Abstract—A 4500-year archaeological record of Pacific cod (*Gadus macrocephalus*) bones from Sanak Island, Alaska, was used to assess the sustainability of the modern fishery and the effects of this fishery on the size of fish caught. Allometric reconstructions of Pacific cod length for eight prehistoric time periods indicated that the current size of the nearshore, commercially fished Pacific cod stocks is statistically unchanged from that of fish caught during 4500 years of subsistence harvesting. This finding indicates that the current Pacific cod fishery that uses selective harvesting technologies is a sustainable commercial fishery. Variation in relative Pacific cod abundances provides further insights into the response of this species to punctuated changes in ocean climate (regime shifts) and indicates that Pacific cod stocks can recover from major environmental perturbations. Such palaeofisheries data can extend the short time-series of fisheries data (<50 yr) that form the basis for fisheries management in the Gulf of Alaska and place current trends within the context of centennial- or millennial-scale patterns.

A 4500-year time series of Pacific cod (*Gadus macrocephalus*) size and abundance: archaeology, oceanic regime shifts, and sustainable fisheries

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Fishing is a size-selective process that tends to remove larger fish and reduce the life span and mean size of individuals, especially in heavily exploited systems (Shin et al., 2005; Trites et al., 2006). Reductions in size-at-age and age-at-maturation have been reported for a number of heavily exploited species of fish (Trippel, 1995; Rochet, 1998; Bianchi et al., 2000) and may cause evolutionary change (Ernande et al., 2004; Hutchings, 2005; Law, 2007). Knowledge of body size is therefore an important metric for fisheries management because it can affect market price and reflects the spawning potential of the fish population (Shin et al., 2005).

Most fisheries management and conservation research has been restricted to interpreting trends and data sets that span just a few decades (Pauly et al., 1998; Worm et al., 2006), and tend not to incorporate the longer-term perspective that can be obtained by including palaeoecological data (Willis and Birks, 2006). Combining palaeoecological data with biological data can provide a signifi-cantly longer time series for measuring population and ecosystem health for conservation biology and resource management, and for understanding how current decadal trends fit within the context of centennial- or millennial-scale cycles (Jackson et al., 2001; Braje et al., 2006). Humans have been sampling species and ecosystems for thousands of years and have left rich data sets of both natural ecosystem dynamics and human interactions with animal populations that are preserved in archaeofaunal remains (animal bones found on archaeological sites).

Sanak Island is the center of a small, low-lying archipelago on the edge of the continental shelf in the western Gulf of Alaska (Fig. 1). This island group was a hub of the North Pacific Pacific cod (*Gadus macrocephalus*) fishery from the 1870s to the 1930s (Reedy-Maschner, 2004). Local Aleuts reported that Pacific cod disappeared in commercial quantities in this region between 1942 and 1975 but returned and have supported the modern Pacific cod fishery since the 1975 oceanic regime shift.
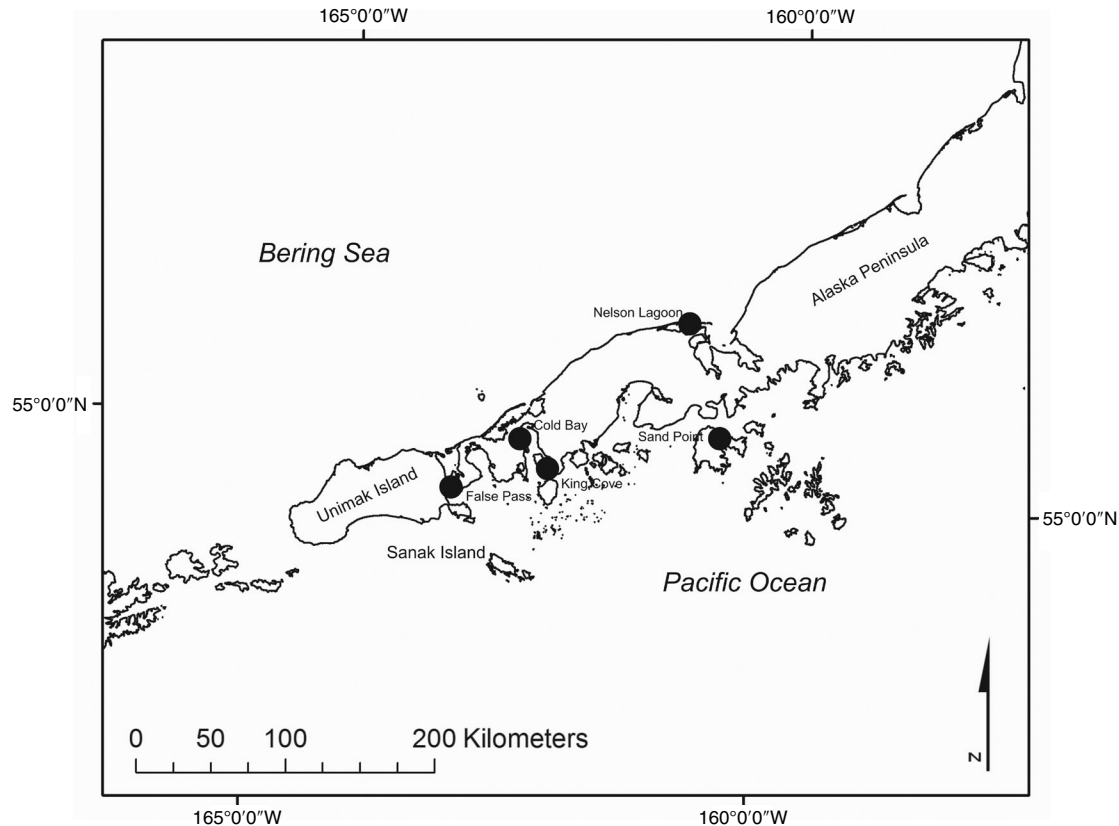
Figure 1
The North Pacific and the western Gulf of Alaska region showing Alaska and the location of Sanak Island where bones were collected at archeological sites to determine whether a change in fish size was evident over the 4500 archeological record.

The Sanak Pacific cod fishery now includes mostly fishermen of Aleut-Scandinavian descent who use jigs, pots, and longlines in nearshore waters, but the fishery has deep, prehistoric roots (Tews, 2005). Archaeological data indicate that Aleuts have occupied Sanak Island for over 6000–7000 years and Pacific cod bones dominate the matrices of all preserved midden deposits from over 120 prehistoric village sites found on the island. These remains provide a novel laboratory for constructing long-term time series of Pacific cod populations.

The goal of this study was to compare archeological data with modern fisheries data to assess whether industrialized fishing has changed the size of Pacific cod in the North Pacific Ocean and to investigate whether or not Pacific cod size and abundance may be influenced by climate change. Pacific cod are among the most heavily exploited and consumed species of fish in the Northern Hemisphere and have declined significantly in most parts of the world in the past 30–40 years. In eastern Canada, fishing resulted in Atlantic cod (*Gadus morhua*) becoming smaller and reaching sexual maturity at younger ages as fisheries reduced the populations by more than 90% (Fanning et al., 2003; Hutchings, 2005; Lilly et al., 2005). Evolutionary reductions in body size caused by fishing have also been reported for

Baltic cod (*Gadus morhua callarias*) (Andersen et al., 2007). In the Gulf of Alaska, Pacific cod are generally thought to be fished at sustainable levels, but there is a limited time series to assess whether fisheries have changed the size of fish caught over the past 50 years (Thompson et al., 2006). It is, however, possible to use paleofisheries data to assess whether the lengths and, by correlation, average fecundity of fish caught today are comparable to those caught thousands of years ago before the advent of industrialized fisheries, and to use lengths and frequencies of Pacific cod harvested in prehistory to assess the role of climate in the structure of Pacific cod populations.

Materials and methods

All of the samples used to estimate the sizes of fish over the prehistoric time sequence were derived from shell-midden deposits that were excavated by trowel and sieved through 6-mm mesh, an appropriate sieve size given specimen sizes in the region (e.g., see *Discussion* in Cannon, 1999), and our results were substantiated by direct comparisons with bulk samples processed with 3-mm mesh). In our analysis, we controlled for possible

spatial differences in procurement of samples by including only sites located at the eastern end of the island that were associated with rocky intertidal coastlines. We further controlled for possible seasonal differences in procurement by including only midden deposits that were stratigraphically associated with winter villages (as denoted by the presence of large semisubterranean house ruins). Sample sizes for Pacific cod in each of these faunal assemblages ranged between 48 and 3219 specimens (individual bones). Actual sample sizes for measured Pacific cod skeletal elements ranged from a low of 10 to a high of 507 elements. By archaeological standards, the number of fish bones recovered from these middens was large, and thus the data set was relatively robust. Nevertheless, we recognize the possibility of potential sample-size effects, and present the entire data set as a case study.

The majority of Pacific cod bones recovered contained significant biometric information because they were not fragmented and came from well-preserved deposits. Because length figures prominently in modern fisheries management research (Shin et al., 2005; for the Gulf of Alaska see Thompson et al., 2006), allometric relationships developed by Orchard (2001, 2003) were used to establish the live length of an individual from the skeletal elements of Pacific cod. As an exercise to present the types of data that can be reconstructed from ancient Pacific cod bones, the fecundities of Pacific cod were estimated from their length distributions, by means of regressions developed by Karp (1982). More accurate reconstructions could be based on average fecundity relationships specifically recorded for Pacific cod in the Gulf of Alaska, although these data were not available at the time of publication of this article. Thus, the assemblages of skeletal remains recovered from middens in our study contained information about Pacific cod populations that could be compared to information on modern population structures for a large-scale view of changes in size and abundance over time.

Measurements were taken from the ascending process of premaxillas and the centra of trunk vertebrae from Pacific cod derived from eight archaeological sites spanning the period ca. 2550 BC to 1540 AD (radiocarbon years were calibrated to calendar years by using the methods of Stuiver and Reimer, 1993). Although these data were time averaged, the samples were from single stratigraphic units dated by multiple radiocarbon measurements and likely represent a single depositional episode that took place over one or a few seasons. From these data, the estimated length of the individuals that contributed each element was computed from Orchard's (2001, 2003) regression equations and the combined measures were used to produce length-frequency distributions for each time slice.

The modern length distribution of Pacific cod was obtained from the longline survey done by the Alaska Fisheries Science Center in the Gulf of Alaska in 2005 ($n=3308$; Thompson et al., 2006). Longline surveys are a fishing method that may be most comparable with prehistoric jigging practices. However, it should be noted that modern longline gear may subtly select for smaller size fish, as discussed by Halliday (2002). The mean longline survey data (Thompson et al., 2006) are presented as frequencies in specific size bins, and mean length was calculated by using procedures in Gedamke and Hoenig (2006).

We also measured the relative abundance of Pacific cod in the prehistoric middens using a measure known as an abundance index (AI). This measure can be used to track shifts in the relative abundance of taxa in relation to other taxa in a faunal assemblage and represents a normed ratio of a highly ranked (in terms of human foraging efficiency) taxa A to a lower ranked taxa B, measured as $AI=A/[A+B]$ (Bayham, 1979; Ugan and Bright, 2001). Values close to 0 indicate a complete absence of taxa A, and values close to 1 indicate a dominating presence. We used an abundance index because they are generally robust and are resistant to taphonomic (conditions affecting preservation) and collection biases, as long as these biases are systemic to all the assemblages being compared (Ugan and Bright, 2001)—a situation applicable to the Sanak Island data. Although simple to calculate, the measures can be powerful. For example, shifts in the index can reflect changes in human foraging efficiency because they incorporate body-size–based caloric relationships. In the model, it is assumed that larger bodied prey are often more highly ranked than smaller bodied prey (because they contain more calories per unit of effort); therefore when a highly ranked or large-bodied prey is compared to a lower-ranked, or smaller-bodied prey, the values can be used to determine the occurrence of resource depressions, or declines in foraging efficiency. Abundance indices are a well-established and peer-reviewed method of measuring changes in the frequencies of taxa through time from archaeological data (Broughton, 1994, 1997; Butler, 2000; Ugan and Bright, 2001; Nagaoka, 2002; Betts and Friesen, 2006).

Problems can arise in the interpretation of AI measures when inappropriate B taxa, or lower-ranked taxa, are chosen for comparison with higher ranked A taxa. Betts and Friesen (2006) demonstrated that these issues can be overcome by 1) carefully selecting B taxa that occur in moderate, but relatively stable frequencies in the assemblages, and 2) comparing multiple low-ranked B taxa and assessing overall trends. Here we compared Pacific cod to smaller-bodied species of fish—Cottidae, Hexagrammidae, Pleuronectidae, and *Oncorhynchus*. The former three taxa were found in the same resource patch (i.e., in the nearshore jig fishery), and likely entered the procurement system as bycatch. The last taxon, salmon, was likely captured at stream mouths and head waters with weirs and nets, and was included in our analyses for comparative purposes. Mean lengths of Pacific cod recovered from different eras were compared by using t-tests and analysis of variance, and linear regressions were used to determine the significance of trends over time.

Table 1

Comparisons of mean fork lengths of Pacific cod (*Gadus macrocephalus*) caught by Aleuts from 1540 AD to 2550 BC compared to the mean fork lengths of fish captured in 2005 by longline surveys in the Gulf of Alaska. Comparisons were made by using *t*-tests, and values in bold indicate no significant difference at the *P*<0.01 level. Sample size *n* is the number of measured bone elements from the prehistoric eras. The site numbers reflect individual winter village sites on Sanak Island from which the archaeological samples were derived.

| Site number	Era	Mean fork length (cm)		*t*-value	df	*P*	*n*
		Prehistoric	Modern				
111	2550 BC	67.5	67.5	0.003	26	**0.997**	27
054	1750 BC	70.7	67.5	5.932	573	<0.001	467
036	840 BC	72.1	67.5	5.471	340	<0.001	313
061	595 BC	64.1	67.5	−1.181	9	**0.267**	10
058	80 BC	69.7	67.5	3.801	601	**0.012**	507
056 Upper	520 AD	65.5	67.5	−2.011	175	**0.046**	166
056 Lower	1030 AD	66.6	67.5	−0.981	257	**0.327**	241
110	1540 AD	62.8	67.5	−6.223	515	<0.001	464

Results and discussion

Measuring changes in Pacific cod size and abundance

The mean size of Pacific cod has varied considerably in the Gulf of Alaska over the last 4500 years (Fig. 2; range 62.8–72.1 cm; $F_{(8, 5503)}$=11.97, *P*<0.001). However, modern mean lengths did not differ significantly from the mean lengths of fish caught around 2550 BC, 595 BC, and 1030 AD (Table 1 ; *t*-tests *P*>0.05), or when compared with lengths of those taken around 80 BC and 520 AD (Table 1; *t*-tests *P*>0.01).

Fecundities of Pacific cod (estimated from body length distributions) varied dramatically, ranging between 2.1 and 3.9 million eggs per individual (Fig. 3). Average fecundity varied consistently with changes in mean length as expected, but the apparent trend shown in Figure 3 towards decreasing fecundity over 4500 years was not significant (*r*=−0.42, *P*=0.35).

The AI measures revealed changes in the relative abundance of Pacific cod over the past 4500 years (Fig. 4). All of the AIs were highly variable between 2550 and 2580 BC, but were synchronized after 520 AD. They indicated high relative abundance of Pacific cod in middens spanning 2550–1750 BC and showed an opposite trend in the abundance of salmon, which was consistent with the inverse relationship previously noted for this region and time period (e.g., Tews, 2005; Misarti, 2007). From 840 BC to 80 BC another period of variability occurred when salmon AI was opposite that of the groundfish taxa. During this time, the AIs for Pleuronectidae and Hexagrammidae indicated a slight decline in relative abundance of Pa-
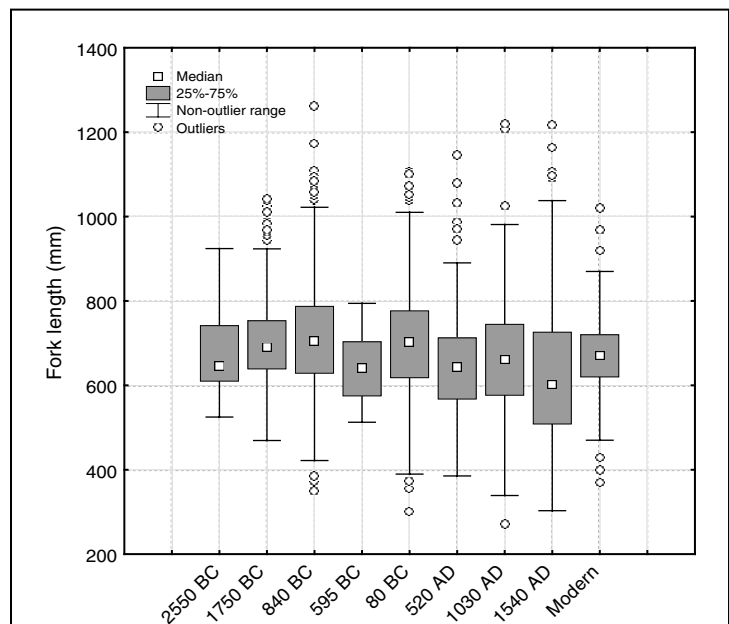
Figure 2

Box plots showing the fork-length (mm) distributions of Pacific cod (*Gadus macrocephalus*) caught in the Gulf of Alaska since 2550 BC. The prehistoric distributions were reconstructed from skeletal elements (premaxilla and centra from trunk vertebrae) by using allometric relationships established by Orchard (2003). The modern length distributions were compiled from data collected from longline surveys conducted in the Gulf of Alaska by the Alaska Fisheries Science Center between 1978 and 2006 (Thompson et al., 2006).

cific cod, whereas the Cottidae index indicated a greater decline in Pacific cod abundance. Taken in tandem, however, all of the groundfish taxa recovered from the

middens indicate that there were slight or moderate declines in Pacific cod during this early period. On the basis of the remains in the middens, there was a sharp decline in the relative abundance of Pacific cod (compared to the other three taxa) beginning around 520 AD. This declining trend intensified drastically in the 1030 AD assemblage, and was followed by a sharp increase in Pacific cod abundance at 1540 AD.

The declining AIs strongly indicate that a form of resource depression occurred from 520 through 1030 AD (for a similar interpretation of declining fish AIs, see Nagaoka, 2001, 2002). Resource depressions can be related to a number of factors, such as exploitation pressure, behavioral changes, and microhabitat (range) shifts (e.g., Charnov et al., 1976). The apparent decrease in Pacific cod abundance that we noted is intriguing given the lack of any technological, procurement, or other cultural changes (e.g., increased territoriality) that could have influenced the encounter or success rate of the Aleut Pacific cod fishery. Instead we suspect the decline in Pacific cod reflects an environmentally-driven natural change in abundance and note that the increase in mean length during this period corroborates this interpretation (see Shin et al., 2005).

Interpreting the effects of climate on Pacific cod size and abundance

Punctuated shifts in ocean climate (regime shifts) are believed to explain many of the changes observed in abundances of some species in the North Pacific Ocean

Figure 3

Mean estimated fecundity of Pacific cod (*Gadus macrocephalus*) over time based on the relationships between body length and fecundity established by Karp (1982). This graph indicates that estimated mean fecundity of Pacific cod has varied widely over the past 4500 years, despite concomitantly small changes in mean Pacific cod length (compare with Fig. 2). Although the graph indicates an apparent trend toward decreasing fecundity, the relationship is not significant; $r=-0.42$, $P=0.35$.

during the past century (Hare and Mantua, 2000; Benson and Trites, 2002; Trites et al., 2007) and these shifts may explain the variations noted in Figure 4. Pacific cod populations may be susceptible to fluctuations in oceanic regimes to the extent that they periodically disappear in significant numbers from the ecosystem, only to reappear in greater numbers at a later date. This condition has deep historical roots; the ancient Aleut name for Pacific cod translates literally into "the fish that stops" because this species periodically disappears (Black, 1981), a situation that occurred, according to traditional Aleut knowledge, at least once in the mid-19th century, and again in approximately 1942.

Several small variations in mean Pacific cod length were evident over the temporal sequence. Correlating the shifts in body size with climatic shifts does not appear to explain the fluctuating sizes of Pacific cod between 2550 BC and 80 BC, which occurred during the generally cool and wet conditions of the Neoglacial period (the first major postglacial cooling period from approximately 2500 BC to AD 1). The average lengths of Pacific cod (Fig. 2) increased as the warming and drying of the Medieval climatic anomaly began (a period of hemispheric climatic fluctuations ca. AD 1000–1300 across the Northern Hemisphere) and decreased slightly during the cool and wet conditions of the Little Ice Age (ca. AD 1400–1850). Marine productivity during the Medieval climatic anomaly and the Little Ice Age, as recorded by Finney et al. (2002) and Misarti (2007), appears to be inversely related to Pacific cod lengths but positively related with Pacific cod numbers (Fig. 4).

Such inverse relationships between mean fish length, abundance, and productivity have been noted by Shin et al. (2005) (i.e., increased productivity and abundance is usually associated with decreases in mean length, presumably because of the increase of juvenile fish in the population). The impact of these types of processes on fish lengths over the long time scales has never been assessed, and so this must remain a working hypothesis. Regardless, it is also notable that the mean length of Pacific cod during the Medieval climatic anomaly was not statistically different from that of the modern era codfish (Table 1)—two of the warmest periods in the last 4500 years.

The effects of oceanic regime shifts that have dominated the dynamics of marine ecosystems in the North Pacific for the past century (Benson and Trites, 2002; Polovina, 2005) are difficult to monitor in the prehistoric period because of an important complicating factor—an overwhelming lack of data. Although climatic and oceanic warming AD 1000 to 1300 have been documented around the North Pacific (Calkin et al., 2001; Hu et al., 2001), and its effects are beginning to be understood (Jones et al., 1999), the full effects of climate change on Pacific cod stocks over the entire period are difficult to measure because not a
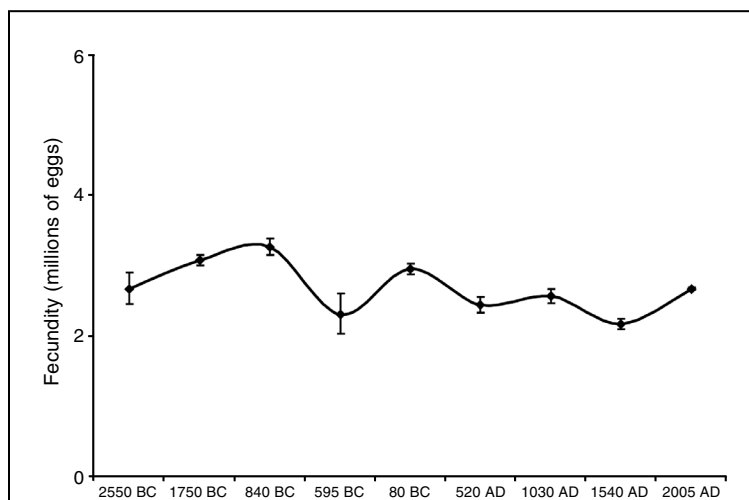
single preserved Pacific cod bone dating from AD 1100 to 1300 in the Sanak archaeological data has been recovered despite the presence of village sites. The period between AD 1100 and 1300 were the only centuries during the last 5000 years of extensive global warming that occurred before the modern era. Pacific cod returned in the middens only during the hemispheric cooling associated with the Little Ice Age. Interestingly, regardless of periodic regime shifts in ocean climate, Pacific cod populations appeared to have returned to the western Gulf of Alaska with approximately the same length structure as that before they disappeared.

The perturbations in the body lengths of Pacific cod did not correlate with changes in their frequencies of occurrence in the middens (Fig. 4). For example, the most extreme shift in mean Pacific cod length occurred between 2550 BC and 80 BC, yet Pacific cod abundances varied minimally during this time. It is noteworthy that this entire period occurred during the Neoglacial, a period of generally cooler and wetter oceanic conditions. This relationship may indicate that perturbations in abundance, at least during cold periods, were not related to systemic fluctuations in the length or fecundity structure of the Pacific cod populations in the Gulf of Alaska.

At the end of the temporal sequence ca. 1030 AD and 1540 AD, an inverse relationship is noted between mean length and abundance of Pacific cod. The mean lengths increased during the Medieval climatic anomaly and decreased during the Little Ice Age, whereas overall relative abundances decreased during the Medieval climatic anomaly and increased during the Little Ice Age. This finding would indicate that Pacific cod were more abundant but smaller during cool periods and less abundant but larger during warmer periods. Although the inverse relationship between length and abundance is intriguing, it is uncertain how they are related. The shift in mean Pacific cod length between these periods was small (less than 3 cm), yet abundances fluctuated widely.

Climatic regime shifts appear to have had minimum effects on the length structure of Pacific cod populations in the Gulf of Alaska, but have had dramatic effects on their numbers and possibly geographic range. The apparent drop in Pacific cod numbers during periods of warming may reflect a shift in Pacific cod distribution (e.g., Charnov et al., 1976), and may explain why the Aleut word for Pacific cod is the "fish that stops."

General observations regarding the prehistoric Pacific cod data

Additional insights about Pacific cod can be made from the analyzed bones, which show, for example, that Pacific
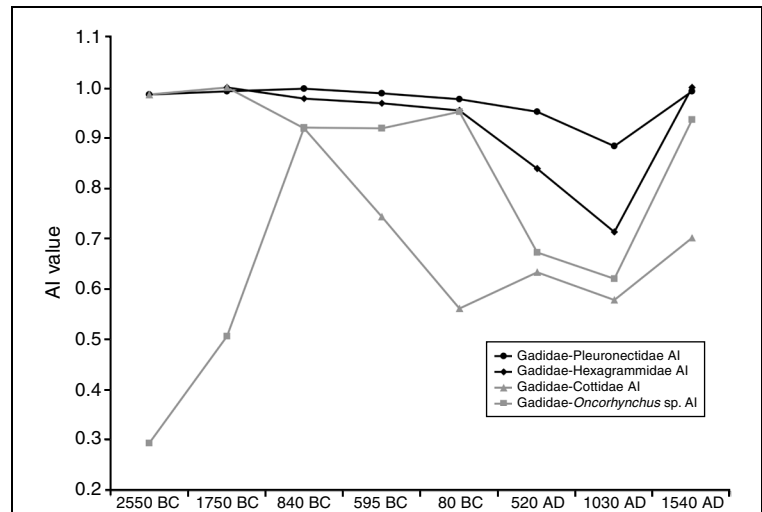

Figure 4

Abundance indices (e.g., *AI=Pacific cod* / [*comparison taxon + Pacific cod*]), calculated from the number of identified specimens (bone fragments) for each taxon recovered from nine archaeological deposits on Sanak Island. The index ranges between 0 and 1, with 0 indicating the complete absence from the middens and 1 indicating a complete dominance of Pacific cod (*Gadus macrocephalus*). Sample sizes from the deposits ranged between 426 and 8339 identified bone specimens. All indices indicate a decline in Pacific cod abundance beginning at 520 AD, except for the Gadidae-*Oncorhynchus* spp. index, which is included to show the difference between riverine (*Oncorhynchus* spp.) and nearshore marine fish (the other families of fish represented in the graph) during this period. This decline in abundance continues throughout the period until 1030 AD, after which we see a recovery in Gadidae abundance at ca. 1540 AD. The correspondence in the multiple measures negates the mathematical conundrum of closed arrays and indicates real changes in the relative abundance of Pacific cod in Sanak middens.

cod have long-term, millennial-scale population dynamics that appear to have a complex relationship with climatic shifts. Pacific cod seem to be vulnerable to major climatic regime shifts, particularly warming conditions, and appear to rapidly recover from major perturbations to their environment. This conclusion would signify that oceanic regime shifts have no long-term (centennial- to millennial-scale) ramifications on the overall structure of Pacific cod populations. Furthermore, Pacific cod stocks appear to have largely maintained their population structure over some 4500 years despite the pressures of commercial harvesting in the modern era.

The trends uncovered for Pacific cod in the North Pacific are significantly different from those in the North Atlantic. Swain et al. (2007) concluded that length distributions can be a key indicator of genetic changes in Pacific cod as a result of overfishing, and that these changes can persist for decades despite low harvest pressure. In particular, they found that rapid evolutionary changes can result from size-selective overfishing, and these changes can far outpace the levels expected for natural mortality as a result of disease or regime shifts.

The archaeological record in the western North Atlantic shows that the average length of Pacific cod caught today by commercial fisheries is at least 40 cm smaller than that of prehistoric times, and indicates that the Pacific cod populations have been impacted by modern fisheries (Kenchington and Kenchington, 1993; Jackson et al., 2001). Similar shifts have been discovered in the central North Atlantic where Amorosi et al. (1994) demonstrated significant differences in the length distributions of Pacific cod between the Medieval period and the modern era. In contrast, we found that the minimum difference in the average length of Pacific cod taken by longline fisheries was only 3–4 cm larger than the smallest prehistoric mean size fish caught by the ancient Aleuts using jigs. The implications of these regional differences are intriguing given the different historical trajectories in commercialization of the groundfish fisheries in these two regions, namely a different emphasis on harvesting technologies (i.e., a much higher proportion of the North Pacific catch is taken with cod pots, compared to the North Atlantic, where cod pots have seen minimal use). The North Pacific cod pot fishery, in particular, reduces the catch of juvenile fish.

This study points to ways in which ancient archaeological deposits can be used to significantly extend the time-depth of fish population studies and can provide important insights into long-term sustainability. Such palaeofisheries research is important for placing modern decadal population trends within a longer-term perspective. In the case of Pacific cod, the paleoecological records indicate that today's Pacific cod are comparable in size to fish that inhabited the Gulf of Alaska thousands of years ago. This finding indicates that modern fisheries have not altered the average length distributions of Pacific cod in the Gulf of Alaska when measured over long time scales.

The fact that modern Pacific cod length distributions are within the range of precommercial variability indicates that the current commercial Pacific cod fishery has sustained the length structure (and therefore average fecundity structure) of the prehistoric (noncommercial) Gulf of Alaska Pacific cod population. Compared to the North Atlantic, the changes we observed in fish length between the prehistoric and modern eras in the Gulf of Alaska are more consistent with natural fluctuations than with harvesting pressure. The fact that the present-day size-structure of Gulf of Alaska Pacific cod stocks is consistent with a sustainable fishery (Thompson et al., 2006) and that the current size-structure is comparable to that of pre-industrially fished populations indicates that current Pacific cod fisheries management policies and harvesting techniques in the western Gulf of Alaska are working. That is, management practices and harvests are maintaining a natural Pacific cod population structure based on mean size as a comparative metric of sustainability. However, we caution that global warming may become a complicating factor for modern management practices given that Pacific cod populations may be vulnerable to pressures caused by increasing oceanic temperatures, as appear to have occurred circa AD 1000–1300.

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