2	16	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.3	0.3	15	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	12.5	0.3	5	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	12.9	0.6	4	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.1	0.2	2	Barrow (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.4	0.7	122	Barrow (AK, USA)	Dehn et al. 2006; includes data from Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.2	0.7	24	Eastern Beaufort Sea (AK, USA)	Lee et al. 2005
Bowhead whale (*Balaena mysticetus*)	muscle	14.3	0.8	18	Eastern Beaufort Sea (AK, USA)	Schell 1992 in Lee et al. 2005
Bowhead whale (*Balaena mysticetus*)	muscle	13.1	0.2	4	Kaktovik (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	12.8	0.4	3	Kaktovik (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.6	0.6	3	Kaktovik (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	muscle	13.5	0.9	2	Kaktovik (AK, USA)	Hoekstra et al. 2002
Bowhead whale (*Balaena mysticetus*)	baleen	14.4	0.8	71	Western Arctic Sea	Hobson & Schell 1998
Bryde's whale (*Balaenoptera edeni*)	skin	15.8	0.6	2	Bahia de la Paz (Mexico)	Gendron et al. 2001
Fin whale (*Balaenoptera physalus*)	skin	15.4	1.1	2	Bahia de la Paz (Mexico)	Gendron et al. 2001
Gray whale (*Eschrichtius robustus*)	baleen	15.1	0.1	2	Baja California Sur (Mexico)	Caraveo-Patino et al. 2007
Gray whale (*Eschrichtius robustus*)	baleen	13.5	0.5	4	Baja California Sur (Mexico)	Caraveo-Patino et al. 2007
Gray whale (*Eschrichtius robustus*)	skin	14.2	0.7	4	Bering Sea, Chukchi Sea (AK, USA)	Schell et al. 2000
Gray whale (*Eschrichtius robustus*)	muscle	12.0	0.9	17	Russia	Dehn et al. 2006
Humpback whale (*Megaptera novaeangliae*)	skin	12.4	0.1	122	Bering Sea (AK, USA)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	14.7	0.1	128	CA and OR, USA	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	12.1	0.2	56	Eastern Aleutian Islands (AK, USA)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	13.0	0.1	135	Pacific Ocean (BC, Canada)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	13.6	0.1	199	Gulf of Alaska (AK, USA)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	12.5	0.2	67	Russia	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	12.7	0.1	227	Pacific Ocean (AK, USA)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	14.6	0.1	53	Pacific Ocean (BC, Canada)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	11.4	0.3	14	Western Aleutian Islands (AK, USA)	Witteveen et al. 2009
Humpback whale (*Megaptera novaeangliae*)	skin	13.1	0.1	104	Gulf of Alaska (AK, USA)	Witteveen et al. 2009
Beluga whale (*Delphinapterus leucas*)	muscle	16.7	0.6	49	AK, USA	Dehn et al. 2006
Beluga whale (*Delphinapterus leucas*)	muscle	16.6	0.6	6	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Beluga whale (*Delphinapterus leucas*)	muscle	16.4	0.3	4	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Beluga whale (*Delphinapterus leucas*)	muscle	16.6	0.1	22	Point Lay (AK, USA)	Hoekstra et al. 2002
Dall's porpoise (*Phocoenoides dalli*)	NA	11.5	NA	NA	Bering Sea (AK, USA)	Ohizumi & Miyazaki 2001 in Worthy 2008
Dall's porpoise (*Phocoenoides dalli*)	NA	12.3	NA	NA	Gulf of Alaska (AK, USA)	Hirons unpub. data in Worthy 2008
Harbor porpoise (*Phocoena phocoena*)	bone	15.7	0.7	29	Monterey Bay (CA, USA)	Toperoff 2002

Species	Sample type	δ¹⁵N (‰)	standard error / standard deviation	*n*	Location	Reference
Harbor porpoise (*Phocoena phocoena*)	muscle	15.2	0.8	29	Monterey Bay (CA, USA)	Toperoff 2002
Harbor porpoise (*Phocoena phocoena*)	skin	16.0	0.7	29	Monterey Bay (CA, USA)	Toperoff 2002
Killer whale (*Orcinus orca*), offshore	blubber	17.2	0.6	3	AK, USA	Herman et al. 2005
Killer whale (*Orcinus orca*), offshore	blubber	16.8	0.3	2	Trinity Island, Gulf of Alaska (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), resident	blubber	17.9	NA	1	Aleutian Islands (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), resident	blubber	15.6	1.5	11	Central Aleutian Islands (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), resident	blubber	15.1	0.9	2	Central Aleutian Islands (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), resident	blubber	16.7	1.2	11	Eastern Aleutian Islands (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), resident	blubber	16.0	1.1	5	Eastern Aleutian Islands (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), resident	blubber	17.2	0.8	8	Gulf of Alaska (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), resident	blubber	21.0	NA	1	Gulf of Alaska (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), resident	blubber	17.8	1.0	20	Prince William Sound (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), resident	blubber	17.9	0.5	4	Trinity Island, Gulf of Alaska (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), southern resident	blubber	16.9	0.6	4	Pacific Ocean	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	18.7	1.8	2	Central Aleutian Islands (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	17.9	0.5	9	Eastern Aleutian Islands (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	17.8	0.2	2	Aleutian Islands (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), transient	blubber	19.8	NA	1	Gulf of Alaska (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	17.8	1.0	2	Gulf of Alaska (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), transient	blubber	18.3	1.0	9	Prince William Sound (AK, USA)	Worthy 2008
Killer whale (*Orcinus orca*), transient	blubber	20.0	0.8	2	Prince William Sound (AK, USA)	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	17.6	NA	1	Pacific Ocean	Herman et al. 2005
Killer whale (*Orcinus orca*), transient	blubber	21.2	NA	1	Pacific Ocean	Herman et al. 2005
Minke whale (*Balaenoptera acutorostrata*)	muscle	12.2	1.0	43	Western North Atlantic (Greenland)	Born et al. 2003
Narwhal (*Monodon monoceros*)	muscle	15.8	0.7	4	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Narwhal (*Monodon monoceros*)	muscle	15.9	NA	2	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Marine Mammals (Order: Carnivora)						
Sea otter (*Enhydra lutris*)	NA	14.7	NA	NA	Aleutian Islands (AK, USA)	Hirons unpub. data in Worthy 2008
Sea otter (*Enhydra lutris*)	NA	13.6	NA	NA	Prince William Sound (AK, USA)	Hirons unpub. data in Worthy 2008
Sea otter (*Enhydra lutris*)	NA	18.3	NA	NA	Prince William Sound (AK, USA)	Wooler et al. 2005, in Worthy 2008
Sea otter (*Enhydra lutris*)	bone	14.5	1.4	88	Sanak Islands (AK, USA)	Misarti 2007
Walrus (*Odobenus rosmarus*)	muscle	12.5	0.6	6	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Walrus (*Odobenus rosmarus*)	muscle	13.5	1.0	6	Barrow (AK, USA)	Dehn et al. 2006
Walrus (*Odobenus rosmarus*)	muscle	12.8	0.4	3	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Bearded seal (*Erignathus barbatus*)	muscle	16.8	0.2	4	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Bearded seal (*Erignathus barbatus*)	muscle	16.7	0.9	47	Barrow (AK, USA)	Dehn et al. 2005
Bearded seal (*Erignathus barbatus*)	muscle	16.8	0.4	6	Barrow (AK, USA)	Hoekstra et al. 2002
Bearded seal (*Erignathus barbatus*)	muscle	16.8	0.5	4	Hudson Bay (Canada)	Young et al. 2010
Bearded seal (*Erignathus barbatus*)	muscle	15.7	1.2	2	Hudson Bay (Canada)	Young et al. 2010
Bearded seal (*Erignathus barbatus*)	muscle	14.5	0.3	6	Hudson Bay (Canada)	Young et al. 2010
Gray seal (*Halichoerus grypus*)	serum	16.2	0.3	2	Quebec Aquarium (Quebec, Canada)	Lesage et al. 2002

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Gray seal (*Halichoerus grypus*)	serum	16.7	0.2	5	University of Guelph (Ontario, Canada)	Lesage et al. 2002
Harbor seal (*Phoca vitulina*)	bone	17.1	1.7	37	Sanak Islands (AK, USA)	Misarti 2007
Harbor seal (*Phoca vitulina*)	bone	16.7	2.1	17	AK, USA	Burton & Koch 1999
Harbor seal (*Phoca vitulina*)	bone	18.0	1.2	20	AK, USA	Burton & Koch 1999
Harbor seal (*Phoca vitulina*)	NA	19.9	NA	NA	Aleutian Islands (AK, USA)	Hirons unpub. data in Worthy 2008
Harbor seal (*Phoca vitulina*)	bone	18.0	2.2	9	Bering Sea (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	14.8	0.8	2	Bering Sea (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	16.5	0.2	2	Bering Sea (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	18.4	0.6	2	Bering Sea (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	17.5	1.4	8	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	20.2	0.0	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	17.9	1.4	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	17.3	0.2	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	16.9	0.3	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	16.4	1.2	3	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	16.2	0.6	5	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	muscle	18.6	0.3	9	Copper River Delta (AK, USA)	Hobson et al. 1997
Harbor seal (*Phoca vitulina*)	muscle	16.3	0.3	10	Hudson Bay (Canada)	Young et al. 2010
Harbor seal (*Phoca vitulina*)	muscle	16.3	0.5	4	Hudson Bay (Canada)	Young et al. 2010
Harbor seal (*Phoca vitulina*)	muscle	17.2	0.1	2	Hudson Bay (Canada)	Young et al. 2010
Harbor seal (*Phoca vitulina*)	NA	16.5	NA	NA	Prince William Sound (AK, USA)	Hirons unpub. data in Worthy 2008
Harbor seal (*Phoca vitulina*)	NA	16.4	NA	NA	Prince William Sound (AK, USA)	Wooler et al. 2005 in Worthy 2008
Harbor seal (*Phoca vitulina*)	serum	16.0	0.4	3	Quebec Aquarium (Quebec, Canada)	Lesage et al. 2002
Harbor seal (*Phoca vitulina*)	serum	15.6	0.3	4	Shippagan (New Brunswick, Canada)	Lesage et al. 2002
Harbor seal (*Phoca vitulina*)	bone	15.8	NA	1	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	19.0	1.4	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	bone	16.4	0.7	5	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harbor seal (*Phoca vitulina*)	serum	16.6	0.2	3	University of Guelph (Ontario, Canada)	Lesage et al. 2002
Harbor seal (*Phoca vitulina*)	bone	17.1	1.2	8	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Harp seal (*Phoca groenlandica*)	serum	17.4	0.3	8	Memorial University (Newfoundland, Canada)	Lesage et al. 2002
Northern elephant seal (*Mirounga angustirostris*)	bone	18.2	0.7	10	CA, USA	Burton & Koch 1999
Northern fur seal (*Callorhinus ursinus*)	bone	16.1	2.4	27	Sanak Islands (AK, USA)	Misarti 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	17.6	1.3	10	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	15.7	1.1	55	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	15.3	1.0	30	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	15.6	0.9	50	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	15.3	0.9	35	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	dentine	15.7	1.2	40	Saint Paul Island (AK, USA)	Newsome et al. 2007
Northern fur seal (*Callorhinus ursinus*)	bone	17.4	2.1	9	AK, USA	Burton & Koch 1999
Northern fur seal (*Callorhinus ursinus*)	bone	16.6	1.4	10	AK, USA	Burton & Koch 1999
Northern fur seal (*Callorhinus ursinus*)	bone	17.6	1.8	13	Bering Sea (AK, USA)	Hirons et al. 2001

Species	Sample type	δ¹⁵N (‰)	standard error / standard deviation	*n*	Location	Reference
Northern fur seal (*Callorhinus ursinus*)	bone	16.1	0.8	2	Bering Sea (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	bone	20.3	0.9	2	Bering Sea (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	bone	18.9	1.6	2	Bering Sea (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	bone	18.9	1.5	5	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	bone	18.0	0.6	3	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	muscle	16.6	0.5	7	Pribilof Islands (AK, USA)	Hobson et al. 1997
Northern fur seal (*Callorhinus ursinus*)	skin	17.3	0.1	46	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	16.7	0.1	28	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	18.1	0.1	3	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	fur	14.8	0.1	28	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	muscle	15.6	0.2	30	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	brain	16.9	0.1	29	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	17.1	0.1	30	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	16.0	0.2	17	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	liver	16.0	0.2	30	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	kidney	16.3	0.2	26	St. George Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	skin	17.3	0.1	46	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	16.5	0.2	20	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	15.6	0.2	5	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	17.4	0.3	11	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	skin	18.1	0.2	15	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2001
Northern fur seal (*Callorhinus ursinus*)	fur	14.9	0.2	39	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	muscle	15.1	0.2	38	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	brain	17.0	0.1	39	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	17.1	0.1	36	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	15.8	0.2	31	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	liver	16.2	0.1	40	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	kidney	16.4	0.2	37	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	fur	16.3	0.8	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002

Species	Sample type	δ^{15}N (‰)	standard error / standard deviation	*n*	Location	Reference
Northern fur seal (*Callorhinus ursinus*)	fur	17.4	NA	1	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	muscle	16.1	0.5	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	muscle	16.1	0.3	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	brain	17.9	0.1	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	brain	17.7	0.2	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	18.0	0.4	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	18.9	NA	1	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	16.5	0.6	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	blubber	18.3	NA	1	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	liver	17.6	0.0	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	liver	16.8	0.1	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	kidney	16.9	0.2	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	kidney	17.0	0.5	2	St. Paul Island (Pribilof Islands) (AK, USA)	Kurle & Worthy 2002
Northern fur seal (*Callorhinus ursinus*)	bone	18.2	1.3	4	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Northern fur seal (*Callorhinus ursinus*)	bone	18.5	0.4	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Polar bear (*Ursus maritimus*)	muscle	21.1	0.6	3	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Polar bear (*Ursus maritimus*)	muscle	20.6	0.6	10	Barrow (AK, USA), Alaska	Dehn et al. 2006
Polar bear (*Ursus maritimus*)	muscle	19.6	0.5	5	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Ringed seal (*Pusa hispida*)	muscle	17.3	1.1	9	Lancaster Sound (Nunavut, Canada)	Hobson & Welch 1992
Ringed seal (*Pusa hispida*)	muscle	16.9	0.6	78	Barrow (AK, USA), Alaska	Dehn et al. 2005
Ringed seal (*Pusa hispida*)	muscle	16.9	0.2	33	Barrow (AK, USA), Alaska	Hoekstra et al. 2002
Ringed seal (*Pusa hispida*)	muscle	17.2	0.7	25	Holman (NW Territories, Canada)	Dehn et al. 2005
Ringed seal (*Pusa hispida*)	muscle	12.9	0.3	9	Hudson Bay (Canada)	Young et al. 2010
Ringed seal (*Pusa hispida*)	muscle	13.8	0.3	4	Hudson Bay (Canada)	Young et al. 2010
Ringed seal (*Pusa hispida*)	muscle	14.6	0.3	3	Hudson Bay (Canada)	Young et al. 2010
Ringed seal (*Pusa hispida*)	muscle	16.4	0.2	20	Lancaster Sound (Nunavut, Canada)	Atwell et al. 1998
Spotted seal (*Phoca largha*)	muscle	17.6	0.9	34	Little Diomede and Shishmaref (AK, USA)	Dehn et al. 2005
Steller sea lion (*Eumetopias jubatus*)	bone	18.4	1.4	15	Sanak Islands (AK, USA)	Misarti 2007
Steller sea lion (*Eumetopias jubatus*)	bone	17.0	NA	1	Bering Sea (AK, USA)	Hirons et al. 2001
Steller sea lion (*Eumetopias jubatus*)	bone	18.1	1.9	2	Bering Sea (AK, USA)	Hirons et al. 2001
Steller sea lion (*Eumetopias jubatus*)	bone	18.0	0.1	2	Bering Sea (AK, USA)	Hirons et al. 2001
Steller sea lion (*Eumetopias jubatus*)	bone	18.7	0.8	3	Bering Sea (AK, USA)	Hirons et al. 2001
Steller sea lion (*Eumetopias jubatus*)	red blood cells	15.6	0.2	5	Central Aleutian Islands (AK, USA)	Kurle & Gudmundson 2007
Steller sea lion (*Eumetopias jubatus*)	serum	16.4	0.3	5	Central Aleutian Islands (AK, USA)	Kurle & Gudmundson 2007
Steller sea lion (*Eumetopias jubatus*)	bone	18.5	NA	1	Gulf of Alaska (AK, USA)	Hirons et al. 2001
Steller sea lion (*Eumetopias jubatus*)	red blood cells	17.8	0.7	5	Eastern Aleutian Islands (AK, USA)	Kurle & Gudmundson 2007
Steller sea lion (*Eumetopias jubatus*)	serum	19.0	0.9	5	Eastern Aleutian Islands (AK, USA)	Kurle & Gudmundson 2007

Species	Sample type	$\delta^{15}N$ (‰)	standard error / standard deviation	*n*	Location	Reference
Steller sea lion (*Eumetopias jubatus*)	enamel	18.7	0.5	113	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Steller sea lion (*Eumetopias jubatus*)	enamel	18.1	0.7	113	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Steller sea lion (*Eumetopias jubatus*)	enamel	17.6	0.6	113	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Steller sea lion (*Eumetopias jubatus*)	enamel	17.5	0.7	107	Gulf of Alaska (AK, USA)	Hobson, Sinclair et al. 2004
Steller sea lion (*Eumetopias jubatus*)	red blood cells	17.9	0.1	11	Gulf of Alaska (AK, USA)	Kurle & Gudmundson 2007
Steller sea lion (*Eumetopias jubatus*)	serum	19.3	0.2	11	Gulf of Alaska (AK, USA)	Kurle & Gudmundson 2007
Steller sea lion (*Eumetopias jubatus*)	muscle	17.5	0.2	13	Copper River Delta (AK, USA)	Hobson et al. 1997
Steller sea lion (*Eumetopias jubatus*)	bone	17.4	0.6	2	Gulf of Alaska (AK, USA)	Hirons et al. 2001