

An Introduction to the Biocomplexity of Sanak Island, Western Gulf of Alaska¹

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Abstract: The Sanak Biocomplexity Project is a transdisciplinary research effort focused on a small island archipelago 50 km south of the Alaska Peninsula in the western Gulf of Alaska. This team of archaeologists, terrestrial ecologists, social anthropologists, intertidal ecologists, geologists, oceanographers, paleoecologists, and modelers is seeking to understanding the role of the ancient, historic, and modern Aleut in the structure and functioning of local and regional ecosystems. Using techniques ranging from systematic surveys to stable isotope chemistry, long-term shifts in social dynamics and ecosystem structure are present in the context of changing climatic regimes and human impacts. This paper presents a summary of a range of our preliminary findings.

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THE GREATER NORTH Pacific region hosts one of the world's most important fisheries. Recent dramatic decreases in the numbers of many species in this region have perplexed biologists, caused sweeping and underinformed management decisions, and are provoking cultural disintegration of many Alaska Native villages. But twentieth-century data show clearly that there have been other periods of low productivity for species, often followed by periods of abundance (Trites et al. 2007; H.D.G.M., A.W.T., K.L.R.-M., M.W.B., A.T., and M.L., unpubl. data), as do historical, paleoecological, and archaeological data from the last 5,000 years (e.g., Moser 1902, Finney 1998, Maschner 1998, Finney et al. 2000, 2002, Savinetsky et al. 2004, Maschner et al. 2008). The global problem is thus: under varying population cycles of humans, salmon, groundfish, sea mammals, birds, and many other species in the North Pacific region, and with varying harvests by the higher trophic levels, how do we sustain populations, ecosystems, and the peoples and cultures who depend on them for their social, political, economic, and cultural survival?

Most modern investigations of this question have had limited temporal data. For example, studies of possible long-term cycles in populations of Steller sea lions in the

North Pacific were handicapped by limited and short-term data, although cycles may be much longer (Ocean Studies Board and Polar Research Board 2003). Further, attempts to model the effects of human fishing on the population dynamics of cod, pollock, or sea lions, for example, typically begin with an assumed pre-fishing or pre-hunting state (e.g., Castellini 1993). Yet indigenous peoples have harvested large quantities of these species for thousands of years, requiring that we assume that there is no ecologically meaningful time period without humans, at least not since deglaciation 16,000 years ago. Thus, archaeological data provide the essential temporal perspective for such an analysis.

From both anthropological and ecological viewpoints, and building on the work of Crumley (1994 and papers therein), the roles of humans must be considered as one of many linkages within ecosystems that include other biotic components, as well as abiotic constraints and drivers. A sweeping article in *Science* (Jackson et al. 2001) suggested large-scale roles of humans in ecosystems, arguing that changes in marine ecosystems are complex, systemic, and have a long historical context (e.g., see papers in Rick and Erlandson 2008). However, most of the suggested relationships between trophic structure, species extinctions, marine productivity, and human exploitation remain untested. Our research was developed to directly test the sorts of relationships suggested by Jackson et al. (2001), as well as provide fundamental data on the role of humans in ecosystem dynamics in the North Pacific over millennia. This project focuses on whole-ecosystem complexities of the region, which are founded on predator-prey and other food-web interactions, cultural harvesting strategies, long-term changes in the North Pacific ecosystem and climate, and direct human impacts on coastal environments.

We have constructed a transdisciplinary approach to studying humans as part of the northern ecosystem, incorporating the modern and prehistoric, the terrestrial and marine, the local and regional, and used both empirical and theoretical exploration. We suggest that this multidimensional approach

is not only possible but necessary to our understanding of the region. The implications of this approach are profound and require integration of anthropology, archaeology, geology, ecology, mathematics, climatology, and history; the perspective of many spatial and temporal scales; and the seamless merging of theoretical approaches from many fields. Because indigenous peoples have been harvesting resources in the North Pacific for thousands of years, we must include them in models and reconstructions of this ecosystem, in which they may function as ecosystem engineers, as more ordinary components of food webs and landscapes, or as passive responders to a world that is primarily driven by largely external forces such as climate and geomorphic evolution, or some combination of all three. We expect this human role to vary temporally and spatially, with cultural context, and our work provides a framework and a test case for understanding the history of people as components of ecosystems.

This project is being conducted in the Sanak Island archipelago, 50 km south of the tip of the Alaska Peninsula (Figure 1), and draws on past and ongoing work on the nearby western Alaska Peninsula and Aleutian regions. Sanak Island is about 120 km² in area, with 92 km of shoreline, and is the largest island of its archipelago. The islands have a 6,000-year archaeological record. They were populated by a number of villages at Russian contact, were the center of sea-otter harvesting in the nineteenth century and cod harvesting in the early twentieth century, and supported active cattle ranches until the 1960s. The islands are surrounded by a massive reef system that supported some of the largest populations of groundfish and sea mammals in the region. Millions of tons of cod were harvested here in the early twentieth century, and, today, commercial fishermen from False Pass and King Cove fish here for cod in spring or halibut in summer. These islands supported the last major populations of sea otters to be commercially harvested. At least three river drainages have runs of sockeye, humpback, and chum salmon. In the last 100 years, the landscape has been altered by large herds of now feral

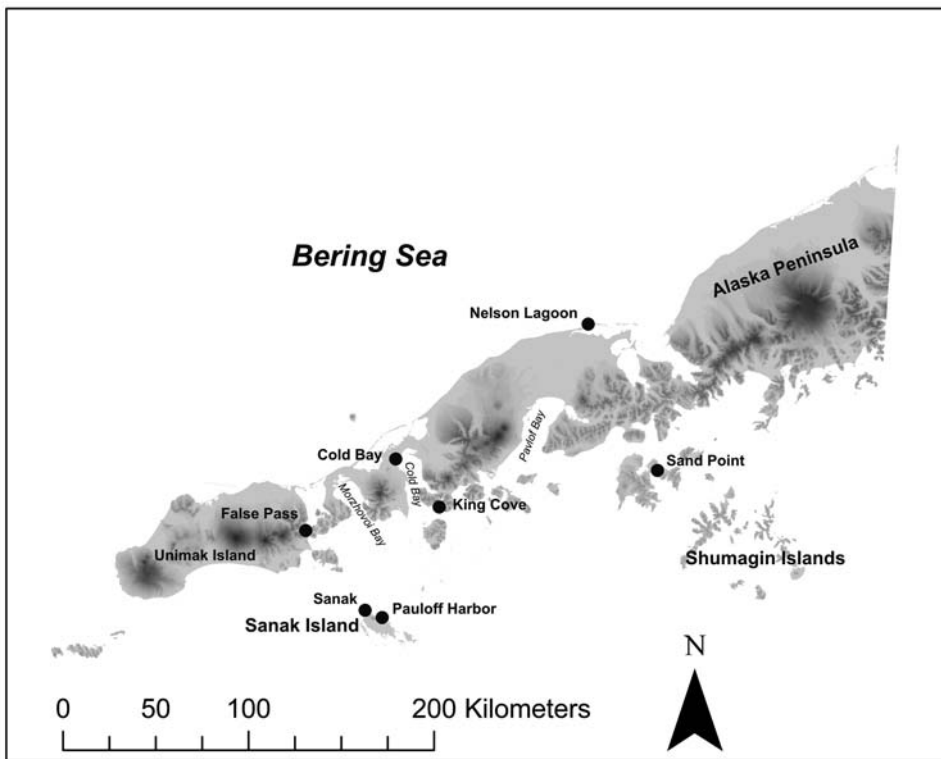
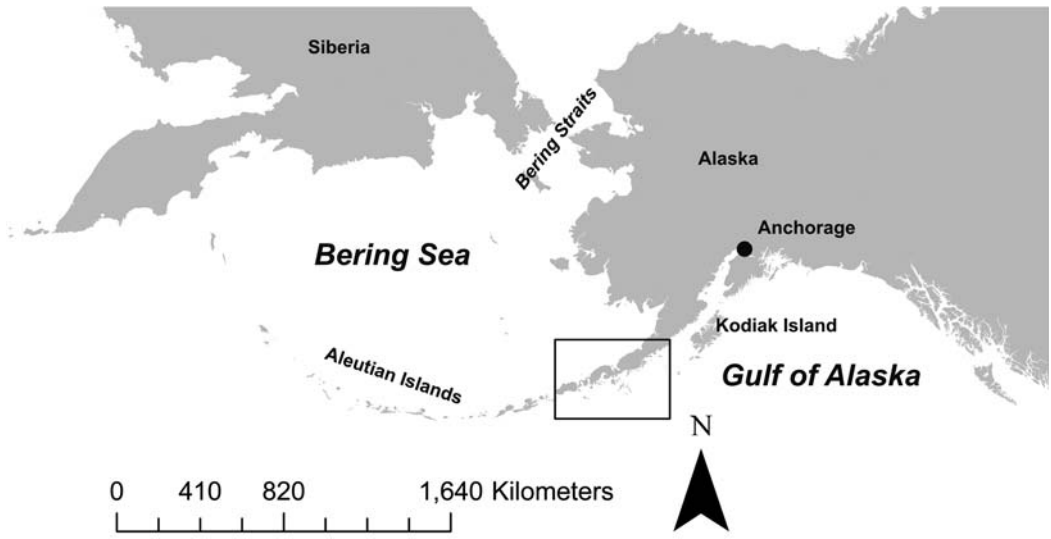


FIGURE 1. Map of western Gulf of Alaska. Sand Point, False Pass, Nelson Lagoon, and King Cove are modern Aleut communities. Sanak and Pauloff Harbor are abandoned.

cattle that are an important part of local subsistence in the region. Finally, local peoples lived on these islands for many years before their abandonment in the 1960s. Families in Sand Point, King Cove, and False Pass, Alaska, have provided a wealth of local knowledge about the landscape. Given the archaeological, historic, and ethnographic data, the local knowledge of the region, and the relative isolation of this archipelago from the mainland peninsula, the Sanak Island region is a perfect location to investigate the complex dynamics of human-landscape relations and the role that humans have played in the structure of the North Pacific ecosystem over the last several thousand years.

Humans function within ecosystems in many ways; they are one of many consumers, whose roles within food webs may range from strong top predators, to omnivorous and generalized consumers, to builders and husbands of domesticated or industrialized resource supply systems. They can be ecological engineers (Jones and Lawton 1995, Jones et al. 1997, Power et al. 1998), changing the physical structure of ecosystems, and can link terrestrial and marine ecosystems, as do other organisms (e.g., seabirds or salmon) and abiotic processes (Polis and Hurd 1996, Polis et al. 1997). For instance, they may alter or mediate movements of resources from marine to terrestrial regions and may modify geological or hydrological linkages deliberately or as unanticipated side effects of their activities. Humans draw from the Ecosystem Services of nature (e.g., supply of freshwater and food, medicinals, esthetics), and these have played strong historical roles in patterns of human settlement, health, and culture (Dale et al. 2000). Nevertheless, humans have only rarely been evaluated explicitly as integral components of ecosystems (e.g., Ellis and Swift 1988, Ellis and Galvin 1994) with properties that can be compared with those of other biotic and abiotic components within an evolving system, the trajectory of which may be disproportionately influenced by people and their behaviors. The interdependence of people and their ecosystems makes explicit study and evaluation of humans as integral parts of ecosystems critical to study. Much

ecological theory addresses the dynamics and interactions of species within ecosystems (e.g., Chesson and Huntly 1994, 1997, Jones and Lawton 1995, Polis and Winemiller 1996, King and Schaffer 2001, Dunne et al. 2002, Turchin 2003, Worm and Myers 2003, Williams and Martinez 2004a), and we are applying such approaches to the study of the Aleut (sometimes referred to as Unangan) and their ecosystems of the western Gulf of Alaska.

Evidence suggests that humans have been key components of the regional ecosystem for millennia. Standing crop, diversity, species composition, and the abundances of edible and medicinal plants all differ between areas inhabited by Aleuts and those that have not been (Bank 1953, Shacklette 1969, Amundsen 1972, Johnson 2003). The distributions of plants typically influence the distributions of animals (Morrison et al. 1998), including mammals and birds that, in turn, influence human populations and cultures. Additional ecosystem-level interactions are caused by cultural systems of exploitation, such as fisheries and the keeping of domestic livestock. Moreover, humans have repeatedly removed and exterminated species, which may have altered food webs and ecosystems profoundly. For instance, in the 1780s, Russian documents reported three species of foxes on Sanak Island, but in the 1920s, no foxes were reported. In recent decades, arctic foxes were reintroduced only to be exterminated in the last few years. In 1823, the Russian Orthodox Church removed the Aleut people from the islands to protect one of the last commercially viable sea otter populations in the North Pacific. We suspect that this removal again reorganized ecosystems, which again were altered when Scandinavian fishermen and their Aleut wives recolonized Sanak in the 1870s.

Our research is different than the more traditional (and highly successful) approaches previously attempted in the region. Yesner's (1980, 1981, 1987, 1988, 1998) studies, for example, were some of the first to identify the role of the Aleutian ecosystem in the structure of ancient Aleut society. He was also one of the first to attempt to identify

human impacts on that ecosystem. Simenstad et al. (1978) made an early foray into the complex dynamics between human harvesting and the restructuring of the marine ecosystem in the Aleutians. Building on these early studies, one focus of our work has been the linkages involving humans within the Sanak ecosystem. We are investigating major biotic components, both terrestrial and marine, of the food webs and ecosystems that include the Aleut, and include primary abiotic drivers such as climate (e.g., Pacific Decadal Oscillation, Aleutian Low) and geomorphic factors. We are testing hypotheses as to the linkages of humans within ecosystems, beginning with a series of descriptors of the effects of humans on terrestrial and marine populations and the landscape, and following through to analyze potential ramifying effects of these to other ecosystem components and processes. Hypotheses are being addressed from contemporary to ancient times, using sites on Sanak and the western Alaska Peninsula that date back to 6,000 years ago to address pattern and process in deep time.

A second focus is the dynamic importance of humans to other components of the food web and landscape over the last several millennia, as well as the dynamics of the human population itself. Here, the emphasis is on population and community dynamics, as possible to reconstruct from long-term indicators and contemporary, more precise, measures, and from models. This focus more directly tests Jackson et al.'s (2001) assertion that humans may have cascading effects on marine (or other) food webs that are realized over decades, centuries, and millennia and over large spatial scales. This work additionally examines population and social dynamics of humans in correlation with resource and landscape dynamics over millennia. Thus, we are directly addressing the conditions under which humans have sustainable patterns of resource supply and exploitation. We are investigating pattern and process at multiple points in time and in space, as well as the linkages and transitions through time and across space.

The modern history of Sanak Island offers a final important research focus, a unique op-

portunity to view both of the above research themes in finer detail and with comparisons that include modern domestic agriculture (e.g., cattle) and technology (e.g., canneries, regulated commercial fisheries). Here, we are investigating contrasts between traditional and modern domestic-technological exploitation ecosystems. Given this context, we provide some of our preliminary results here. Although still in the early phases of analyses, some distinct patterns are beginning to emerge from these investigations.

The first section of our preliminary findings covers the ethnohistory and history of the last 200 years. This is followed by a geological and paleoenvironmental review. The archaeological data are then used to assess the temporal distribution of sites and the distribution of sites with shell middens to reconstruct the population history of the island, to investigate cod and otariid histories, to compare the modern intertidal ecosystem with the prehistoric exploitation of shellfish, to track regional paleoenvironmental data using modern and prehistoric samples for isotopic analysis. We conclude with our first exploration into the reconstruction and analysis of food webs.

Finally, restating our research question in more specific and testable form: What have been the roles of prehistoric, historic, and modern peoples in the structure and functioning of the North Pacific ecosystem, and is it possible for that role to continue and to viably sustain the communities that live in this ecosystem today? This paper provides a first assessment of a number of specific findings that contribute directly to this fundamental question of the project, especially in regard to how humans shaped the North Pacific region, and, in turn, how the complexities of the North Pacific conditioned the behaviors, adaptations, and histories of the people who lived there.

PRELIMINARY RESULTS

An Economic and Social History

An analysis of the ethnohistoric data, as well as many hours of interviews with former

residents of the island, demonstrates the dynamic and volatile economic history of the Sanak archipelago. This historic volatility is partially a product of changing political economies and partly a product of the realities of human impacts on these islands creating changing economic and social opportunities (Reedy-Maschner 2001, 2004, 2007).

The inhabitants of this region today, at the time of historic contact, and as far as we can surmise for at least the last 6,000 years, are the Aleut. In the eighteenth century, the Aleut lived in large, sedentary villages. They were organized into lineage-based households that included from six to 10 families in a single dwelling, perhaps larger in the eastern Aleutian Islands (Lantis 1984, McCartney 1984, Liapunova 1996, McCartney and Veltre 1999). The Aleut were ranked, with hereditary nobility, a middle class made up of kinsmen to the nobility, people without property or kinsmen, and slaves, who were in a separate class altogether (Townsend 1980, 1983, Veniaminov 1984). Because most transportation and communication were by kayak, the Aleut participated in trade and warfare over extremely long distances (Maschner and Reedy-Maschner 1998). Ethnographic and archaeological investigations have demonstrated that the Aleut lived corporately, sharing supplies, work areas, and other aspects of household maintenance (Hoffman 2002). Economically, they were oriented specifically toward the sea and utilized most edible resources. Only on the Alaska Peninsula and adjacent nearby islands are terrestrial resources found and only in a few time periods did the Aleut regularly exploit caribou, bear, and smaller terrestrial mammals found locally.

The Aleut of the Sanak Islands were a ranked polity of perhaps a few hundred living in several villages across the islands before Russian contact. They were in an antagonistic trade relationship with the Alaska Peninsula Aleut and frequently at war with Kodiak Islanders. The first historical reference to the islands is in 1762, describing their sea otter wealth, which initially provoked Russian interest and hostilities (Black 1999:61–64,

O’Leary 2002), and later, peaceful contacts that included baptisms and trade (Black 1999:66). In 1778, Captain James Cook anchored his ship *Discovery* off Sanak Island and took so many large halibut that he named the group the “Halibut Islands” (Beaglehole 1967). But the Russians had a foothold on Alaska, and after 1808 Sanak was reorganized into an artel, the last of six primary artels, or workers cooperatives under Imperial Russia, for the purposes of mass harvest and export of sea-otter skins. Artels were led by Russian baidarshchiks (captains), with Russian and Aleut employees supplying the company with skins.

Sea-otter hunting was conducted using Aleut labor, methods, and gear, in parties of up to 15 baidarkas (kayaks) in the calmer summer months (Veniaminov 1984:330). Records from that era are sparse, but Khlebnikov’s report in 1818 ranks Sanak as a top producer compared with the other artels (1994:170). Aleut hunters were also held in debt to the Russian America Company. In 1823, after a decline in otters on the islands, hunters of the Sannakh Artel were transferred to Bel’kovskaia Bay on the mainland and placed under the Unga baidarshchik, even though Sanak continued to be hunted from a distance.

Sanak was not resettled until after the U.S. purchase of Alaska in 1867. Unga and Belkofski Aleuts gradually returned to Sanak alongside Euro-American hunters who were hunting the few remaining sea otters. Former villages were resettled, and new villages were established. The Alaska Commercial Company built a trading post on the north end of the island at Sanak village. Scandinavian immigrants took a particular interest in the region, first for sea otters (until they were hunted out in the 1890s), and then more intensively for the codfish industry. These men married locally and have left an indelible legacy within the eastern Aleut community.

The cod fisheries began in the Aleutians in the 1870s, with Scandinavian dory fishermen arriving in the Shumagin Islands, Sanak Islands, and up to Port Moller in the Bering Sea. Schooners from San Francisco to Vancouver sailed to the region stacked with do-

ries and fishermen who fished for cod with handlines (Shields 2001). This developed into a shore-based fishery, and codfish stations for salting and storing in barrels were established at Company Harbor (townsite of Sanak), Pavlof Harbor (now Pauloff) and several other locations on Sanak Island, as well as several on the Alaska Peninsula and in the Shumagin Islands (Figure 1). By 1915, there were 17 shore stations operating in the region taking over 1 million fish each year (Shields 2001:20). Scandinavian fishermen and Aleuts shared communities to some extent and worked alongside one another.

After 1915, fish began to disappear around the Shumagins and Sanak, and by 1930 shore stations began to close (Shields 2001). But by 1899, salmon canneries had been built by the Pacific American Fisheries Company on the Alaska Peninsula, offering a viable economic alternative, but with local environmental consequences (Figure 2). Villages were established around these canneries, and gradually residents of Sanak and several other former sea otter and codfish based communities moved to these new villages, which remain the viable fishing villages of King Cove, Sand Point, False Pass, and Nelson Lagoon today.

Fox farming and cattle industries were also attempted on the Sanak Islands with mixed success but allowed some residents to stay until 1980. Today, the island supports wild cattle and horses from those economic experiments; the Aleut harvest cattle annually for subsistence. Sanak Island is now owned and managed by the Sanak Corporation and Pauloff Harbor Tribe in Sand Point, and many Aleuts in the region continue to visit the island and fish its waters.

The historic Aleut were adept at taking advantage of changing social, political, and environmental dynamics. Regardless of the global political and economic dominance of the time, the Aleut translated their long history of harvesting the North Pacific and southern Bering Sea into adaptations that reflected the larger forces around them but maintained their identity as coastal foragers. As we show in the following sections, this flexibility was present in the prehistory of the Sanak region as well.

Environmental Background

GEOLOGICAL CONTEXT. The Sanak Island archipelago is located at the edge of the continental shelf above the Aleutian Trench

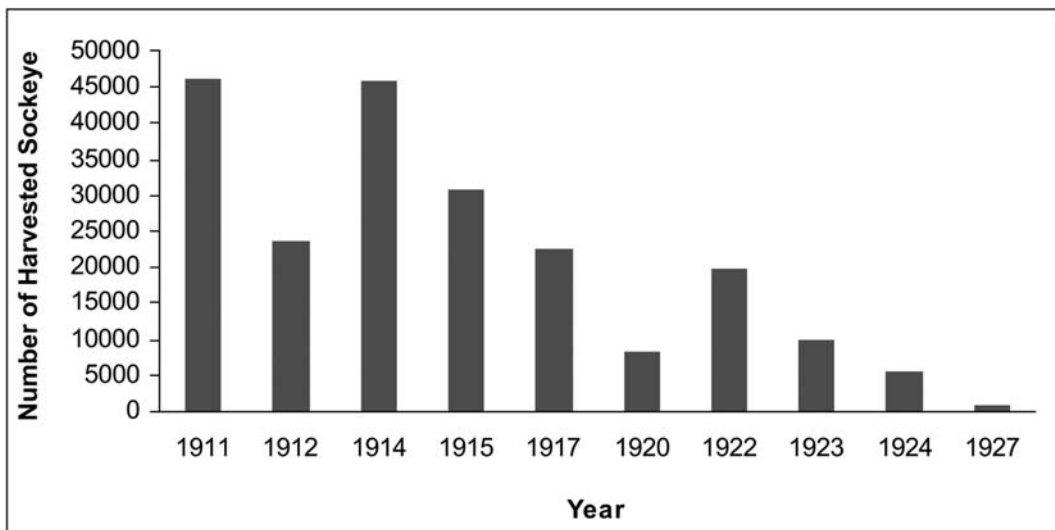


FIGURE 2. Long-term effects of the sockeye salmon harvest on Sanak Island, 1911 to 1927. Today there are fewer than 3,500 fish returning to the combined streams of Sanak Island (data from Rich and Ball 1930).

subduction zone and is separated from the Alaska Peninsula by 50 km of open water. The island group is geographically part of the greater eastern Aleutian Island archipelago, but its location south of the western Alaska Peninsula effectively separates it from the Bering Sea, a physiographic characteristic that distinguishes it from the rest of the Aleutians. The Sanak archipelago is geologically related to the Shumagin Island group to the northeast (Moore 1974) and is composed principally of rocks of the Cretaceous-aged Shumagin Formation—continental shelf slope and turbidite deposits consisting of medium- to fine-grained sandstone interbedded with mudstone. Fault-bound Jurassic to Cretaceous-aged chert, volcanic and marine sedimentary rocks occur between Sanak and Long Island (Figure 3). Sanak Island proper is topographically dominated by Sanak Peak, a Tertiary intrusive granitic massif at the northwestern end of the island. Although its bedrock geology is distinct from that of

the Alaska Peninsula, its proximity is critical in the paleoenvironmental history and dynamics of the Sanak archipelago, primarily due to the influence of the peninsula on glaciation of the regional continental shelf and the proximity and eruption frequency of its closely spaced Holocene volcanic centers, and seismic province. New paleoenvironmental evidence from Sanak Island (sea level and vegetation and climate proxies) is remarkable because it provides spatial context and temporal depth to the record of postglacial environmental change in the region.

Before this project, our view of the glacial history of the western Gulf of Alaska was dominated by a handful of mapping or modeling studies (Detterman 1986, Mann and Peteeet 1994, Dochat 1997, Wilson and Weber 1999), none of which included field observations in the Sanak Islands. The Sanak archipelago was overrun by ice from a source area to the north during the last glacial maximum, but field evidence indicates that ice thickness

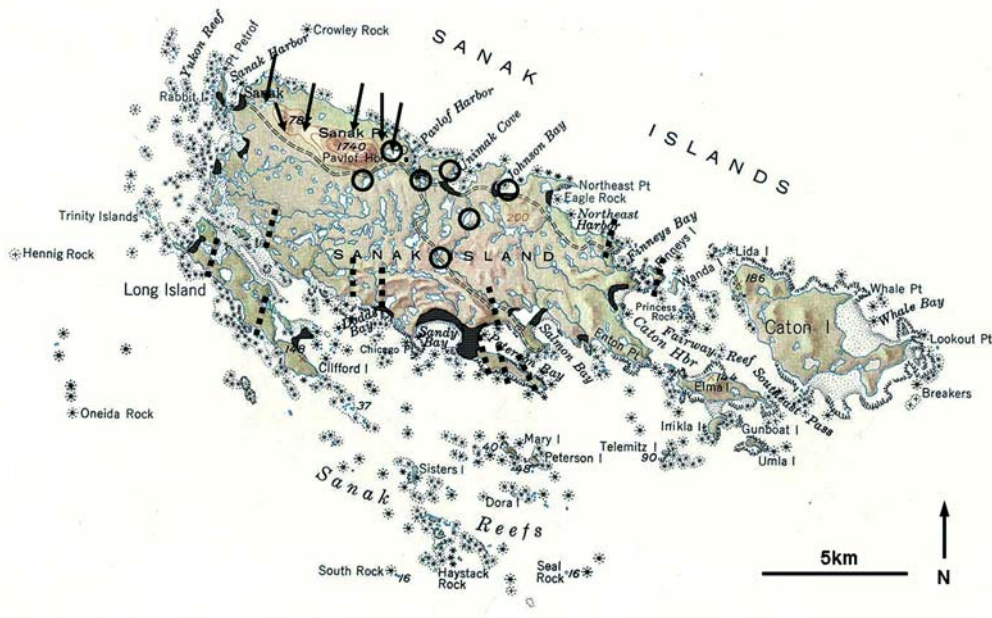


FIGURE 3. Sanak Island paleoenvironmental sites: lake and peat core sites (circles), glacial striations or grooves cut on granodiorite (arrows), and ice override (drumlinoid) features (dashed lines). Stippled areas indicate location of beach ridge complexes.

did not exceed 70 m above modern sea level (asl) (Jordan et al. 2007), an important downward revision of ice thickness modeled by Mann and Peteet (1994). Glacial striations and ice flow indicators oriented north-south across Sanak, the spatial pattern and limited thickness of till on the island, and till lithology distinct from that observed in Cold and Morzhovoi bays on the peninsula all indicate that the Sanak Group was outboard of a regional ice sheet axis (J.W.J., unpubl. data), the thickness and position of which was reconstructed by Mann and Peteet (1994) and suggested by Dochat (1997) to have been centered near Sanak. Basal ages from lakes cored on Sanak during our project indicate that ice had disintegrated from the archipelago by about 16,000 cal years B.P., several millennia earlier than on the peninsula based on the current chronology there. (All dates in this paper are calibrated years B.P., unless the date concerns near-modern events.)

New insights from field evidence of glaciation on Sanak are critical for understanding the record of postglacial sea-level change in the archipelago and across the adjacent shelf. A thin last glacial maximum ice margin at Sanak constrains our estimates of glacial-isostatic depression and uplift to values lower than those of the peninsula and is consistent with the elevation of marine terraces documented on the island (4 to 5 m asl) relative to the isostatically uplifted shorelines observed in areas around Pavlof, Cold, and Morzhovoi bays (25 m +) (Figure 1) (Wilson et al. 1998, Jordan 2000, Jordan et al. 2007). Shoreline and ice thickness data from the Alaska Peninsula (Mann and Peteet 1994, Jordan 2000) included in the regional postglacial rebound model of James (2001) support his findings of relatively low mantle viscosity and limited glacial-isostatic rebound values relative to those of previous global-scale models (cf. Peltier 1994). An important implication of James' work for the western Gulf of Alaska and the Sanak archipelago is that current-day vertical motions due to ice mass changes in the late Pleistocene are expected to be of the magnitude of ~1 mm or less per year (James 2001), suggesting that sea-level fluctuations recorded by late Holo-

cene terraces and beach ridges on Sanak are driven by nonisostatic processes (e.g., changing storm regimes, seismic events, tsunamis, eustatic sea level change). A well-developed shore platform cut in sedimentary bedrock deposits around the islands suggests vertical stability of the crust at time scales on the order of one to two millennia (Trenhaile 2002). Sand and gravel storm beach ridge sets have been deposited in bay heads on Sanak during the past 1,000 years, particularly in Sandy Bay (Figure 3), which was rapidly infilled with an extensive sandy beach ridge plain during that time. Historic records and field observations (Lander 1996, Fryer et al. 2004, Jordan et al. 2007) document the effect of tsunamis on Sanak; run-up heights exceeded 10 m during the 1788 and 1946 events, and although those events were locally catastrophic, the impact alongshore was constrained by the direction from which the tsunamis originated.

PALEOENVIRONMENT. Pollen stratigraphies were compiled from lake cores (Figure 3) and represent the vegetational history of Sanak Island as it evolved in response to climatic and environmental change since deglaciation. *Artemisia*, adapted to cool/dry conditions, was abundant during initial deglaciation. *Artemisia* was also abundant during the subsequent Younger Dryas. Cyperaceae, generally adapted to wetter climates, increased as *Artemisia* decreased. Ericaceae peaked between ~7,000 and 4,000 cal B.P., before the onset of neoglaciation. Sedges and grasses then dominated from 4,000 to 1,000 B.P., and Ericaceae decreased. Sedges declined after 1,000 B.P., and Ericaceae increased. The Sanak pollen data are in general agreement with sites on the peninsula (Table 1 and associated references) but extend the regional paleovegetation record by several millennia. Changes in pollen stratigraphy are regionally conspicuous during the Holocene, and suggest a shift at ~4500 BP from generally warmer (and drier) to cooler conditions in the eastern Aleutian Islands, the Shumagin Islands, and on the central Alaska Peninsula (Heusser et al. 1985). Localized dunes were active at that time based on the lack of stable surfaces in regional eolian deposits. After 3,200 B.P. vegetation changes indicate the

TABLE 1
Climatic Regime Shifts in the Western Gulf of Alaska and Sanak Archipelago

Period	Age Range	Approximate Climatic Conditions
Early Holocene	9,000–6,200 B.P.	Cool and dry
	6,200–4,500 B.P.	Warm and wet
Neoglacial	4,500–3,200 B.P.	Cool and wet
	3,200–2,100 B.P.	Cool and wet (increased storminess)
Pre-Medieval climatic anomaly	2,100–1,700 B.P.	Warmer
	1,700–1,100 B.P.	Cold
Medieval climatic anomaly	1,100–700 B.P.	Warmer and dry
Little Ice Age	700–100 B.P.	Cold and wet
Recent era	100 B.P.–Present day	Very warm

Note: Shading highlights periods recording important changes in air and sea-surface temperature, storminess, and enhanced ocean productivity reconstructed from various climatic proxies for the North Pacific and Gulf of Alaska (Huessler et al. 1985, Mason and Jordan 1993, Mann and Hamilton 1995, Calkin et al. 2001, Hu et al. 2001, Mann 2001, Finney et al. 2002, Jordan and Krumhardt 2003, D'Arrigo et al. 2005, Loso et al. 2006, Misarti 2007). There is a cool period at approximately 5,400 B.P. and a warm period between 3,000 and 2,600 B.P. that have been documented in multiple Arctic records. Neither of these is currently visible in our regional proxy data, but both are possibly present in our settlement and midden data.

onset of cooler and wetter conditions that initiated neoglacial advances on the peninsula and higher peaks of the Aleutians, and the regional stabilization of dunes. Modern coastal tundra developed after 1,000 B.P., broadly reflecting the influence of the region's maritime climate. Multiple tephra preserved in lake cores imply that vegetation on Sanak responded periodically to this disturbance mechanism (Heusser 1990), and organic carbon analysis of a peat core from Unimak Cove (Figures 3, 4) indicates cyclical interruption of marsh productivity during the past 5,500 years, which may relate to periods of storminess and the delivery of inorganic shoreline sediment onto the marsh.

Archaeological Research

The archaeology of Sanak Island was completely unknown before our first preliminary survey in 2002. Since that time, over 120 archaeological sites spanning nearly 6,000 years have been surveyed, mapped, and most have been tested (Figure 5). The goals of our archaeological research have been to create a local prehistory of the Sanak Islands that could be correlated with the better-known prehistory of the western Alaska Peninsula to investigate macroregional changes in social, economic, and political interactions;

identify regional changes in land use and site distributions; reconstruct the population history of the island based on measures of site size, density, and numbers of house depressions; sample middens for a fine-grained faunal record to be analyzed in the context of modern species distributions and in light of the paleoclimatic record; to use faunal data, and the isotopic analysis of those specimens, to track changes in the structure and functioning of the marine ecosystem; and to use the faunal data to reconstruct prehistoric food webs and to assess changes in the modern marine ecosystem. The first two of these goals are reviewed in this section, and the remaining goals are discussed in the following sections. This is considered a very preliminary assessment of the archaeological data in light of these project goals.

Critical to all of these analyses is that settlement archaeology is feasible in the region. House depressions are clearly visible on the surface, and most sites are single component, or if multicomponent, the components are spatially or stratigraphically distinct. This allows population reconstructions based on site size or surface depressions to be possible. It also contributes to our ability to distinguish spatial and temporal trends in the settlement system.

The archaeology of the western Alaska

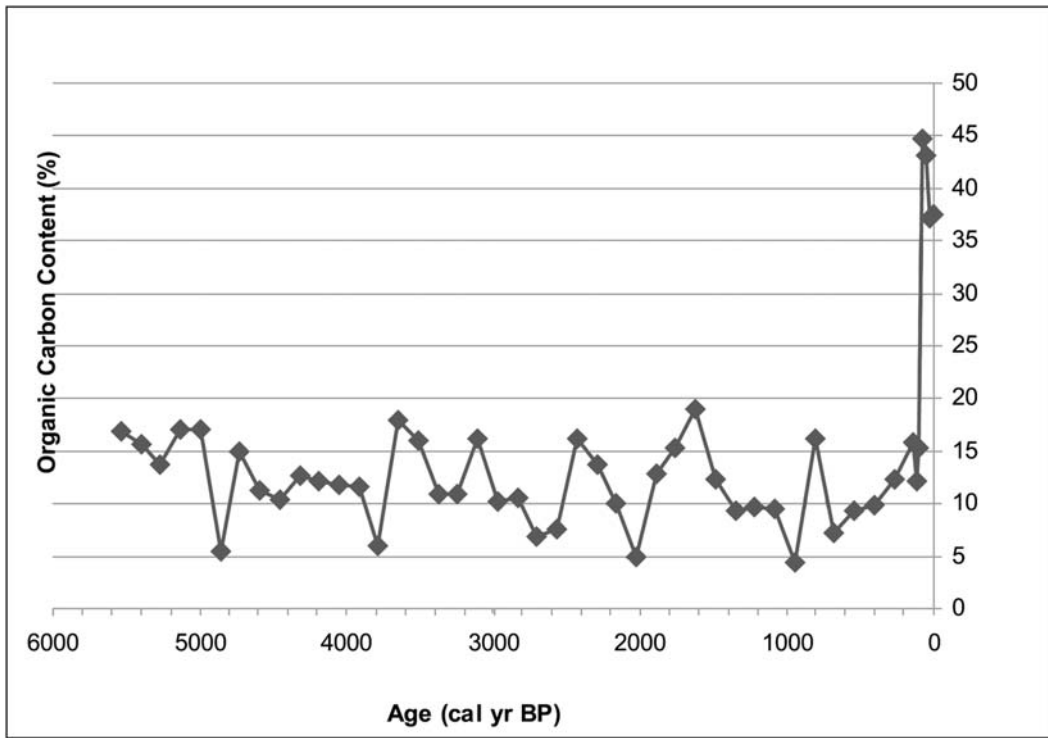


FIGURE 4. Total organic carbon (TOC) measurements for the Unimak Cove peat core. Low organic carbon is a proxy measure of increased storminess; higher TOC is a measure of calmer oceanic conditions.

Peninsula has been the focus of intensive research for nearly 15 years (Maschner 1998, 1999a,b, 2000, 2004a,b, 2008, Maschner and Reedy-Maschner 1998, 2005, Jordan 2000, 2001, Jordan and Maschner 2000, Maschner and Jordan 2001, 2008, Hoffman 2002, Maschner and Bentley 2003, Maschner and Hoffman 2003, Maschner et al. 2008, 2009). When these data are combined with previous studies from the region (Weyer 1930, Workman 1966, McCartney 1969, 1974, 1984, 1988, Okada 1980, Yesner 1985, Johnson 1988, 1992, Johnson and Winslow 1991, Holland 1992, Johnson and Wilmerding 2001), a rather complete regional overview is possible.

Extending from Unimak Pass in the west to the central Alaska Peninsula in the east is a region that shares a number of important historical trajectories in technology, house form, art, and other factors that permit its classification as an archaeological region—

one that shared some sort of social, political, and probably ethnic identity. Everything that we have discovered so far for Sanak Island falls squarely within our understanding of the prehistory of the western Gulf of Alaska region. Over 150 Accelerator Mass Spectrometry (AMS) dates on charcoal from house floors, shell middens, and other features demonstrate a continuous 6,000-year occupation of the island, matching our regional prehistory for the mainland to the north (Figure 6).

The earliest sites are small groups of house depressions with square stone slab box-hearths along one wall. These houses may have been covered with skins as opposed to more permanent structures. Artifacts include large laurel-leaf lance blades, cruciform-based bone and ivory harpoons, and a small number of microblades (Maschner 2008). There are few sites with faunal preservation

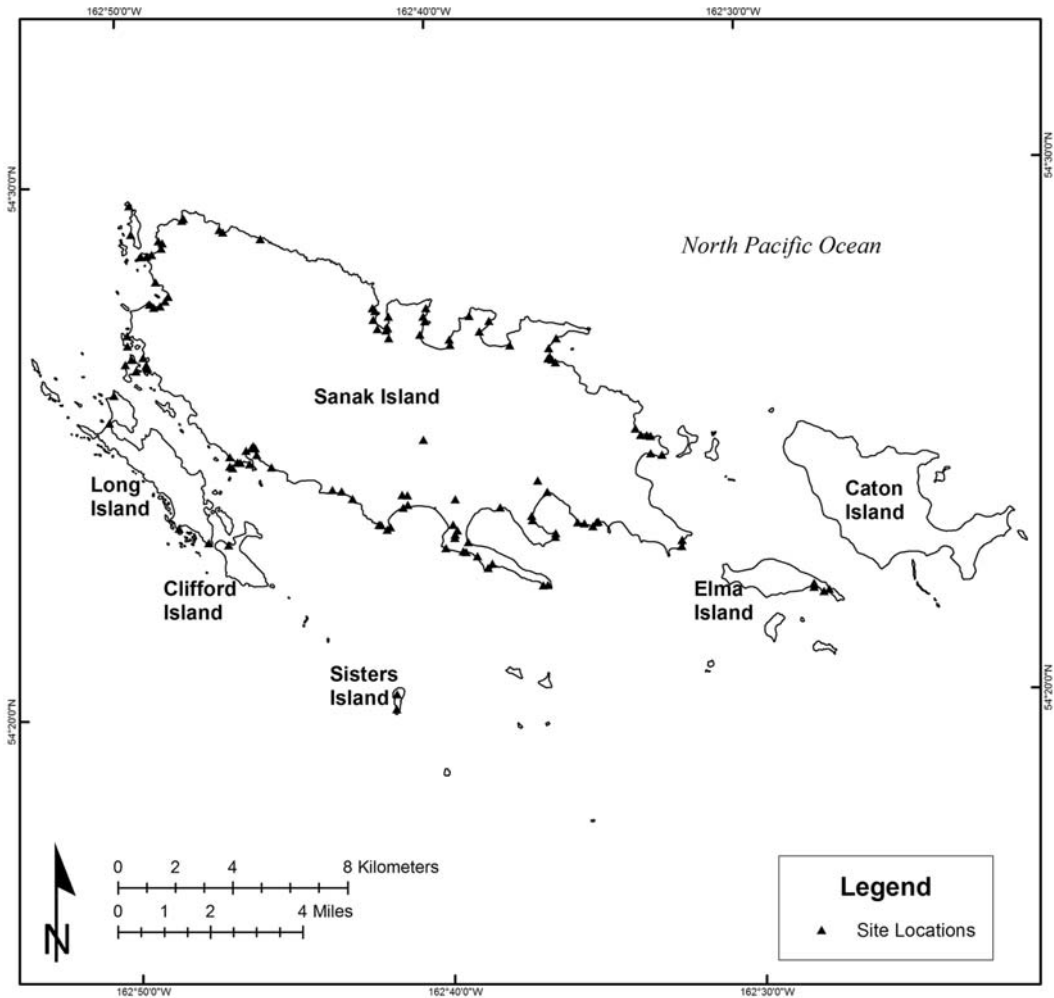


FIGURE 5. Map of the Sanak Islands showing archaeological sites in the project area.

between 6,000 and 4,000 years ago because there appears to have been little early emphasis on shellfish. The earliest preserved midden deposits are dated to approximately 4,500 B.P.

By 3,800 years ago, shell middens are found across the island, much like the mainland. Although there does not appear to be a greater number of sites, the economic focus has clearly shifted to a greater diversity of species. Shell middens again disappear after 3,300 years ago, only to become common after 2,600 years ago. In fact, there are regular

disruptions in the use of shellfish, and a plot of all dates on preserved middens demonstrates this clearly (Figure 7). Thus, although there appears to be a continuous occupation of the island based on Figure 6, the distribution of shell-based middens is discontinuous at best.

At approximately 2,400 B.P., on both the mainland and the islands, there is a period of village formation where much larger groups and larger households arise for a 400-year span. Although villages are smaller on the islands than on the mainland, the trend is

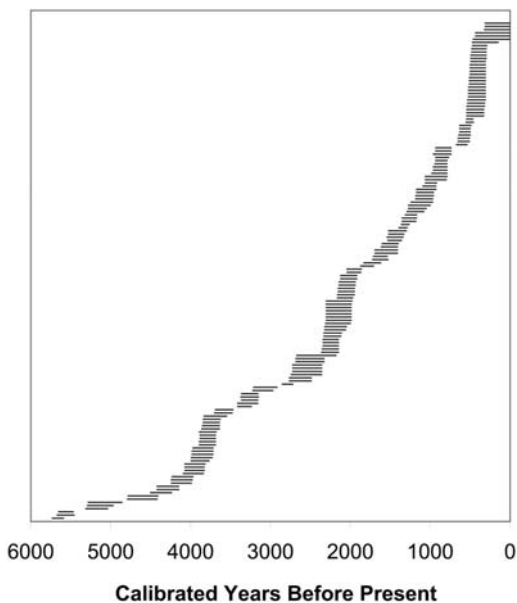


FIGURE 6. A temporal density plot of 2s ranges of all radiocarbon dates in the Sanak archipelago. All radiocarbon dates in the paper are presented as calibrated years before present.

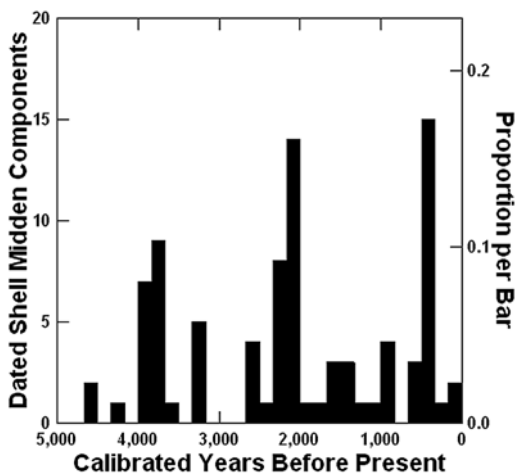


FIGURE 7. Histogram of mean calibrated dates of individual shell midden components in the Sanak archipelago.

large shell middens are rare. The years between 1,000 B.P. and 600 B.P. are tumultuous, with the rapid rise and fall of villages, a brief abandonment of the region, and the development of the historic house form (Maschner 1999a,b). About 400 years ago, the development of large, corporate multi-roomed houses is continuous across the entire region as is a massive population increase (Hoffman 2002, Maschner and Hoffman 2003). Currently, the analysis of the archaeological data is only in its infancy.

A brief summary of the regional climate history based on our data and a review of the literature shows a strong association between climate shifts and the distribution of shell middens in time (e.g., Table 1), especially in regard to storminess described earlier (Figure 4). It will become obvious in the next section that the demographic trends on the island partly mimic the distribution of shell middens as well and the preliminary climatic history presented here. One major disruption in the cultural sequence on the western Alaska Peninsula mainland is a disappearance of most villages and their populations during the Medieval climatic anomaly approximately 750 B.P. (Maschner et al. 2009). All indications are that Sanak Island went through a similar population decline. A full evaluation and analysis of these trends is in preparation.

Regionally, the artifacts and house styles, with a trend toward increasing technological complexity, increasing house size, and increasing village size, show the same patterns as those on the Alaska Peninsula (Maschner 1999a,b, Maschner and Bentley 2003, Maschner and Hoffman 2003), although the trends are not necessarily linear and our first impression is that the trends appear to be conditioned by marine productivity. Specific artifact types at key chronological transitions over the last 6,000 years point to regular contact between the Sanak archipelago and the western Alaska Peninsula, a connection that was observed among historic peoples by early explorers in the region as well. But these data also lead us to recognize, especially in harpoon and end blade types, that there were regional interactions spanning over 1,000 km of the North Pacific Ocean from Kodiak Island in the east to Umnak Island in the west.

much the same. On both Sanak Island and the Alaska Peninsula, the period between 1,900 and 1,000 B.P. is poorly known, and although there are a large number of sites,

A Population Prehistory of Sanak Island

Critical to our long-term understanding of the role of humans in the structure and functioning of the Sanak ecosystem, and, in turn, the role of that ecosystem in human adaptive capabilities is modeling the history of human populations on the island. One common method for estimating changes in human populations from archaeological data is to convert analyses of temporal frequency distributions of house or settlement size into estimates of human population (Hassan 1978, Chamberlain 2006). This method relies upon ethnographic parallels that allow past population densities to be estimated from modern or historical information concerning the relationship between house size and population density (Hassan 1981, Kolb 1985) or settlement size and population density (Wiessner 1974). An important assumption is that higher frequencies of dated sites represent higher population densities (Brantingham et al. 2004, Holdaway et al. 2005). Temporal frequency distributions, however, may be affected by taphonomic bias where the loss of data increases with time, which Surovell and Brantingham (2007) suggested may be largely responsible for the positive curvilinear frequency distributions often observed in archaeological, paleontological, and geological data. One potential improvement to population models based on temporal frequency distributions could be to focus on short-term variations, which presumably occur at different rates than either the time-dependent effects of taphonomic bias or the long-term trends in other factors that affect human populations, such as climate change. Surovell and Brantingham (2007) ended their paper with an intriguing aside concerning the possibility of extracting population trends from biased data by converting temporal frequency data into “dimensionless” ratios or proportions, such as the ratio of juvenile to adult humans, which should preserve information on demographic change despite the potential effects of taphonomic bias.

Another, largely ignored, problem with population estimates based on temporal frequency distribution models is the uncer-

tainty introduced by carbon dating. Modern techniques of carbon dating can produce very precise date estimates, but these estimates always come with an estimated error range. Usually, only the midpoint carbon date is used to place an archaeological sample into one time period or another. Given the fact that the estimated error associated with any given carbon date may well be plus or minus 100 years or so, it is possible to construct multiple estimates of population density, based on the estimated error of all the carbon dates. One method for dealing with this problem is to use the estimated error associated with each carbon date to define a possible window of occupation for each site based upon probabilistic resampling.

To estimate changes in human occupation on Sanak Island we developed a sophisticated model called “wigglesites” in R (version 2.4.1, R Core Development Team, 2006) to calculate a “human occupation index” (HOI) using temporal frequency data. The wigglesites model combines the idea that it should be possible to extract persistent short-term demographic trends from temporal frequency distributions despite potential taphonomic bias with the idea of a dimensionless index that can describe trends in human population over time without having to estimate precisely the magnitude of change.

The model uses probabilistic resampling to assign an “occupation window” from within the estimated carbon date range for each village. The size of the window determines the amount of overlap in time between sites, with a longer window resulting in more overlap and a greater smoothing of the index. In this case we used a window length of 100 years. Using a smaller window typically results in less smoothing but does not substantially change the shape of the resulting index.

After assigning an occupation window to each site the model calculates the total occupied village area active in each 10-year period. The model uses a conversion factor of one person per 100 m² of site area (from regional ethnographic data) to estimate population density from the occupied area. The model repeats the entire process 1,000 times and reports the results as 25th, 50th, and 75th quan-

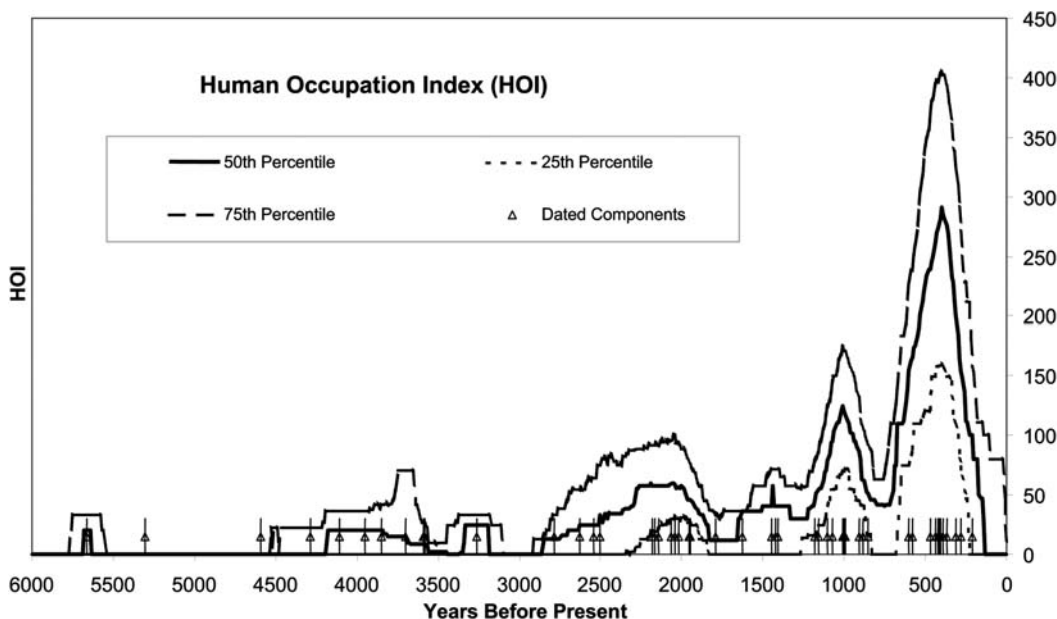


FIGURE 8. The Human Occupation Index (HOI). The HOI is a model of possible ranges of human population on Sanak Island based on site area and numbers of houses.

tiles. Because the goal of the model is to show how human occupation changes over time, the shape of the resulting index is more important than the absolute numbers derived from the index.

The HOI for Sanak Island shows three relatively well-defined periods of human population growth and decline (Figure 8). The first period is between approximately 3,000 and 1,800 B.P. with a peak around 2,000 B.P. The second period peaks at about 1,000 B.P., and the third period peaks at about 400 B.P. The 25th quantile shows that, given the possible range of carbon dates for all the sites, the population of Sanak could have been zero at some points during the timeline, such as between approximately 1,800 and 1,200 B.P. and even 1,100 to 700 B.P., but it also shows that using even the most conservative estimate of population still reveals the three distinct periods of population growth and decline.

One potential issue with the HOI is that it does not appear to accurately track the paucity of human occupation on both Sanak and

the lower Alaska Peninsula, ca. 1,000 B.P. and 700 B.P. (see later in this section). This is because there are several small sites on Sanak that all date to the period surrounding ca. 1,000 B.P., and the probabilistic model is unable to track the sudden and precipitous decline in sites directly after that time.

Like many temporal frequency distributions, the HOI does exhibit what appears to be an exponential increase over time, which may be due in part to taphonomic bias. However, although taphonomic bias might be partly responsible for the differences in peak population between the three periods noted earlier, bias cannot account for the general shape of the HOI. Instead, the results show that regardless of possible taphonomic bias, the Aleut population on Sanak Island probably experienced large fluctuations over time.

Given the HOI we can now ask questions that link changes in human population on Sanak with changes in ecology, climate, and culture. As discussed earlier, the distributions of sites, and the distributions of sites with middens, is at least partially correlated with

the occupation index. But this is not tautological. There are many sites, some quite large, that have no middens leading to large population estimates between the midden peaks described in the previous section. The implication is that although there is some relationship between population size and cooler climates, and a relationship between cooler climates and midden use, there is a large amount of variation that is not measured by a simple climate model.

Faunal Studies

The archaeofaunal remains described in the following analyses are derived from seven discrete archaeological contexts (many more are currently being analyzed) that form a time series spanning the period ca. 4,500 to 500 B.P. All were recovered from single stratigraphic units dated by multiple radiocarbon determinations on wood charcoal. These deposits were screened through 8 mm (1/4 inch) mesh, a sieve gauge we consider appropriate to the "specimen sizes" for the taxa under investigation (e.g., Cannon 1999).

To assess the changes in relative taxonomic abundance through time, we used the climatic model for the western Gulf of Alaska presented in Table 1. From a marine ecosystem perspective, these perturbations may be referred to as macrolevel regime shifts (Benson and Trites 2002, Polovina 2005, Finney et al. in press) and are used here to assess major shifts in the distributions of key resources and their harvests.

COD POPULATION HISTORIES. The middens on Sanak Island contain important information on the population histories of fish taxa. For example, fish bones are allometrically linked to animal size and weight, and therefore measurements from preserved fish bones can be utilized to reconstruct length frequency distributions for prehistoric fish populations (e.g., Wheeler and Jones 1989). The ability to do such analysis is critical because fish grow throughout their life span, and thus most life history traits in fish stocks are correlated with size (Reiss 1989). Size is therefore an important metric in modern fisheries management research (e.g., Shin

et al. 2005). As a result, allometric analysis can provide a crucial means to compare the preindustrial fisheries record with modern fisheries management data.

As outlined in Maschner et al. (2008) (see also Betts et al. in press a), we reconstructed a deep time series of Pacific cod (*Gadus macrocephalus*) length frequencies over our sequence and compared this with modern fisheries lengths taken from the Gulf of Alaska in 2005 (Thompson et al. 2006). Here we provide an overview of this analysis and provide an updated and in-depth discussion of relationships between changes in cod size and climatic shifts.

Measurements on the cod remains were derived from the length of the ascending process of premaxillas and the anterior-posterior length of the centra of abdominal (trunk) vertebrae. We estimated the size of each measured element using regression equations developed by Orchard (2001, 2003). Sample sizes for the Sanak assemblages ranged between a low of 10 to a high of 507 elements. The modern average length of Pacific cod was obtained from data obtained from longline surveys done by the Alaska Fisheries Science Center in the Gulf of Alaska in 2005 ($n = 3,308$) (Thompson et al. 2006). Although data from baited jigs (the fishing technique used by the prehistoric Aleut) were not available, modern longline-obtained cod are likely to be most comparable with fish taken by prehistoric jigging practices. The mean length recorded for the 2005 longline survey, which occurs as frequencies in size bins, was calculated using procedures in Gedamke and Hoenig (2006).

Figure 9 displays a time series of average Pacific cod lengths spanning the preindustrial (prehistoric) to recent period. To us, the graph indicates that: (1) preindustrial mean length varies in a cyclical fashion of increasing and then decreasing size, in apparent multacentennial cycles; and (2) the modern mean length of Pacific cod appears to fall within the range of precontact (prehistoric) variability. In fact, *t*-tests reveal that the modern mean is not significantly different from that of five of the precontact assemblages ($P < .01$).

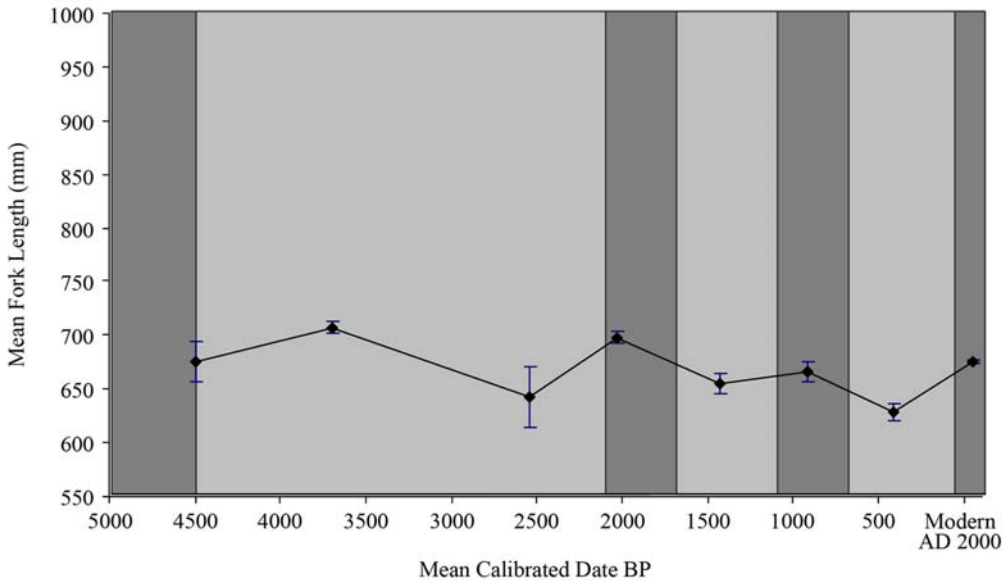


FIGURE 9. Gulf of Alaska reconstructed mean cod lengths with the modeled climatic reconstruction demonstrating that there is a relationship between climatic regimes and cod length, especially after 2,000 B.P. (adapted from Betts et al. in press a and Maschner et al. 2008). Light gray bars are cooler regimes; dark gray bars are warmer regimes.

This latter point is not an unexpected correlation; we know from modern management records that Gulf of Alaska cod populations are not overexploited (e.g., Thompson et al. 2006, 2007) and therefore should not exhibit a significant harvesting-mediated size reduction (for a discussion of the relationship between average size and exploitation pressure see Shin et al. [2005]). We have previously suggested (Maschner et al. 2008) that modern fisheries practices are largely maintaining the preindustrial population structure of Pacific cod, and, therefore, using sized-based indicators as a metric, modern cod harvest practices appear to be “sustainable.”

What is perhaps equally intriguing is the apparent oscillation in cod size over the last 4,500 years. When we compare this profile with our climatic model (light gray bars are cold regimes, dark gray bars are warmer regimes), we see a correlation (Figure 9). In general, the trends appear to suggest an increase in mean length with warm regimes and a decrease in mean length with cold regimes. We draw specific attention to the cor-

respondence between size and the Medieval climatic anomaly (1,000–700 B.P.) and Little Ice Age (700–100 B.P.), respectively the two climatic periods immediately preceding the modern era. Following these trends, it is tempting to speculate that the slight increase in cod length at the end of the sequence may in fact reflect a stock response to global warming, similar to the increase in mean size that occurred during the Medieval climatic anomaly. The implications of this correlation are unclear, but we propose that global warming may be a complicating factor in the recent population histories of Pacific cod.

OTARIIDS, CLIMATE, AND HUMAN INTERACTIONS. We assess the relationship between Steller sea lions (*Eumetopias jubatus*) and humans by tracking the relative frequencies of otariid bones in middens and comparing shifts in the resulting profiles. We measure shifts in the frequency of Steller sea lions over the sequence by means of several abundance indices, a procedure that we note is necessary to control for potential perturbations in the frequency of the com-

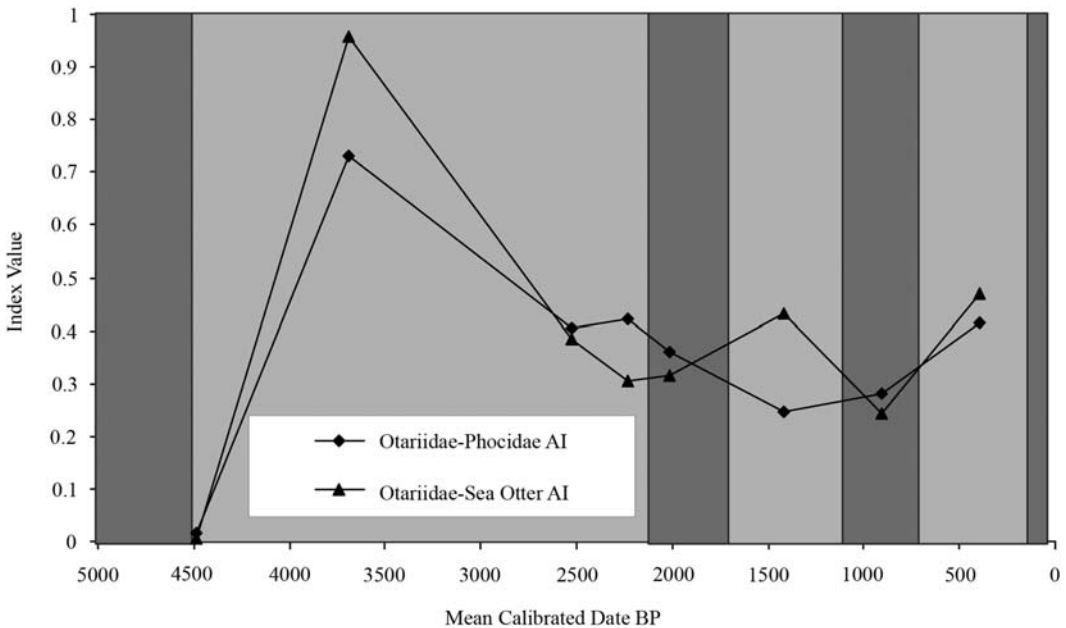


FIGURE 10. Otariid abundance indices (AI, Index Value on chart) as compared with climatic model. Cooler regimes (light gray bars) appear to positively influence otariid abundance (from Betts et al. in press b, Lech et al. in press; H.D.G.M., A. W. Trites, K.L.R.-M., M.W.B., A.T., and M. Livingston, unpubl. data). Dark gray bars are warmer regimes.

parison taxa and thus eliminate the issue of “closed arrays” (e.g., Betts and Friesen 2006; see Lyman [2008] for discussion about closed arrays).

An abundance index (AI) represents a normed ratio of a highly ranked taxon (A), in terms of body size, to a lower-ranked taxon (B), measured as $AI = A/A + B$. Decreasing index values imply a decline in the abundance of a taxon, and higher values indicate an increase in abundance. Because the measures incorporate caloric relationships based on body size (i.e., larger-bodied animals have a higher caloric return), shifts in the index can reflect changes in return/encounter rate and thus foraging efficiency (e.g., Hildebrandt and Jones 1992, Broughton 1994, 1997, 1999, Janetski 1997, Butler 2000, Cannon 2000, Grayson 2001; for discussion see Lyman [2003], Betts and Friesen [2006]). As a result, when judiciously calculated, AIs can be used to track the occurrence of resource depressions, defined as a reduction in return/

encounter rate caused by availability of prey (e.g., Charnov et al. 1976, Stephens and Krebs 1986).

In Figure 10, we assess changes in two otariid abundance indices against changes in climate. Here the dark boxes represent warmer and less-productive climatic regimes, and the lighter boxes indicate cooler and stormier periods (from Table 1). A relatively clear correlation occurs between the climatic model and the post-Neoglacial sequence after ca. 2,100 B.P. Specifically, we note an increase in the otariid abundance index during a cold period from ca. 1,700 to 1,100 B.P., a decline in otariid abundance during the Medieval climatic anomaly ca. 1,100–700 B.P., and an increase in otariid abundance during the Little Ice Age ca. 700 to 100 B.P.

We interpret this correspondence as otariid populations responding to climate and marine productivity shifts. In fact, the graph suggests that during times of warmer and less-productive climatic regimes, otariids

experienced a form of resource depression, likely a classic ecological depression (e.g., Charnov *et al.* 1976). In general the two AIs correspond well, although the otariid–sea otter AI appears to correspond more favorably with the climatic model (Table 1), especially after the post-Neoglacial period ca. 2,100 B.P. Specifically, the otariid–sea otter AI indicates an increase in the otariid abundance during a cold period from ca. 1,700 to 1,100 B.P., a decline in otariid abundance during the Medieval climatic anomaly ca. 1,100–700 B.P., and an increase in otariid abundance during the Little Ice Age ca. 700 to 100 B.P. The discordance between the two AIs, ca. 2,300 B.P. and 1,500 B.P., is explored in a detailed manner in Betts *et al.* (in press b); however it is believed that the discordance is the result of disproportionate decreases and increases in phocid seals during those periods relative to other taxa. Given the close relationship of phocid seals to ice platform, it may be noteworthy that the decrease in phocid seals ca. 2,300 B.P. (resulting in a slight increase in the otariid-phocid AI) was associated with stormier environments, and the potential increase in phocid seals (resulting in a decrease in the otariid-phocid AI) was associated with very cold environments (see Table 1). It may be that the otariid–sea otter index more closely tracks the natural abundance of otariids, especially as this relates to climatic shifts (see Betts *et al.* in press b for discussion).

Using the human occupation index described in Figure 8, the archaeological record indicates that human populations were relatively stable during the Neoglacial but began to rise steadily, and at a relatively predictable rate for hunter-gatherers, during the pre-Medieval climatic anomaly ca. 2,100–1,100 B.P. During the Medieval climatic anomaly, populations declined sharply. This was followed by a notable increase in population during the Little Ice Age.

Comparing our schematic population curve (derived from Figure 8) against otariid abundance indicates interesting correlations between otariid and human populations (Figure 11). The trend during the Neoglacial is again murky, but post-Neoglacial there is a

positive correspondence between the number of humans and the number of otariids. To us, this suggests two things. First, it appears that humans were not overexploiting sea lions in the past, at least on Sanak Island. If they were, declines in otariids should be associated with an increase in the number of predators (humans), the hallmark of a classic exploitation depression (Charnov *et al.* 1976). The exact opposite is evident here. The second implication of this relationship is that humans and sea lion populations appear to respond to climate changes in exactly the same fashion, at least post-Neoglacial. This strongly implies that changes in climate and oceanic productivity were an important force in the population histories of large-bodied, top-tiered predators, which includes both humans and sea lions.

Stable Isotopes of C and N and Changing Pacific Regimes

Stable isotopes have been used in ecological and archaeological studies to trace diet and geographic location for the past few decades. In this study, we integrated both paleoecological studies and archaeological studies to determine changes through time in marine ecosystems utilized by the Aleut for the last 4,500 years. Stable isotope signatures are preserved in many different types of tissue, including bone collagen, and bone is often well preserved in shell middens in coastal Alaska. Bone is also particularly well suited to studies that span hundreds or thousands of years because it has a slower turnover rate than organs, blood, and muscle tissue and therefore reflects a longer period in an organism's life (Ambrose and Norr 1993, Lambert and Grupe 1993). This allowed us to compare an organism's overall trophic levels without concerns about seasonal or short-term foraging area changes. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are used in trophic level and dietary reconstructions, and in theory, if changes are discerned in either isotope, they can be linked to changes in foraging habits (Post 2002). Samples of Pacific cod, sockeye salmon, harbor seal, northern fur seal, sea otter, and Steller sea lion were collected from archaeological middens span-

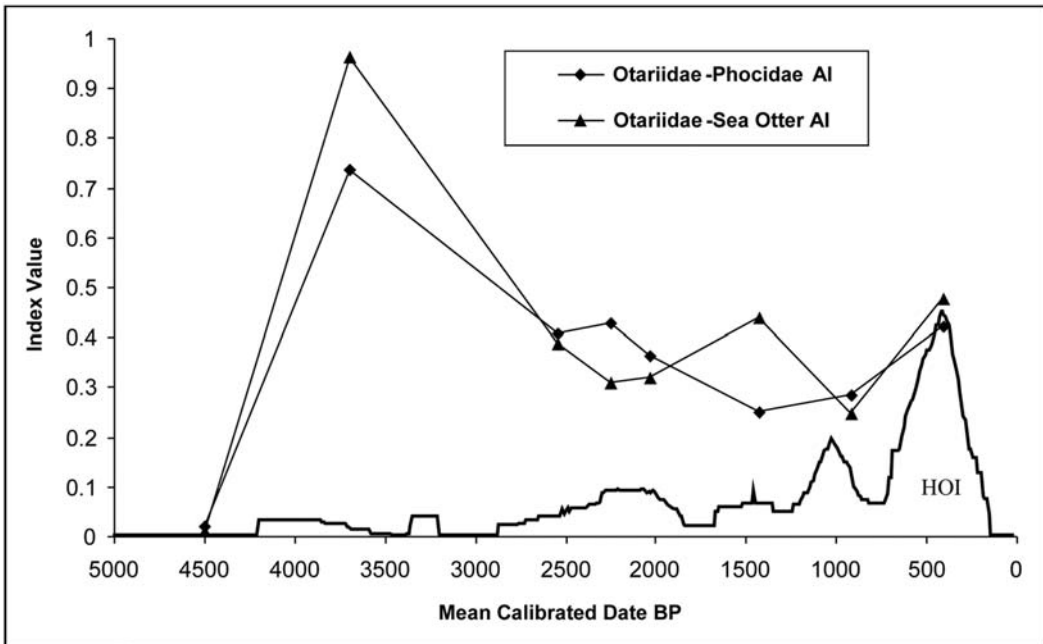


FIGURE 11. Otariid abundance indices (AI, Index Value on chart) compared with the relative human occupation index (HOI) from Figure 8 (without scale). Although there are many more sites included in the HOI than in the faunal data, patterns do emerge. The increase in the otariid AI during the Little Ice Age, the decrease during the Medieval climatic anomaly, and the higher AI value during the general population increase between 1,700 and 1,100 B.P. (another cool period) track closely, indicating some relationship between otariid abundance, human populations, and climate after 2,000 B.P. (see also Betts et al. in press b). Before 2,000 B.P., there is no obvious relationship.

ning the last 4,500 years on Sanak Island. Bone collagen was extracted from 250 individuals from all six species and analyzed for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$.

In general, mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of all six species from 4,500 to 200 cal years B.P. maintain expected trophic positions when compared with modern prey species (Figure 12). Three species, salmon, cod, and sea otter, were compared within six archaeological time periods. There are significant changes in isotope concentrations within that time frame for salmon and sea otter but not for Pacific cod. Sea otters had a significant difference in $\delta^{13}\text{C}$ (single-factor ANOVA, $F = 3.644$, $df = 120$, $P = .07$) and in $\delta^{15}\text{N}$ (single-factor ANOVA, $F = 3.767$, $df = 120$, $P = .003$), and changes in $\delta^{13}\text{C}$ of salmon were significant (single-factor ANOVA, $F = 3.012$, $df = 32$, $P = .028$), but no changes were found in $\delta^{15}\text{N}$ of salmon (Mis-

arti 2007; Misarti et al. in press). $\delta^{15}\text{N}$ is utilized as a marker for trophic position, and $\delta^{13}\text{C}$ is more often linked to the type of plant at the base of a food web, geographic location of an organism, and productivity levels (Fry and Sherr 1984, Schoeninger and DeNiro 1984, Michener and Schell 1994, Doucett et al. 1996, Hobson et al. 1996, Hirons et al. 2001, Schell 2001, Post 2002, McCroy et al. 2004). These data suggest that otters, with changes in both carbon and nitrogen isotopes, may have been feeding at slightly different trophic levels through time. For example, sea urchins, a favored prey item, are secondary producers in a kelp forest ecosystem while pelagic fish, also otter prey species, are not only in higher trophic positions but also have phytoplankton as the base of their food web (Estes and Duggins 1995, Watt et al. 2000, Steneck et al. 2002, Estes et al. 2003, Bodkin et al. 2004, Reisewitz et al. 2006). The

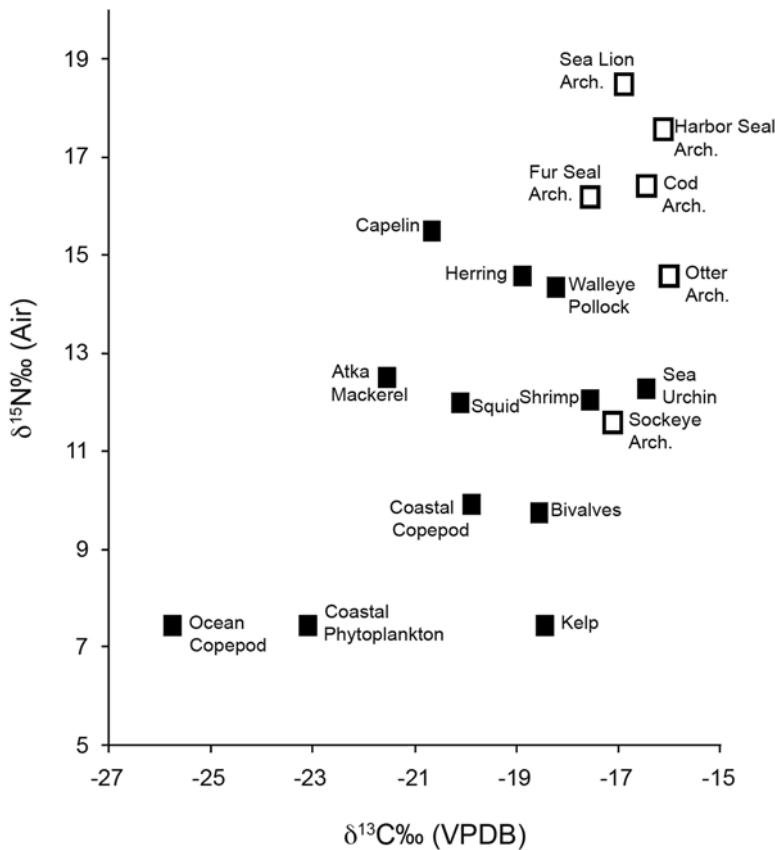


FIGURE 12. Trophic position of archaeological mammals and fish with some selected modern prey species. All samples corrected for fractionation from muscle tissue to bone collagen. Prey data compiled from Schoeninger and DeNiro (1984), Duggins et al. (1989), Boutton (1991), Hobson and Welch (1992), Hobson et al. (1997), Satterfield (2000), Hirons (2001), Kline and Willette (2002). Archaeological data from Misarti (2007).

changes in sea otter carbon and nitrogen isotopes may be explained by a change in percentage of diet represented by each of these prey items. Only $\delta^{13}\text{C}$ changed in salmon over time, suggesting that there was a change in productivity throughout the Gulf of Alaska or a change in geographic area inhabited by the fish but not a change in trophic position of salmon. The lack of change in either $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ of cod in the archaeological record is interesting. Studies over the past 50 years have noted a change in diet for Pacific cod during regime shifts in the northeastern Pacific, but no change in foraging location

has been recorded (Albers and Anderson 1985, Yang 2004, Ciannelli and Bailey 2005). If all prey items, even though changing throughout time, held the same trophic positions and were in the same foraging areas, then there would be no discernable change in either $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$.

The Intertidal Landscape

The intertidal habitats of the Sanak archipelago provide a wealth of human resources that were a key source of food for residents during times of low oceanic productivity or

decreased offshore access such as storms. Primarily these intertidal regions are rocky benches and cobble beaches, with occasional sand or pebble shores. Food resources of the intertidal areas are relatively plentiful, quickly renewed, and predictable; all ethnographic and archaeological sources agree that there is thus little doubt that the intertidal has been critical to the history of this region. The preserved middens, described earlier, provide information on the structure of the prehistoric intertidal.

Results from experimental collections on Sanak indicate that an hour of collection of contemporary intertidal resources (i.e., shellfish) provides up to 23 kg of meat mass (an average of 4 kg and a median of 316 g across all shellfish taxa collected). Given such contemporary resource abundance it would be feasible to meet a reasonable daily protein requirement for humans (e.g., 40 g/day [Erlandson 1988]), especially in concert with a readily accessible source of carbohydrate (e.g., seeds or bulbs from terrestrial plants; or even marine algae, which contain roughly 3 kcal per gram of dry mass [Paine 1971]). Some of these resources are quickly gathered in large volume (e.g., littorine snails, marine algae); others (e.g., sea urchins) are slower to harvest but may provide a substantial food value in a reasonable amount of time (i.e., 1 hr of harvesting time could provide well in excess of one individual's requirements). Thus, similar to elsewhere in Alaska (e.g., Erlandson 1988), contemporary intertidal communities could provide substantial resources for human populations on Sanak Island. So, do we see evidence that Sanak Islanders relied upon the intertidal for such resources, and is there evidence that these intertidal communities have changed through time—whether an artifact of human behavior or otherwise?

Using archaeological and contemporary biological surveys, we now explore whether there have been shifts in the composition of intertidal communities around the island over the last 5,000 years. Our contemporary surveys involve exhaustive vertical transects (sampled using 0.25 m² quadrats in which all macroscopic organisms were recorded) providing a robust sample of the intertidal

biological communities around Sanak Island. For comparison between ancient and modern data we use whole-organism biomass, calculated from samples of modern abundance and ancient shell mass (using experimentally derived regressions to back-calculate animal biomass from shell mass), as our response. There are clear differences in the biomass composition of modern intertidal community assemblages and ancient shellfish middens on the island (Figure 13). This pattern is driven primarily by differences in abundances of chitons, snails, and mussels. These three taxa account for 66% of the dissimilarity between modern and ancient assemblages in a similarity percentage (SIMPER) analysis (Clarke 1993), which quantifies species' contributions to sample dissimilarity (further results not presented). Snails and mussels are more abundant in the ancient midden records, but chitons are more characteristic of the modern intertidal assemblages. What is driving these differences? We ought to be able to explain the differences between modern and ancient assemblages by shifts in either (1) intertidal habitat types (e.g., from rocky to sandy); (2) preferences of harvesters; or (3) productivity, climate, or weather that alter ecosystems or the accessibility of certain habitats. Here we explore the first two drivers of change and draw attention to earlier sections of this paper for discussion of the climatic changes on the island.

First, there is no evidence of shifts in the proportions of rocky versus sedimented shoreline habitat. The midden remains are dominated by rocky shore species, with no evidence of sandy shore taxa dominating the assemblage, throughout the course of available data. A substantial shift in shoreline habitat types would be expected to be evident in the relatively continuous midden record available here; thus we conclude that it is unlikely that there have been large-scale shifts of the fundamental habitat types around the island over the last 5,000 years (see similar analyses with opposite results in Graham et al. [2003] or Masters and Gallegos [1997]).

To assess the harvesting preferences for particular taxa, we quantified return on collection effort using empirical data from Sanak

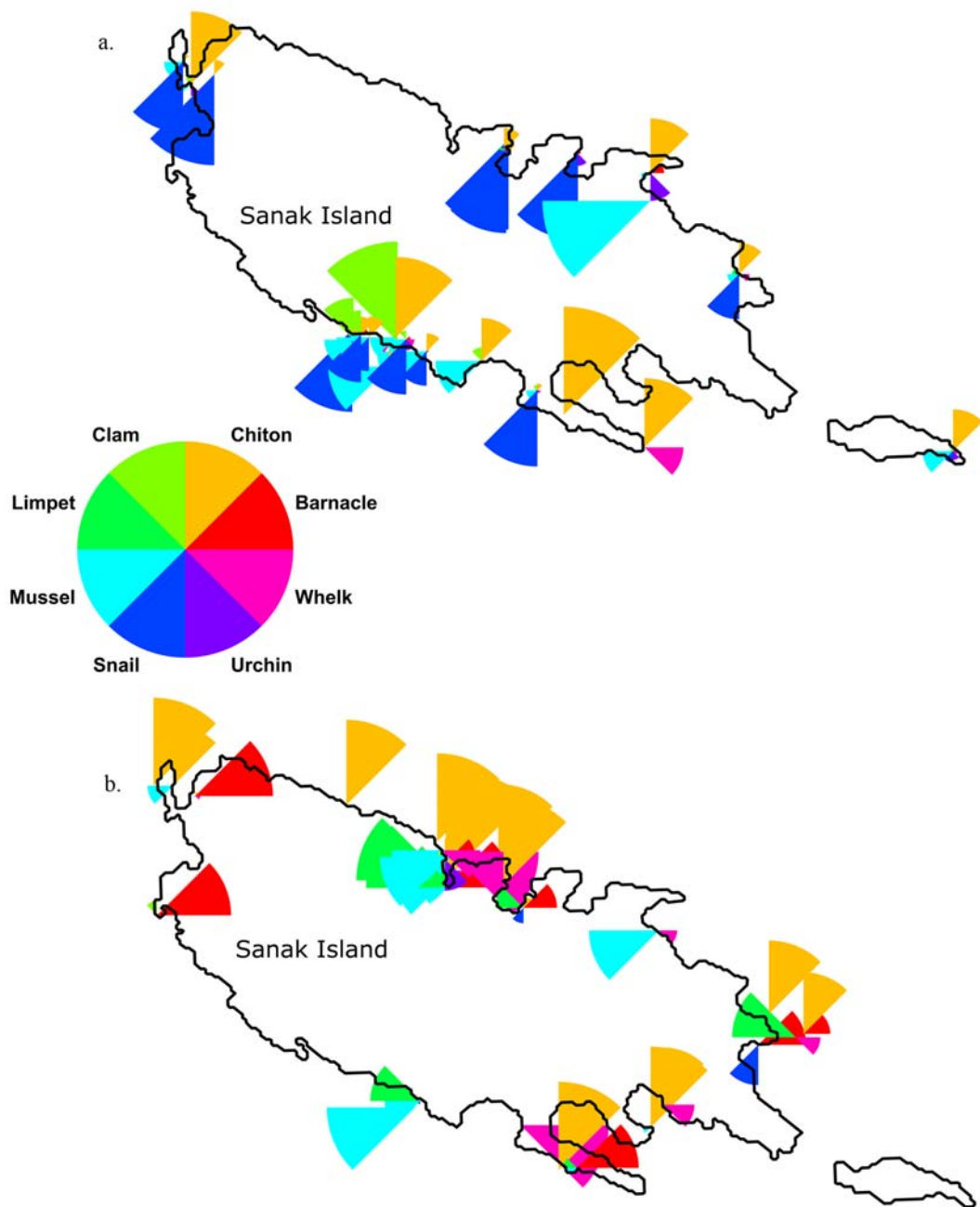


FIGURE 13. Comparison of ancient midden (*a*) and modern intertidal (*b*) abundances of major taxa around Sanak Island. The length of each wedge represents the relative abundance of the taxon in the sample unit (a vertical transect survey of the modern assemblage and one midden sample of the ancient assemblage).

Island. Total meat weight collected over time (taxon-specific timed collections by knowledgeable individuals repeated at different locations at appropriately low tide levels) is normalized by modern abundance (from surveys mentioned earlier) for each group of taxa to estimate a standardized return on collecting. The results indicate that three taxa are expected to be preferred: snails, mussels, and chitons. This helps explain the abundance of snails in the middens relative to the modern shores; snails provide more meat for a given time spent collecting. Further, littorinid snails are often found in massive aggregations and occur on wave-sheltered high intertidal shorelines that are accessible much of the year. It is interesting that although chitons are a rewarding and thus likely a preferred shellfish, they are less abundant throughout the midden record. If the midden record reflects the natural abundance of chitons, this result indicates that rocky intertidal communities on the island may have varied over the course of settlement history.

The intertidal record for Sanak Island indicates that: (1) humans relied heavily upon the intertidal for food resource needs (based on the rich and extensive midden record on the island); (2) the intertidal communities could nutritionally support substantial human populations on the island (based on reconstructions of prehistoric biological communities); and (3) although the modern communities appear different from ancient midden assemblages, there is little evidence for clear temporal trends in the harvesting of intertidal communities over the course of the 5,000-year midden record on Sanak Island (data forthcoming). This implies that the structure and dynamics of the intertidal ecosystem has likely had a strong influence on human history on Sanak Island, yet human history does not appear to have had a powerful influence on the intertidal system.

Role of Humans in the Intertidal Food Web

Through a combination of field observations of the current intertidal communities of Sanak Island, additional trophic (feeding) information culled from the literature, detailed

zoarchaeology of Sanak Island middens, ethnographic data, and interviews with modern Aleuts in the region, a detailed picture of the Sanak Island intertidal food web, and the position of humans in it, begins to emerge (Figure 14). Initial results reveal a species-rich and complex food web with 725 feeding links among 164 taxa represented, making this the most diverse intertidal food web ever compiled and one of the few food webs to explicitly include humans as a node (see also Link 2002).

The Sanak Island intertidal food web is a cumulative community food web—it represents the feeding relationships among co-occurring taxa that live or feed in the intertidal, as integrated over space (multiple Sanak intertidal sites) and time (the last 5,000 years). For initial analyses of the network structure of trophic interactions among species that live or feed in the Sanak intertidal system, we assume that the composition of the Sanak Island intertidal communities has not changed dramatically over the last few thousand years in terms of what species are present. For example, all intertidal species collected in the middens are also present in the current intertidal community. Although abundances of those and the other species clearly change through time, abundance data are not necessary to analyze basic properties of food-web structure. This initial version of the web is incomplete because it still lacks some of the terrestrial taxa, particularly birds, that feed in the intertidal, and inasmuch as no food web can ever be entirely complete because there are always species and links that remain unidentified. However, it does give a useful first look at the structure of the food web and how the Aleut fit into it.

On average, each species in this initial version of the Sanak intertidal food web has 4.4 trophic links to other species (i.e., links per species, or $L/S = 4.4$) through links to resource (prey) species plus those from consumer (predator) species. The connectance (C) of the food web, which describes the proportion of possible links among all species that actually occur, usually calculated as links per species² (L/S^2), is 0.027, or 2.7%. This falls at the low end of the range observed for

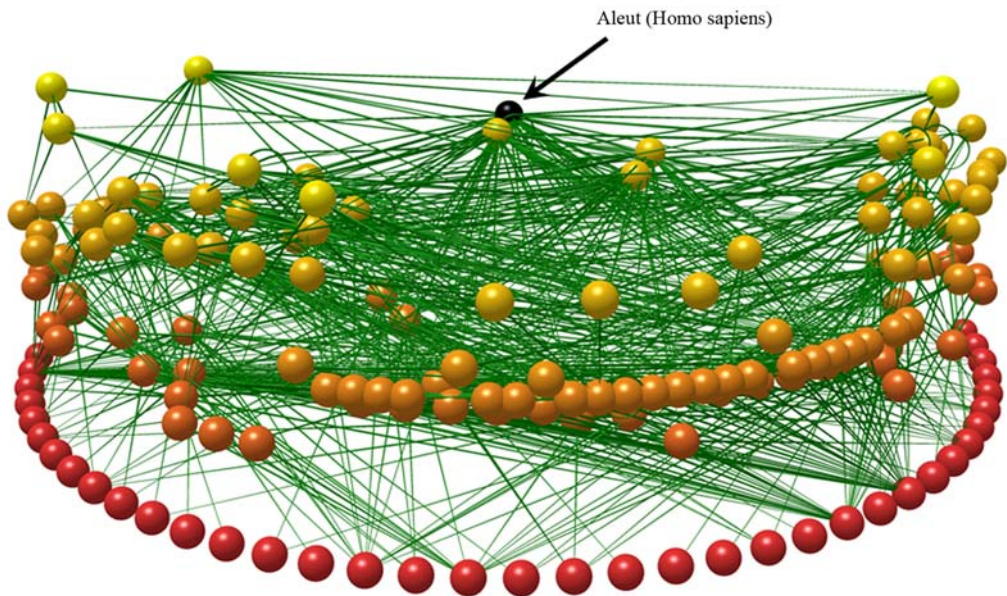


FIGURE 14. Sanak Island intertidal food web. Spheres represent 164 taxa and links represent 725 feeding interactions. Basal taxa (autotrophs such as algae as well as detrital categories) are shown at the bottom, with the highest trophic level taxa shown at top. Aleut are indicated by the labeled black sphere and are located in the background due to their high number of links (40) to resource taxa. Image produced with FoodWeb 3D, www.Foodwebs.org.

other food webs of $\sim 2\%$ to 30% (Dunne et al. 2004). The mean trophic level of the species in the food web is 2.2. Trophic level represents how many steps energy must take to get from an energy source to a species. By convention, primary producers are assigned a trophic level of 1, and obligate herbivores have a trophic level of 2. Trophic level can be calculated in a variety of ways; here we use the short weighted trophic level algorithm (Williams and Martinez 2004b). On average, the shortest chain of feeding links connecting each pair of species is 2.6 links long. This “path length” gives an indication of how quickly trophic effects can spread through a food web, with 2.6 indicating a longer mean path, and thus longer potential propagation time, than seen in most other webs (Williams et al. 2002). Twenty-three percent of the taxa in the web are basal (i.e., autotrophs or detrital categories), including a diverse set of algae taxa, 65% are invertebrates, 9% are fishes, and 3% are mammals

(including humans). There is excellent resolution of basal and invertebrate taxa, unlike most published marine and estuary food web data sets (Dunne et al. 2004). In terms of trophic roles, 14% of the taxa are herbivores or detritivores, 6% are cannibals, and 56% are omnivores (i.e., feed on taxa at more than one trophic level). The harbor seal (*Phoca vitulina*) has the highest trophic level (3.7), and the most common resource is detritus, which is consumed by 60 taxa.

Until they left the island in the late 1970s, humans played important roles in the Sanak intertidal food web. They fed directly on 40 taxa, making them the most general consumer of intertidal taxa, with the next most general species, a sea star (*Pycnopodia helianthoides*), consuming 35 taxa. They were strong omnivores, feeding on everything from algae to a variety of invertebrates to the highest trophic level taxon, the harbor seal, making their own trophic level intermediate at 2.9. In addition to the 40 taxa humans fed on

directly, 92 additional taxa occurred within human-topped food chains, with only 31 taxa (only one basal species) having no direct or indirect trophic linkages to humans. Thus, humans played unique roles in the Sanak Island intertidal food web through their extreme generality and omnivory, and there was a large potential for humans to affect the intertidal ecosystem directly and indirectly through hunting and gathering, as well as through mechanisms such as food storage, technology, planning, and prey switching.

Future work will include analyses of the topological roles of humans in the other major habitat types of Sanak Island (i.e., terrestrial, freshwater, marine) and comparisons of the structure of those habitat-specific webs with each other, with the larger metaweb encompassing all four habitats, and with other food webs (Dunne et al. 2008). Early-stage research is making use of the initial intertidal topological analyses to create scenarios for modeling the dynamics of complex ecological trophic networks (Brose et al. 2006) to explore how humans' roles and capabilities tended to promote or inhibit species and community persistence and other measures of ecosystem stability in this type of pre-industrial coupled human-natural system.

DISCUSSION AND CONCLUSIONS

The late Holocene paleoecology of the western Gulf of Alaska, and the Sanak Island region in particular, has shown considerable variation in general climate regimes, particularly in regard to the Pacific Decadal Oscillation (PDO). Trites et al. (2007) have shown, as have Finney et al. (in press), Misarti (2007), and others, that these changing climatic regimes alter regional marine productivity in a number of complex ways and that basic marine productivity is key to understanding the population histories of most higher mammals (including humans) and other species (Maschner et al. 2009).

We suspect that the human occupation index, which is identical to population trends in the greater Alaska Peninsula region (Maschner et al. 2009), highly similar to those in the entire North Pacific (Maschner 1997, Ames

and Maschner 1999, Fitzhugh 2003), and parallel with new data from the South Pacific (Nunn 2007), is directly a product of rapid and rather radical regime shifts affecting primary productivity. This appears to be especially true of the higher trophic levels, affecting human and sea mammal populations directly, and is even perceptible in the shifts in the size of Pacific cod (e.g., Maschner et al. 2008).

In historic times this does not appear to have had the same impact. The ethnohistoric data imply that Sanak Island populations were not so constrained or influenced by marine productivity but rather by the mitigating effects of global economic and political regimes. But marine productivity does appear to influence which economic forces have precedence at any one time. For example, the collapse of the nineteenth-century sea otter stocks, as well as the decline in the Atlantic cod fishery (both human caused), certainly led to the success of the early twentieth-century cod fishery in the North Pacific. But the collapse of the North Pacific cod fishery in the late 1930s, leading to cattle and other economic diversification on Sanak, and cod's resurgence in the mid-1970s as a dominant fishery appears to have been driven by oceanic regime shifts (Maschner et al. 2008; Reedy-Maschner et al. unpubl. field notes).

It should be recognizable that there is some correlation between the human occupation index (Figure 8), the distribution of sites with preserved shell middens (Figure 7), and the total organic carbon data (Figure 4). Foraging models would predict that higher populations would result in an expansion of the subsistence base, requiring an increase in the use of lower-ranked, small-package foods, such as shellfish. The correlation between the HOI and the distribution of middens implies this to be true. But the periods with the greatest numbers of middens occur during cooler oceanic regimes, the periods with the highest marine productivity. The total organic carbon (TOC) data provide a key to this discrepancy. Decreasing TOC in nearshore cores is likely a product of increasing storminess. Storms are the only condition that keeps traditional hunters and fishermen from going

offshore. So although marine productivity is up during cooler periods, increasing storminess results in fewer days out hunting and fishing, requiring the use of lower-ranked species during storm periods. Conversely, this implies that during warmer, less-stormy periods, the decreased marine productivity provided sufficient resources, except in the worst of climatic regime shifts.

Elsewhere, we have argued (Maschner et al. 2009; H.D.G.M., A.W.T., K.L.R.-M., M.W.B., A.T., and M.L., unpubl. data) that one of the key factors in Aleut interactions with sea mammals was their constant need for Steller sea lion skins, the only viable covering for ocean-going kayaks. We wonder if the close relationship over the last 1,500 years between the human population index and the otariid AI is not simply a product of the fact that Aleut males had to harvest up to six Steller sea lions every year to cover their kayaks, meaning that the actual sea lion harvest is not dictated by diet but by the number of Aleut males owning kayaks.

Likewise, it is possible that the changes in the archaeological record of otter nitrogen and carbon stable isotopes are driven by Aleut harvesting practices (Misarti 2007). Sea otters are a more-localized, nearshore species, and hunting may have changed population structure over time. If population size affects the availability of otter prey then the Aleut may have inadvertently affected what food items were available to otters depending on how heavily otters were hunted at any one time. Salmon on the other hand, although heavily harvested along the Alaska Peninsula, seem to have been more affected by marine productivity and climate regimes. Perhaps salmon were less impacted prehistorically by numbers harvested by the Aleut and more by changes to the marine ecosystems out in the deep ocean.

The archaeological data concerning Pacific cod allow us to draw two critical conclusions. The first is that minor variations in the population structure and size structure of Pacific cod appear to be driven by overall marine productivity, as measured in changing climatic regimes. The lack of change over 4,500 years in the stable isotope data for cod

is another line of evidence that leads us to the same conclusion. But more important, the size structure of modern populations does not appear to have been affected by modern commercial fishing, a strong case for the sustainability for that species and fishery (e.g., Maschner et al. 2008), a situation unlike the history of the North Atlantic (Betts et al. in press a).

In nearshore areas, it appears that humans harvested large quantities of shellfish during particular time periods, especially 3,600, 2,200, and 400 years ago, and that these shellfish were important contributions to the diet. Our first attempts to place the local and prehistoric peoples in the structure of a dynamic food web show that humans have complex interactions at multiple levels. Harvesting over 40 taxa of intertidal species, the ancient Aleut are the most connected species in the intertidal food web. This means that removing the Aleut from the food web, as occurred both in the 1820s and then again in the 1970s, probably had measurable organizing effects on the structure of the intertidal system.

It is also clear from the species harvested (M.W.B. and H.D.G.M., unpubl. data) that humans did have local impacts on the structure of the intertidal zone, harvesting lower-ranked species as the intertidal zone was increasingly exploited. On the other hand, there were periods when, despite large human populations, shellfish were rarely harvested or not harvested at all. But it is important to note that although the modern intertidal zone is different from the intertidal regimes harvested by the prehistoric Aleut between 5,000 and 400 years ago, the modern regime does not appear to be a product of human activities but rather may be more closely caused by changing oceanic conditions.

These observations are at best preliminary. We are just now to the stage in the investigations that more complex modeling efforts will be possible and we may with confidence begin addressing in detail the hypotheses put forward at the beginning of this paper. But one observation is clear—modern 25- to 50-year fisheries and climate data sets for the North Pacific region represent little of the

dramatic shifts in climate, productivity, and human feedbacks that have occurred over the last 5,000 years. Although there is some evidence forthcoming that humans have had long-term impacts on the structure of the intertidal zone, or even on offshore fisheries, what is clear is that much of the behavioral ecologies of many species such as sea lions, or of the interactions among species around village sites, are products of both passive and active human engineering of those behaviors. As such, at least for the last few thousands of years, there is no “natural” North Pacific ecosystem without humans as one of the key species in that ecosystem.

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