

REVIEW

Stable Isotope Studies of North American Arctic Populations: A Review

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We review the major stable carbon and nitrogen isotope studies conducted on human remains in the North American Arctic (NAA) and discuss the findings with respect to two major research themes: diachronic subsistence, and the development of food cultures across the NAA. The interpretation of stable isotope data from human bone collagen and hair keratin is complicated by issues of equifinality in addition to uncertainty arising from the high fat/high protein diets of Arctic hunter gatherers. We suggest future lines of inquiry which may help to alleviate some of these challenges. Our review of Arctic stable isotope studies shows the ongoing potential of stable isotope analysis of Arctic hunter-gatherers and faunal populations, but we include the caveat that regardless of how cutting-edge or refined the analytical method, future stable isotope studies must be contextualized with other lines of evidence from well-excavated sites, and would profoundly benefit from the incorporation of indigenous perspectives and research priorities.

Keywords: Inuit; stable isotope analysis; archaeology; bioarchaeology

Introduction

Human populations settled the North American Arctic (NAA) relatively late in human history as the resource-limited terrestrial landscape prompted the development of specialized technological and cultural adaptations to extract resources from marine and riverine environments. The focus of this paper is on the Late Holocene (1000–100 BP) human occupation of Greenland, and the Canadian and Alaskan Arctic coasts. Circa 800 years BP ancestors of modern Inuit and Yupik groups, known collectively as the Thule culture, spread from northwestern Alaska eastward across the Canadian Arctic to Greenland and south to Labrador and the Quebec Lower North Shore, in some cases supplanting local Pre-Inuit groups (Friesen, 2000; Friesen & Arnold, 2008; Raghavan et al., 2014). In most of these regions, there is a direct line of genetic descent from the Thule culture to modern Inuit and Yupik populations (Raff, Rzhetskaya, Tackney, & Hayes, 2015; Raghavan et al. 2014; Tackney, Jensen, Kisielinki, & O'Rourke, 2019), however population movement within regions is known to have occurred (Friesen, Finkelstein, & Medeiros, 2019). Whitridge (2016) has pointed out the negative historical implications of the term *Thule*, and following from this work, we have chosen not to refer to ancestral Inuit and Yupik populations

as Thule. Instead we will refer to groups occupying the NAA during the Late Holocene, but before European contact as precontact Arctic peoples, while those of the post-European contact period will be referred to by their modern names. The cultures of precontact Arctic peoples, including the Old Bering Sea, Birnik, and Punuk cultures, in addition to those known as the Thule, were characterized by the use of sled dogs and large open skin boats (*umiak*, sing. *umiak*) for transportation, sophisticated technology for harvesting and storing a variety of land and sea resources, and social systems featuring settled communities, extended trade and social networks, mortuary ceremonialism, and hierarchical interpersonal relationships (Arutiunov & Sergeev, 1990; Friesen, 2016; Savelle, 2002a; Whitridge, 1999).

In this paper we review the major stable isotope studies conducted to date on archaeological populations dating to the Late Holocene in the NAA. We consider the data with respect to research themes held in common among these works and identify the challenges most frequently cited. We describe how applications of new isotopic methods and analyses may help to refine existing interpretations and emphasize the importance of robust supporting lines of evidence, and the incorporation of indigenous perspectives and community-led research, for the interpretation and success of future stable isotope research.

Environmental and archaeological context

Despite wide geographic separation and a diversity of marine and terrestrial environments (spanning three oceans and myriad currents, freshwater deltas, tundra and boreal forest), arctic subsistence is generally characterised by reliance on only a few primary taxa common to all regions,

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with variable input from other secondary taxa where they are locally common. Marine taxa include seabirds and eggs, fish found at least seasonally in near-shore environments, as well as virtually all arctic marine mammals. Most of these taxa have patchy distributions that vary seasonally. Harp seals, some narwhal and beluga, bowhead whales, some walrus populations, salmonids, and most birds practice long-distance seasonal migrations (Brice-Bennett, 1977; Lavigne, 2009; Schell, Saupe, & Haubenstock, 1989; Turner, 2014), while most other pinnipeds have preferred habitats in terms of sea ice. Thus, harbour (common) seals tend to occupy only open-water environments with access to beaches on which to haul out (including near-shore polynyas in the winter) (Woollett, 2007), and walrus, ringed seals, bearded seals, and hooded seals seek out ice-edge or pack ice environments, bringing them nearer to or farther from human settlements at different times of the year, depending on climate and currents (Stewart & Lockhart, 2004; Kovacs, 2009). Of these migratory taxa, those that tend toward gregariousness have generally been more heavily relied upon where they are present (harp seals, beluga, walrus), as they can be hunted *en masse* and the surplus stored for later consumption (Brice-Bennett, 1977; Turner, 2014). Marine mammals were valued as well for their secondary products, such as blubber for lamps or whale bone and baleen for tool manufacture and house construction, and pinnipeds in particular were valued for their skins, which were used in clothing, footwear, boats, house construction, and for lines (Taylor, 1974). Marine and anadromous fish species played significant roles in annual subsistence rounds in the Western Arctic, including the Aleutian Islands, coastal Western Alaska, and the Mackenzie River Delta (Betts & Friesen, 2004; Britton et al., 2018a; Coltrain, 2010; Masson-McLean et al., 2019). The presence of fish on archaeological sites in the Eastern Arctic is more sporadic due in part to taphonomic bias against delicate fish remains (Whitridge, 2001), but also due to the timing of fish runs conflicting with the availability of higher-ranked resources (Norman & Friesen, 2010). There are fewer indications that fish played an important role in human subsistence on the Labrador coast (Woollett, 2007), but anadromous fish are important to modern Inuit and Métis communities in this region (Ames, 1977).

Far fewer terrestrial taxa have been of significant economic importance, particularly prior to European contact and the adoption of trapping economies by some northern peoples. Minor taxa include freshwater fish, which vary in importance by region (Betts & Friesen, 2004; Morrison, 2000), foxes (used mainly for fur), and ground birds, but these are generally eclipsed in importance by caribou (and/or muskox in certain areas) (Betts, 2005). Caribou migrate seasonally to varying degrees and are at peak condition in the late summer/fall. Caribou were important in virtually every arctic society for their furs, which were the best (and only) choice for warm winter clothing (Betts, 2005; Stefansson, 1914).

Stable Carbon and Nitrogen Isotopes in Arctic Environments

Stable carbon isotope ($\delta^{13}\text{C}$) values are routinely used to distinguish between consumers of marine and terrestrial food, or between consumers of different photosynthetic

groups of plants in archaeological studies (Chisholm, Nelson, & Schwartz, 1983; Tauber, 1981; Van der Merwe, 1982). In the context of the North American Arctic and Subarctic, only C_3 plants and marine sources of carbon are present. Comprehensive reviews of carbon isotope dynamics in terrestrial and marine environments in the Arctic can be found in Szpak, Savelle, Conolly, and Richards (2019), or Coltrain, Tackney and O'Rourke (2016). A range of just under 10‰ (-30‰ to -22‰), has been observed in the $\delta^{13}\text{C}$ values of Arctic and Subarctic plants (Blake, 1991; Hobbie et al., 2009; Kristensen, Kristensen, Forchhammer, Michelsen, & Schmidt, 2011; Ramsay & Hobson, 1991). These differences in baseline values are passed on to upper trophic level consumers: for example, caribou are greater consumers of lichens than other herbivorous species and as a result, tend to have higher $\delta^{13}\text{C}$ values than other local taxa (Britton, 2010; Drucker, Hobson, Ouellet, & Courtois, 2010; Guiry, Noël, Tourigny, & Grimes, 2012; Harris et al., 2019). Marine organisms have considerably higher bone collagen $\delta^{13}\text{C}$ values ranging from -17‰ for some seabirds to between -12‰ and -15‰ for marine mammals (Britton et al., 2013; Coltrain, Hayes, & O'Rourke, 2004; Clarke, Horstmann, de Vernal, Jensen, & Misarti, 2019; Guiry et al., 2012; Harris et al., 2019; McManus-Fry, Knecht, Dobney, Richards, & Britton, 2018; Nelson, Lynnerup, & Arneborg, 2012a; Szpak, Buckley, Darwent, & Richards, 2017; Szpak et al., 2019). Additional variation in $\delta^{13}\text{C}$ values is also observed between nearshore/benthic areas and the pelagic zone (Sherwood & Rose, 2005), but the degree of benthic-pelagic coupling varies across the Arctic Ocean and neighbouring seas (Feder, Iken, Blanchard, Jewett, & Schonberg, 2011; Grebmeier, Cooper, Feder, & Sirenko, 2006).

Stable nitrogen isotope values ($\delta^{15}\text{N}$) are used to track trophic relationships in ancient and extant ecosystems as animal tissues undergo stepwise enrichment in the isotope ^{15}N with increasing trophic level (Minagawa & Wada, 1984). Nitrogen occurs in every amino acid and undergoes considerable isotopic fractionation as amino acids sourced from diet or recycled during protein turnover and catabolism are incorporated into the body during growth or tissue maintenance (Macko, Fogel, Hare, & Hoering, 1987; O'Connell, 2017). Terrestrial plants in the Arctic have very low $\delta^{15}\text{N}$ values, ranging from -8‰ for some evergreen trees to $+1\text{‰}$ for berries (Craine et al., 2009; Hobbie et al., 2009; Kristensen et al., 2011) which in turn produce low $\delta^{15}\text{N}$ values ($+1\text{‰}$ to $+5\text{‰}$) in terrestrial herbivores, like caribou or arctic hare (Coltrain et al., 2004; Drucker et al., 2010). Marine food webs contain more trophic levels, and carnivorous marine organisms, such as seal or polar bear, have high $\delta^{15}\text{N}$ values ($+14\text{‰}$ to $+19\text{‰}$) (Cherry, Derocher, Hobson, Stirling, & Thiemann, 2011; Szpak et al., 2017; Szpak et al., 2019).

Isotope Analyses of Preserved Human Proteins

There are occurrences of natural mummification of deceased individuals in the Arctic in which soft tissues are preserved (e.g. Lynnerup, 2015), but these occurrences are rare, and generally, bone collagen and hair keratin are the most commonly preserved human biological tissues. These tissues can act as proxies for human diet as the isotopic

composition of each is derived from consumed dietary protein, and to a lesser extent, from dietary carbohydrates and lipids (Ambrose & Norr, 1993; Fernandes, Nadeau, & Grootes, 2012). The $\delta^{13}\text{C}$ value of bulk collagen or keratin represents a weighted average of the $\delta^{13}\text{C}$ values of constituent amino acids. Isotopic offsets between collagen and diet average +5‰ but vary with the isotopic composition of different macronutrients (Ambrose & Norr, 1993). If dietary protein has a higher $\delta^{13}\text{C}$ value than whole dietary carbon, a greater diet-tissue isotopic offset will ensue than if dietary protein has a lower $\delta^{13}\text{C}$ value, or a value similar to that of whole dietary carbon (Ambrose & Norr, 1993). Arctic hunter-gatherers accessed different types of marine and terrestrial foods sources, depending on local environmental conditions, therefore it is difficult to apply a blanket diet-tissue offset to all palaeodietary analyses conducted in the region. One way of circumventing this source of uncertainty is to compare human collagen $\delta^{13}\text{C}$ values directly to faunal collagen $\delta^{13}\text{C}$ values as experimental datasets show that the $\delta^{13}\text{C}$ value of consumer bone collagen tends to be offset by approximately +1‰ from that of prey collagen (Bocherens & Drucker, 2003). The offset between hair keratin and collagen $\delta^{13}\text{C}$ values is variable, but keratin tends to have a lower $\delta^{13}\text{C}$ value as it contains fewer Glycine residues than collagen; experimental studies of modern and archaeological humans show an average offset of +1.4‰ between collagen and keratin (Robbins & Kelly, 1970; O'Connell, Hedges, Healey, & Simpson, 2001; O'Connell & Hedges, 1999).

Nitrogen is present in amino acids as NH_2^+ molecule bonded to a carbon skeleton. As with carbon, the $\delta^{15}\text{N}$ value of collagen or keratin depends upon the biosynthetic pathway of amino acids, and more specifically, on the number of metabolic branches in the pathway (Macko et al., 1987; O'Connell, 2017; Petzke, Boeing, Klaus, & Metges, 2005). Isotopic fractionation resulting in a positive increase in $\delta^{15}\text{N}$ values is associated with transfer (transamination) of the nitrogen-bearing amino group from one amino acid to another in the body's amino acid pool (Macko et al., 1987; O'Connell, 2017). Newly synthesized proteins are enriched in ^{15}N relative to whole dietary protein, resulting in a positive shift in $\delta^{15}\text{N}$ values between diet and consumer. The $\delta^{15}\text{N}$ value of proteins can be offset from that of consumed dietary protein by +2 to +6‰ (Bocherens & Drucker, 2003; DeNiro & Epstein, 1981; Minagawa & Wada, 1984; O'Connell, Kneale, Tasevka, & Kuhnle, 2012), and an average offset of +3 to +4‰ is applied in many palaeodietary analyses, including those studies conducted on the collagen and hair of humans and fauna in the Arctic (e.g. Britton et al., 2018a; Coltrain et al., 2004; Coltrain, 2009; Coltrain et al., 2016; McManus-Fry et al., 2018).

The isotopic composition of bone collagen and hair keratin reflect different periods of time in an individual's life. Human bones begin to develop in utero and once fully matured (in early adolescence to young adulthood) undergo regular cellular maintenance through slow turnover of collagen, bioapatite, and bone cells. Stable isotope analysis of collagen produces a long-term average (often greater than 20 years) of consumed and assimilated dietary protein (Hedges, Clement, Thomas, & O'Connell,

2007). In contrast, hair keratin grows approximately one cm per month and once formed is metabolically inert (LeBeau, Montgomery, & Brewer, 2011), effectively sealing in the isotope values incorporated during growth.

Stable Isotope Analyses of North American Arctic Populations

Many subsistence-focused research questions in the NAA can be answered through the analysis of well-preserved zooarchaeological assemblages in tandem with other lines of archaeological and ethnographic evidence, however, there are some cases that seem especially tailored for the addition of stable isotope analysis of human tissues. Butchery practices may bias zooarchaeological assemblages (Betts & Friesen, 2013), while the contribution of taxa such as whales or shellfish to arctic diets can be difficult to estimate due to use and reuse of whale skeletal elements in dwellings and tool manufacture, and incomplete collection and quantification of shellfish remains, respectively (Claassen, 2000; Giovas, 2009; McCartney, 1980; McCartney & Savelle, 1993; Savelle, 1997). A number of stable isotope studies have been conducted on human biological tissues to address the importance of whaling to arctic peoples (Coltrain et al., 2004; Coltrain, 2009; Coltrain et al., 2016), to assess the impacts of past episodes of climate change on arctic subsistence practices (Britton et al., 2013), and to provide further information regarding the diets of individuals (Britton et al., 2018a). Britton et al. (2018a) and Tackney et al. (2016) reviewed a number of these studies and noted significant geographic patterning in the types of foods consumed by pre- and post-contact Arctic hunter gatherers. Betts and Friesen (2004) emphasize the critical role that culture plays in fostering the diversity of dietary practices across the NAA. Inuit and Yupik populations are composed of discrete peoples with distinct food cultures that developed *in situ* in response to local resource availability and stressors (Betts, 2005; Betts & Friesen, 2013; Britton et al., 2018a; Friesen, 1999; Friesen & Arnold, 1995). In the following section, we provide a brief review of the isotope research completed to date with a focus on how these data were integrated with other lines of archaeological evidence to address two broad, related themes in Arctic research.

1) Diachronic perspectives on human subsistence in the Arctic

Stable isotope analysis of human and faunal remains can provide long-term ecological observations that are complementary to traditional ecological knowledge and historical observations, especially if they are used in tandem with palaeoenvironmental proxies (Jones & Britton, 2019). If human isotope data are contextualized against a faunal isotope baseline (Casey & Post, 2011; Van Klinken, Richards, & Hedges, 2002), then stable isotope analysis can be used to identify shifts in the trophic level of prey, or variation in the relative contributions of marine versus terrestrial sources of protein through time. Stable isotope analysis can also act as a blunt, but independent source of verification of observations from the historical period (Jensen, 2019), for example, by identifying deviations in animal behaviour between modern and archaeological

time periods (e.g. Gignoux, Grimes, Tütken, Knecht, & Britton, 2019). Diachronic studies of diet are of particular interest in Arctic and Subarctic archaeology as they can often be linked to fluctuating prey numbers, technological change, cross-cultural interactions, or environmental/climate change (Arneborg et al., 1999; Betts & Friesen, 2006; Duggan et al., 2017; Friesen et al., 2019; Hodgetts, Renouf, Murray, McCuaig-Balkwill, & Howse, 2003). Migration to new physical environments with different suites of resources may have prompted cultural and/or technological adjustments to existing subsistence practices in terms of the types of animals hunted, seasonal harvesting schedules, or technology required to access available prey in sufficient quantities.

The first large-scale stable isotope study to apply a diachronic perspective to an Arctic context was conducted by Coltrain et al. (2004), later followed up by Coltrain (2009). These works estimated the importance of whaling to pre- and post-contact Inuit communities in NW Hudson Bay through $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis of adult skeletons and contemporaneous faunal material. Radiocarbon dating of the skeletons revealed that most individuals post-dated the earliest Inuit occupations of the region and likely lived during the period of Neo-Boreal cooling known as the Little Ice Age which stretched from the 15th to 19th centuries (Coltrain, 2009; Friesen et al., 2019). Statistical modelling of the isotope data produced several findings of note. Coltrain et al. (2004) and Coltrain (2009) argued that intra-individual variation in trophic level (as indicated by $\delta^{15}\text{N}$ values) but not in the intake of marine protein (as indicated by $\delta^{13}\text{C}$ values) suggested differential consumption of low-trophic level marine sources of protein, such as bowhead whale or walrus. Coltrain (2009) posited an increase in consumption of bowhead whale through time at the Silumiut and Kamarvik sites. The suggestion that bowhead whale consumption increased over the Little Ice Age is contradictory to relatively long-held beliefs in Arctic archaeology that increased ice cover during the Little Ice Age would have restricted bowhead whale movements to ice free areas, forcing an increased reliance on animals that thrive in conditions of increased sea ice cover, such as ringed seal (Schledermann, 1971, 1976). Over the same period of time, ringed seal appear to have played a consistent and prominent role in the diets of the Sadlermiut from Southampton Island, also in northwest Hudson Bay (Coltrain et al., 2004; Coltrain, 2009), but these results conflicted with ethnohistoric accounts of Sadlermiut whaling activities, and archaeological site descriptions from the 1950s (Ryan, 2011). The discrepancy between the ethnohistoric and archaeological sources and the isotopic data is difficult to reconcile here. It is possible that the site descriptions and ethnohistoric accounts may not have accurately quantified the foods actually consumed by the Sadlermiut. It is also important to note that stable isotope analysis of bone collagen largely measures consumed protein; animals that contributed mainly lipids to human diet (such as walrus and bowhead whales) may be underrepresented in bone collagen (Cherry et al., 2011; Fernandes et al., 2012). As will be discussed further below,

there is still considerable uncertainty regarding how diets high in protein and fat, and low in carbohydrates will be metabolised by the human body (Newsome, Wolf, Peters, & Fogel, 2014; Wolf, Newsome, Peters, & Fogel, 2015). Further zooarchaeological and material culture analysis of Southampton Island assemblages are required, and this case serves to highlight how critical other lines of evidence are to the interpretation of stable isotope data.

The effects of past episodes of climate change, such as the Medieval Climate Anomaly (AD 950–1250), and the Little Ice Age (AD 1450–1850) on local climates and weather and by extension on lived human experience can be difficult to estimate using environmental proxies which can have variable temporal and spatial resolution, and may not line up with zones of human occupation in the Arctic (Friesen et al., 2019). Recent diachronic comparisons of human hair isotope values from the Norton Pre-Inuit site of Nash Harbour and the precontact Yupik site of Nunalleq in southwest Alaska may evidence human responses to climate change at the scale of the individual. Britton et al. (2013) demonstrated striking differences in the amount of marine protein typically consumed throughout the year between these temporally separated cultures. Norton diets at Nash Harbour were composed of a greater proportion of high trophic level marine foods while the diets of Nunalleq villagers featured mixed contributions of salmonids, marine mammals, and terrestrial protein (Britton et al., 2013; Britton et al., 2018a). The hair samples from Nash Harbour and Nunalleq were recovered from house-floor contexts and hair fragments were of approximately the same length. The isotopic differences in bulk hair samples between each site could be attributed to seasonal differences in diet relating to the period of time over which the hair grew, but the isotopic differences persisted even in sequentially sampled locks of Nash Harbour and Nunalleq hair representing approximately one year of dietary inputs, suggesting that these differences must be due to either cultural or environmental factors (Britton et al., 2013). Britton et al. (2013) attribute these differences to geographic variation in the types of resources that could be accessed between the sites, and also suggest that past periods of climate change may have further influenced prey distributions. This hypothesis received additional support from Masson-MacLean et al. (2019) as they argued that a reliance on marine, anadromous and terrestrial species would have provided the Nunalleq community with a buffer against the direct (resource stress) and indirect (social stress) influences of climate change.

2) Food culture and social life in North American Arctic societies

The study of diet has long been linked to the efforts of past Arctic populations to regulate inter-personal relationships and control the stressors associated with increasing population density (Friesen, 1999). The analysis of archaeological and ethnographic data reveals diverse strategies for coping with social and resource stressors across the NAA that correspond to the type of resources available within the particular regions of study (Friesen, 1999; Savelle,

2002a; Whitridge, 2000). Over the course of the 21st century stable isotope analyses of human remains from a wide range of archaeological contexts are increasingly used to study the relationship between social organization and diet (e.g. Alexander, Gerrard, Gutiérrez, & Millard, 2015; Linderholm, Hedestierna Jonson, Svensk, & Lidén, 2008; Toso, Gaspar, Banha da Silva, Garcia, & Alexander, 2019). Stable isotope studies of pre-contact Arctic peoples have demonstrated regional variability in diet (reviewed in Britton et al., 2018a; Coltrain et al., 2016, and Tackney et al., 2016), providing additional support to zooarchaeological studies linking diet to ethnic identity (Betts, 2005; Betts, 2009). As the works discussed below will demonstrate, stable isotope-based approaches are particularly well-suited to characterizing intra-individual variation in diet and estimating the breadth of the social catchment area of a particular mortuary site. When used with additional lines of evidence from the archaeological record, stable isotope studies can speak to aspects of food culture, such as storage, or seasonality.

Britton et al. (2018a) measured $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of sequential samples taken from eight locks of hair recovered from sealed house floor contexts at the Nunalleq village site in southwestern Alaska to investigate how the diets of individuals varied over the period of sample growth (approximately one year). Given the seasonality of resources in the region, the relative stability of the isotopic patterns of four individuals was somewhat unexpected, but did make sense within the archaeological context, particularly when other lines of evidence from the site were considered. The presence of numerous salmon vertebrae on site, and storage vessels containing aquatic biomarkers, strongly suggested that summer salmon runs may have provided the bulk of dietary protein that *some* individuals consumed throughout the year, likely due to the storage of surplus salmon (Britton et al., 2018a; Farrell et al., 2014; Masson-McLean et al., 2019). Modelling of the human hair isotope data against faunal isotope data provided further supporting evidence for the role of salmon in the diets of Nunalleq villagers (Britton et al., 2013; Britton et al., 2018a). However, not all individuals consumed isotopically static diets: three locks of hair tracked an increase in either $\delta^{13}\text{C}$, or $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ that persisted for several months of growth; a fourth featured covariance of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values over a period of approximately six months; and a fifth featured a significant decrease of $\delta^{15}\text{N}$ values, but little change in $\delta^{13}\text{C}$ values, prompting Britton et al. (2018a) to put forward several possible explanations for the observed variation. Increasing $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values probably evidenced the consumption of higher trophic level marine protein; the rising and falling $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of another individual suggested a reliance on freshwater resources, such as fish or waterfowl, during part of the year followed by increasing contributions from marine protein; and finally, falling $\delta^{15}\text{N}$ values with static $\delta^{13}\text{C}$ values suggested consumption of shellfish or other low trophic level marine protein sources (Britton et al., 2018a). Taken together, the diversity of dietary patterns present in only eight locks of hair has implications for individual

mobility patterns, social roles and social organization at Nunalleq (Britton et al., 2018a). This study was unique for offering a glimpse into the lives of individuals, which are not always accessible using traditional archaeological methods, and is complimentary to studies of population- or community-level trends.

Nelson, Lynnerup, and Arneborg (2012b) did not initially design their study to address questions relating to Inuit diets in Greenland, but rather planned to use Inuit stable isotope data to aid in the interpretation of diachronic isotopic data sets from Greenlandic Norse skeletons. However, the resulting data offered a tantalizing glimpse into Inuit subsistence and revealed geographic and intra-population differences in the types of marine species hunted, and in the relative contribution of marine and terrestrial species to Inuit diets. For example, while diets rich in marine protein were the norm among individuals recovered from coastal sites in southwest Greenland, human bone collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values varied between 23 individuals recovered from the site of Assumiut (Nelson et al., 2012b). Ringed seal appeared to be the predominant source of dietary protein for the majority of individuals, but one adult female and a subadult may have received greater contributions of protein from narwhal, while a second subadult appeared to consume protein with stable isotope values consistent with harp seals (Nelson et al., 2012a; Nelson et al., 2012b). In northeastern Greenland, human bone collagen values plotted along a continuum of increasing contributions of marine-derived dietary protein, and multiple dietary patterns were present at the site of Dødemandsbugten (Nelson et al., 2012b). Nelson et al. (2012b) suggested that, in general, each Inuit community occupied its own territory and did not move widely around the landscape to obtain resources, but the presence of different dietary strategies implied by outlying collagen isotope values at several sites suggested movement of certain individuals who may have spent part of their lives elsewhere (Nelson et al., 2012b).

The patterns of inter-individual differences in diet uncovered by Britton et al. (2018a) and Nelson et al. (2012b) were also found by Coltrain et al. (2016) in their isotopic study of Nuvuk, the largest pre-contact mortuary site in Alaska. Within the site, the $\delta^{13}\text{C}$ values of adults ranged from -15.7‰ to -12.4‰ and the $\delta^{15}\text{N}$ values ranged from $+17.7\text{‰}$ to $+22.4\text{‰}$ (Coltrain et al., 2016). Some of this range in data may be attributable to biological sex: while the mean collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of biological male and female skeletons did not differ significantly, the $\delta^{15}\text{N}$ values of male skeletons were more variable than those of females (Coltrain et al., 2016). Where osteological evidence of biological sex is available for assemblages of human remains in the Arctic, there are consistently no statistically significant differences in the mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of males and females (Coltrain et al., 2004; Coltrain, 2009; Coltrain et al., 2016; Nelson et al., 2012b). However, the breadth of results reported by Coltrain et al. (2016) suggests that some males may have had access to different types of marine protein, perhaps due to their involvement in different subsistence or trade activities.

Challenges and future prospects of stable isotope studies of Arctic populations

In certain archaeological contexts stable carbon and nitrogen isotope ratio analysis of human biological tissues can yield important insights into past human lifeways, particularly in cases where faunal preservation is poor, or when inter- and intra-population dietary variation is under study. However, stable isotope analyses of bulk proteins in the Arctic, as elsewhere, are limited by problems of equifinality. For example, prey species may have overlapping isotope values so that relative contributions of one prey class versus another cannot be distinguished with isotope mixing models (Phillips et al., 2014), or it may not be possible to distinguish physiological influences on $\delta^{15}\text{N}$ values from dietary inputs (e.g. Britton et al., 2018a). Additional problems occur when attempting to assign human remains to an absolute chronological framework. For many years after the adoption of radiocarbon dating, the skeletons of archaeological marine hunter-gatherers were avoided as a source of radiocarbon dates in the Arctic (e.g. Arundale, 1981; Dumond & Griffin, 2002; McGhee & Tuck, 1976; Morrison, 1989), due to the uncertainty associated with the marine radiocarbon reservoir and with estimated contributions of marine carbon to human bone collagen. While a number of authors have developed methods for estimating the contribution of marine carbon to human bone collagen (e.g. Arneborg et al., 1999; Barrett & Richards, 2004; Craig, Bondioli, Fattore, Higham, & Hedges, 2013; Raghavan et al., 2014), local deviations, termed the delta (Δ) R, in the offset between atmospheric ^{14}C concentrations and the marine radiocarbon reservoir remain a major source of uncertainty that must be included in the calibration of ^{14}C ages from human and marine faunal skeletal remains (Bronk Ramsey, 2008; Stuiver, 1986). A discussion of ongoing research on this topic is beyond the scope of this paper, but readers are encouraged to see Dyke et al. (2018), Krus, Jensen, Hamilton, and Sayle (2019), and Ledger, Forbes, Masson-MacLean, and Knecht (2016) for an Arctic perspective on this issue. In the following section, we elaborate on some of the issues associated with equifinality, and present recently developed areas of research that have potential applications in Arctic archaeology.

Asking better questions: Community-led research and bioarchaeology in the Arctic

We begin by focusing on recent developments in indigenous and community-led research in Arctic communities, as further bioarchaeological research cannot proceed without input and consent from descendent communities. With the development of the National Graves and Repatriation Act (NAGPRA) in the United States, and the adoption of similar provincial legislature in Canada, many of the skeletal assemblages that were collected during the 19th and 20th centuries are being returned to Arctic communities, and most bioarchaeological studies are no longer conducted without permission from descendent groups. Through the development of community-led interdisciplinary archaeology projects, such as those at Nunalleq Village and Nuvuk in Alaska, or the Traditions

and Transition project in Labrador, considerable progress has been made to incorporate the priorities of indigenous stakeholders into archaeological research design (Hillerdal, 2017; Jensen, 2012; Traditions and Transitions, 2019). Some Canadian universities, such as the University of Victoria, the University of British Columbia, and Memorial University of Newfoundland, are now developing and implementing indigenous research paradigms, but much still needs to be done to incorporate the voices and concerns of indigenous groups across the Arctic in the development of archaeological questions. The incorporation of traditional knowledge could lead to a much deeper, more nuanced understanding of local environments (past and present), and an overall better interpretation of archaeological data. For example, the development of partnerships between indigenous informants and Western scientists to study biodiversity and conservation in the north has improved the quality and scope of data regarding the ways species and arctic environments are responding to climate change and to the intensification of human exploitation of land and sea resources (Krupnik & Ray, 2007; Stevenson, 1997; Thornton & Scheer, 2012). For bioarchaeologists practicing in the NAA, such an approach would aid in building bridges between academic disciplines and indigenous communities which in turn would lead to more interesting and relevant research questions, and new ways of tackling old problems. The Inuit Tapiriit Kanatami has put forward a clear and concise guide to conducting research on Inuit lands in Canada which includes strict guidelines on the ethical conduct of researchers and open access publication of data. Compliance with published indigenous research guidelines (e.g. FNIGC, 2019; ITK, 2018) would only improve the scope and impact of future bioarchaeological studies, and the relationships between archaeologists and indigenous groups across the Arctic.

Macronutrient routing and physiological inputs to human stable isotope values

As reviewed above, the diets of archaeological Arctic hunter-gatherers were composed predominantly of protein and fats derived from marine mammals, fish, and caribou, with limited sources of carbohydrate. The incorporation of these macronutrients into human tissues is a source of uncertainty that must be considered when conducting palaeodietary analyses of arctic populations. In laboratory settings high protein diets are associated with increased direct routing of dietary amino acids to proteinaceous tissues (collagen, hair, and blood), and a lower diet-collagen $\delta^{13}\text{C}$ offsets (Jim, Jones, Ambrose, & Evershed, 2006). Conversely, the consumption of marine protein may actually increase nitrogen isotope diet-tissue offsets (Webb, Stewart, Miller, Tarlton, & Evershed, 2016). These experimental findings may have implications for palaeodietary studies of Arctic hunter-gatherers, particular with respect to estimations of trophic level. The high marine protein diets of Arctic peoples may increase the diet-collagen $\delta^{15}\text{N}$ offsets and render commonly used trophic discrimination factors inappropriate for this context (Hedges & Reynard, 2007). However, in most of

the cases presented in this paper, the trophic discrimination factors applied to human isotope data appear to be appropriate, based on prior assumptions for the zooarchaeological and archaeological records (Coltrain et al., 2004; Coltrain, 2009; Gullov, 2012; Nelson et al., 2012b), but further support from the application of newer generations of palaeodietary models (e.g. FRUITS [Fernandes, Grootes, Nadeau, & Nehlich, 2015]; or SIMMR [Parnell, 2016]) would be a welcome addition to Arctic stable isotope studies.

The contribution of carbon from dietary lipids to bone collagen is generally considered to be relatively minor (Fernandes et al., 2012). In other, lower latitude contexts, populations accessed wild and cultivated sources of carbohydrates that provided ready sources of energy for amino acid synthesis, however, energy sources in the Arctic are limited to seasonal, and regionally variable, contributions from greens, tubers, berries, and seaweed, with the bulk sourced from animal fats. The influence of dietary lipids, such as whale (*muktuk*) and seal (*nuktuk*) blubber, on collagen $\delta^{13}\text{C}$ values is uncertain: experimental work with other mammals has shown flexibility in the incorporation of dietary lipids into proteinaceous tissues, prompting some researchers to urge caution when designing stable isotope studies of animals (including humans) with high lipid diets as protein-only models may misinterpret the stable isotope data (Newsome et al., 2010; Newsome et al., 2014). As stable isotope studies of arctic populations have thus far been limited to the analysis of bulk proteins (collagen and keratin), the interpretations of resulting isotope data sets have, of necessity, been quite broad. A recent analysis of polar bear blood and adipose tissue samples determined that large-bodied prey (whales and walrus) provided the greatest contribution of dietary lipids, while smaller marine mammals provided the bulk of dietary protein to bears (Cherry et al., 2011). A similar approach using human skeletal remains would be challenging as the $\delta^{13}\text{C}$ analysis of archaeological bone lipids remains relatively unexplored (Colonese et al., 2015). Instead, the $\delta^{13}\text{C}$ analysis of non-essential amino acids found in bone collagen or hair keratin may offer a way forward. Non-essential amino acids can be divided into two groups by biosynthetic precursor: Glucogenic amino acids (Glycine, Alanine, Serine) are synthesized from carbon precursors taken from dietary carbohydrates and lipids, while the ketogenic amino acids (Glutamate and Aspartate) can be synthesized from carbon sourced from all dietary macronutrients (Newsome et al., 2014). As sources of dietary carbohydrates are limited in most of the Arctic, glucogenic amino acids would largely reflect dietary lipid sources. Building from Cherry et al. (2011), it could then be possible, for certain hunter-gatherer populations, to model the contributions of lipid sources from, for example, bowhead whale, seal, or terrestrial sources of fat, using the $\delta^{13}\text{C}$ values of glucogenic, and potentially ketogenic amino acids, too. Further insights could then be gained through comparison with the $\delta^{13}\text{C}$ values of Proline which may be routed directly from dietary protein (Jim et al., 2006).

Dietary stress was proposed as a possible influence on human stable isotope values in the Arctic (Coltrain et al.,

2016). During periods of nutritional stress, protein synthesis in healthy adults tends to slow, but it does not cease completely (Mekota, Grupe, Ufer, & Cuntz, 2006). When insufficient concentrations of amino acids are consumed, the body will catabolise amino acids from skeletal muscle, predominantly targeting glutamic acid and alanine, for tissue maintenance, leading to secondary enrichment in ^{15}N of body proteins (Mekota et al., 2006; Neuberger, Jopp, Graw, Püschel, & Grupe, 2013). Fuller et al. (2005) found evidence of this phenomenon, in the form of increasing $\delta^{15}\text{N}$ values, in modern pregnant people suffering from morning sickness. The influence of dietary stress on collagen $\delta^{13}\text{C}$ values hypothesized by Coltrain et al. (2016) finds support in the work of Neuberger et al. (2013) who, in a study of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in the hair of anorectic patients, posited that the catabolism of body fat would introduce ^{13}C depleted carbon back into the body's carbon pool, thereby reducing the $\delta^{13}\text{C}$ value of amino acids that can use lipid-derived carbon as a substrate. Beaumont and Montgomery (2016) observed this phenomenon in dentine serial sections from Irish Famine Victims. It may be premature to assume that hunter-gatherers in the Arctic were regularly afflicted by dietary stress. While there are recorded occurrences of starvation during the post-European contact period relating to illness and modern declines in Arctic prey species (Boas, 1964; Krupnik & Chlenov, 2013), there is insufficient evidence to assume that nutritional deficits were commonplace across the Arctic during prehistory. However, osteological analyses of skeletal remains from Alaska to Labrador do report skeletal markers that may be consistent with physiological stress, such as that caused by illness, or vitamin deficiencies caused by parasitic infection, or use of non-traditional foods provided by European whaling groups (Keenleyside, 1998; Keenleyside, 1990; Way, 1978). Physiological stress should be considered as a possible source of negatively covarying $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (Beaumont, Montgomery, Buckberry, & Jay, 2015; Beaumont & Montgomery 2016; King et al., 2018), but the application of a blanket correction to palaeodietary models may not be necessary.

Food preparation and storage

Arctic peoples preserved hunted and gathered food resources in a variety of ways (stored in snowpack, mixed with oil or fat, air dried, or carefully fermented) for consumption throughout the year (Friesen & Arnold, 1995; see Yamin-Pasternak, Kliskey, Alessa, Pasternak, & Schweitzer, 2014 for a modern example). In the case of large scale summer or fall hunts, such as caribou in their prime, beluga drives, salmon runs, or bowhead whales, the meat and (especially) fat these provided were often expected to last through the leanest months of winter, from February to April (Betts, 2005; Betts & Friesen, 2006, 2013; Masson-MacLean et al., 2019; Taylor, 1988). It has long been recognised that the subsistence systems of many arctic peoples fall into the category of "collecting" on the spectrum of complex hunting and gathering societies (Binford, 1980; Savelle, 2002b). This distinction, in opposition to patterns of "foraging", is an important one in that collecting is characterised by a lower level of residential

mobility, but a higher level of logistical (or task) mobility and storage of high-bulk focal resources (Betts, 2005; Binford, 1980; Stenton, 1989; Whitridge, 1999; Woollett, 2007). These collecting and storage patterns, combined with variable mobility practices, may have the effect of attenuating expected seasonal differences in isotopic composition of human tissues, even when examined at a finer scale, as suggested by Britton et al. (2018a).

Several stable isotope studies have also proposed that the process of decomposition may raise the $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values of stored meat. Bada, Schoeninger, and Schimmelmann (1989) analysed the effects of artificial protein hydrolysis on the stable isotope values of modern tendon collagen. The hydrolysed protein fragments became slightly enriched in ^{15}N , while the $\delta^{15}\text{N}$ values of unhydrolysed protein increased by up to +20‰ (Bada et al., 1989), possibly due to selective loss of particular amino acids with lower $\delta^{15}\text{N}$ values. Recently Yurkowski, Hussey, Hussey, and Fisk (2017) tested the effects of decomposition and the duration of cold storage on the isotope values of ringed seal meat, Greenland shark tissue, and fish, and suggested that cold storage at a consistent temperature did not have an appreciable effect on stable isotope values, however, decomposition in a closed environment increased ringed seal $\delta^{15}\text{N}$ values by up to +2‰ (Yurkowski et al., 2017). Further experimental archaeology studies may be required, but the effect on human $\delta^{15}\text{N}$ values would probably be minor and may only be visible in incrementally growing tissues such as hair keratin, or tooth dentine.

Isotope baselines

The faunal isotope baseline is a key component of any palaeodietary or radiocarbon study using human bone collagen as an analyte; ideally, human isotope values will be compared to a set of carbon and nitrogen isotope ratio measurements from local, contemporaneous archaeological animals (Van Klinken et al., 2002). Shifts in the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of primary producers are known to occur through time and over geographic space, and higher trophic level animals may also modify their feeding behaviours depending on local environmental conditions or hunting pressures (Betts & Friesen, 2006; Bocherens, Grandal-d'Anglade, & Hobson, 2014; Casey & Post, 2011). Several recent studies of modern and archaeological specimens have shown the influence of climate and other environmental factors on the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of Arctic fauna. Szpak et al. (2019) have demonstrated significant differences in the $\delta^{15}\text{N}$ values of ringed seal populations of the Central Canadian Arctic Archipelago over the past 2000 years. Historic and modern walrus populations of the Chukchi Sea had significantly lower $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values than archaeological specimens (Clark et al., 2019), findings which echoed that of an earlier study conducted on multiple species of archaeological and modern marine mammals from the same region (Szpak et al., 2017). The extensive sampling protocols of the aforementioned studies exceed the scope of most human palaeodietary studies, but they serve to highlight the possibility of temporal differences in isotope baselines that should be considered when conducting human palaeodietary analy-

ses. To date, it is difficult to conduct statistical comparisons of archaeological faunal isotope values across the Arctic due to the varying sizes of published data sets, and incomplete reporting of the archaeological context of the faunal remains used to construct isotope baselines. The increasing popularity of stable isotope analysis as a tool for palaeoenvironmental studies may reduce the sample size disparities in the future, but archaeological palaeodiet studies must still deal with issues arising from legacy collections stored in museums in North America and in Northern Europe. Some of these issues include changes in recovery methods of faunal material between the present and early 20th century (Betts, 2016); difficulties in accessing skeletal material in distant repositories that may or may not have complete inventories; and the recovery of mixed faunal assemblages from sites with multiple, overlapping, Pre-Inuit and Inuit or Yupik contexts, a common occurrence in the NAA (Park, 1993). Sampling protocols may also introduce a bias to the isotope baseline. For example, it has been proposed that in some Arctic and Sub-Arctic regions, hunter-gatherers preferred juvenile prey to adults, and that the nursing effect on $\delta^{15}\text{N}$ values of young prey animals may explain higher than expected $\delta^{15}\text{N}$ values of human bone collagen, but the bones of juveniles animals are often bypassed in favour of those from mature specimens (Nelson et al., 2012b) which are considered more representative of animal populations.

Compound specific isotope analysis of amino acids liberated from archaeological specimens, such as bone collagen, hair keratin, or baleen may alleviate some of the problems associated with equifinality or isotope baselines. Essential amino acids are transferred intact from dietary protein to human tissues, allowing the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of these amino acids to be used as tracers as negligible isotopic fractionation occurs during transfer (Fogel & Tuross, 2003; McClelland & Montoya, 2002; Popp et al., 2007). The $\delta^{13}\text{C}$ values of essential amino acids, when combined in statistical models, can identify the 'isotope fingerprints' associated with different sources of primary production allowing the relative contributions of multiple foodwebs to a consumer isotope value to be characterized (Elliott Smith, Harrod, & Newsome, 2018; Larsen et al., 2009; Larsen et al., 2013; Wang et al., 2018). This method has potential for improving our understanding of arctic diets, particularly when the contributions of prey species are difficult to distinguish using bulk collagen $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values alone. Two studies conducted in the past 10 years have revealed surprisingly variable $\delta^{13}\text{C}$ values (−21.2‰ to −26.3‰) of the amino acid Phenylalanine ($\delta^{13}\text{C}_{\text{Phe}}$) from 10 archaeological Inuit mummies from the Nuusuaq Peninsula in Greenland that otherwise had relatively homogenous bulk collagen $\delta^{13}\text{C}$ values (−13.9‰ to −12.6‰) (Honch, McCullagh, & Hedges, 2012; Raghavan, McCullagh, Lynnerup, & Hedges, 2010). This exceeds the variation in $\delta^{13}\text{C}_{\text{Phe}}$ values measured in the collagen of hunter-gatherers from the coast of the Baltic Sea (−25.3‰ to −24.4‰) (Webb et al., 2015), or the hair of hunter-gatherers from Chile (−24.7‰ to −20.6‰) (Mora et al., 2016). These data suggest that the individuals from Nuusuaq were either consuming different types of marine protein, or the same type of protein, but from regions with

different isotopic baselines. Further analysis of faunal specimens is of course required, but even this small dataset is evocative of the potential of compound specific carbon isotope applications to arctic contexts with respect to human palaeodiet, social organization, and palaeoenvironmental reconstructions.

Breastfeeding and childhood diets

Decisions surrounding breastfeeding initiation, the time at which complementary foods are introduced, and the types of foods given to infants are strongly influenced by cultural attitudes toward female bodies, child rearing, and sexual politics (Fildes, 1986; Palmer, 2009). Breastfeeding and weaning practices, and the foods accessed by children, are closely linked to infant mortality and infection (Sankar et al., 2015), population size, social and economic roles of infant caregivers, and social concepts of childhood (Fildes, 1986). Stable carbon and nitrogen isotope analysis of bone and dental collagen is commonly used to study breastfeeding and weaning practices in disparate archaeological contexts around the world (e.g. Britton et al., 2018b; Eerksen & Bartelink, 2013; Herring et al., 1998; King et al., 2018; Nitsch, Humphrey, & Hedges, 2011), but to date such studies have not been attempted in Arctic contexts. There is little published information about the breastfeeding and weaning practices of Arctic caregivers in the pre- or post-contact periods that can be used to understand the modern trajectory of infant care in the Arctic (Asuri, Ryan, & Arbour, 2011; McIsaac, 2014). Bioarchaeological studies of breastfeeding of pre- and post-contact Arctic populations would be informative of infant and maternal health in the past (Beaumont & Montgomery, 2016). Through sequential sampling and isotopic analysis of human deciduous and permanent teeth it may be possible to identify sub-annual changes in maternal and infant diets (Beaumont et al., 2015), to estimate average breastfeeding practices and by extension, commonly-held attitudes about childrearing (Britton et al., 2018b), to relate breastfeeding practices to the social and economic roles of infant caregivers (Nitsch et al., 2011), and by comparing the diets of infants and adults, gain more insight into social constructions of childhood among arctic hunter-gatherers.

Conclusions

Archaeological research in the North American Arctic benefits from well-preserved faunal assemblages and a rich ethnographic record with which to reconstruct past human subsistence, but stable isotope analysis of human and faunal biological tissues still has a role to play by complimenting site- and region-based analyses with data from individuals. The research discussed in this review demonstrates that stable isotope analyses of human bone collagen and hair keratin have yielded important insights into diachronic shifts in diet, food cultures, and aspects of social organization at the level of the individual, but stable isotope research still faces the same challenges in the Arctic as it does elsewhere; issues of equifinality pose a number of problems in the interpretation of isotope data sets from bulk and sequentially sampled human tissues. There is reason for hope: Arctic researchers are now combining stable isotope analysis with community-led

research agendas, site-based interdisciplinary analyses, and are better able to contextualize human stable isotope data as a result. The application of additional methods, such as compound specific isotope analysis, or the isotopic analyses of breastfeeding and weaning practices, has considerable potential in the Arctic. Future research must continue to incorporate indigenous voices and research priorities as this will only improve the quality of information gleaned from archaeological and bioarchaeological investigations in the Arctic.

Additional File

The additional file for this article can be found as follows:

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The authors have no competing interests to declare.

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