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# Brackish water foraging: isotopic landscapes and dietary reconstruction in Suisun Marsh, Central California

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## ABSTRACT

While bone stable isotope signatures of humans foraging in open coastal and fully terrestrial environments have been relatively well documented, the signature of foraging near brackish-water estuaries is less well known. This study examines the Central California isotopic landscape, or isoscape, showing how foods in different ecosystems have distinctive isotopic compositions. We present new bone collagen and apatite stable isotope data from two Late Holocene sites (CA-SOL-11 and CA-SOL-69) near Suisun Marsh, a low salinity brackish water estuary upstream from San Francisco Bay. Faunal remains at the sites include significant numbers of aquatic resources including fish and shellfish, in addition to terrestrial mammals, while paleobotanical remains suggest mainly terrestrial nuts and seeds. Stable isotope data at the population level corroborate this finding and show consumption of significant levels of brackish water nutrients, including both dietary protein and dietary carbohydrates and fats, paired with terrestrial foods. This dietary focus generates a unique brackish-water isotopic signature that is distinct from others in Central California. The documentation of an isoscape with strong regional gradients can be of tremendous help in reconstructing ancient patterns in subsistence, migration, and trade.

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## 1. Introduction

Archaeologists employ a range of techniques to investigate ancient dietary patterns, each with advantages and disadvantages. While zooarchaeological and paleobotanical analyses allow archaeologists to determine individual species and genera that ancient foragers exploited, bones and charred plant remains enter the archaeological record in a range of ways and can be differentially deposited, preserved, and recovered. This makes straightforward links between faunal and floral remains and ancient diet difficult. Furthermore, such materials were typically discarded by a range of individuals in a society and accumulated over long periods of time. As a result, we are unable to link them back to specific individuals of the past.

Stable isotope analyses on human remains, on the other hand, represent diet over much shorter time intervals and allow us to link diet to particular individuals. As a result, we can examine inter-individual variation in diet across a population, and in some cases, changes in diet over the lifetime of an individual (e.g., Fuller et al., 2003; Eerkens et al., 2011; Beaumont et al., 2012). However, the level of specificity in dietary reconstruction is much lower using stable isotopes, and we are only able to determine general categories of diet such as marine-focused vs. terrestrial-focused, or plant-focused vs. game-focused. Ideally, faunal and paleobotanical analyses are combined with stable isotope analyses of human bone, for a more complete reconstruction of ancient diet.

Analyses of human bone in a range of coastal (e.g., Clayton et al., 2006; Kusaka et al., 2010; Richards and Hedges, 1999; Richards et al., 2005; Walker and DeNiro, 1986), terrestrial (e.g., Gil et al., 2011; Pate, 1998; Tessone et al., 2009), and lacustrine (e.g., Katzenberg et al., 2012; Schoeninger, 1999; Weber et al., 2011) settings have shown the effects of these foodwebs on stable isotope signatures. Consumption of significant amounts of plant and animal resources from these different settings creates distinctive stable isotopic signatures that are preserved in human tissues, including the collagen and apatite in bones and teeth. These signatures help archaeologists reconstruct ancient dietary patterns for populations, subsets of populations, and individuals, and allow us to examine the evolution of diets over long periods of time (Broadhurst et al., 2002; Hublin and Richards, 2009; Richards et al., 2008; Sponheimer and Lee-Thorp, 1999; Sponheimer et al., 2006; Ungar and Sponheimer, 2011).

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By contrast, less research has been undertaken on humans exploiting large brackish water environments, especially low salinity ecosystems that average less than 10‰ practical salinity units (psu). The expectation is that these environments should produce intermediate values between marine and riverine or lacustrine settings in humans, but little empirical data exists to corroborate this intuition (though see Grupe et al., 2009; Liden and Nelson, 1994). Salinity gradients in such environments often range from fully fresh to fully saline and create distinctive stable isotope landscapes, or "isoscapes" (West et al., 2006) within these estuarine systems. For example, Grupe et al. (2009) show that the Schlei fjord in northwest Germany boasts a diverse, multifaceted habitat, but one with many isotopically defined sub-compartments. They suggest further that stable isotope analysis on humans consuming resources from the Schlei fjord can help to delineate where within the broader ecosystem they acquired their foods, which can then be used to reconstruct ancient trade and migration patterns. Likewise, Liden and Nelson (1994) studied stable carbon isotopes in human bone collagen in sites on the Baltic Sea along the Swedish coast. Again, they show a distinctive isotopic signature relative to inland inhabitants. Thus, the small number of existing studies in low-salinity brackish environments suggests tremendous potential for working out foraging strategies in these diverse environments, across an isoscape.

In this paper, we report and discuss bone collagen and apatite stable isotope values for a sample of human remains recovered from CA-SOL-11 and CA-SOL-69, two sites located a short distance from the low salinity brackish Suisun Marsh in the Delta of Central California. Suisun Marsh is one of the largest brackish water marshes in the Western United States. Radiocarbon dates and temporally diagnostic artifacts show these sites were occupied between about 2500 and 1200 years ago.

## 2. An isoscape for Central California

To place the stable isotope data from the two sites in this study in context, we develop a theoretical model based on basic understandings of isotope fractionation in different ecosystems. This model is used to predict bone collagen stable isotope signals for brackish-water foragers at a general level. Next, we assemble existing modern data for Central California for a range of potential food resources to generate a region-specific prediction for bone collagen carbon and nitrogen for Suisun Marsh. Finally, we consider a recent model based on modern controlled feeding experiments to help predict carbon isotope values for bone apatite in Suisun Marsh.

### 2.1. Theoretical model for brackish water foragers

In dietary studies around the world, carbon isotopes ($^{13}C/^{12}C$, expressed as $\delta^{13}C$, see below) often provide an estimate of the consumption of C3 vs. C4 plants. The majority of plants around the world are C3 plants, producing a three-carbon molecule during the fixation of atmospheric carbon. This method of photosynthesis discriminates against the heavier $^{13}C$, resulting in $\delta^{13}C$ values between $-30‰$ and $-22‰$ (Cerling et al., 1998; Ehleringer et al., 1993; Farquhar et al., 1989). By contrast, a small number of plants produce a four-carbon molecule (C4) and produce tissues with $\delta^{13}C$ values typically between $-16‰$ and $-10‰$. While the number of C4 photosynthesizers is low, several important crop plants, such as maize, millet, sugar cane, and sorghum, fall in this category, allowing archaeologists to estimate their importance in local diets. In Central California, there are few C4 plants, and the majority of those are not reported as economically important in the ethnographic record, nor are they typically found in paleobotanical remains from archaeological sites (Bartelink, 2006).

Carbon enters marine environments mainly through exchange with atmospheric $CO_2$ and through photosynthesizing phytoplankton (Boutton, 1991; Burkhardt et al., 1999). $\delta^{13}C$ values of biologically available carbon in marine environments typically overlap with those of C4 plants. Because C4 plants were generally not consumed, we can use $\delta^{13}C$ in Central California as a discriminator of terrestrial- vs. marine-derived carbon, with heavier (less negative) $\delta^{13}C$ indicating a greater contribution of marine organisms to the diet (Bartelink, 2009; Schoeninger et al., 1983; Schwarcz and Schoeninger, 1991).

Brackish water environments, including the large estuaries of the lower Sacramento River and upper San Francisco Bay (San Pablo Bay; see Fig. 1), include a mix of terrestrial- and marine-derived
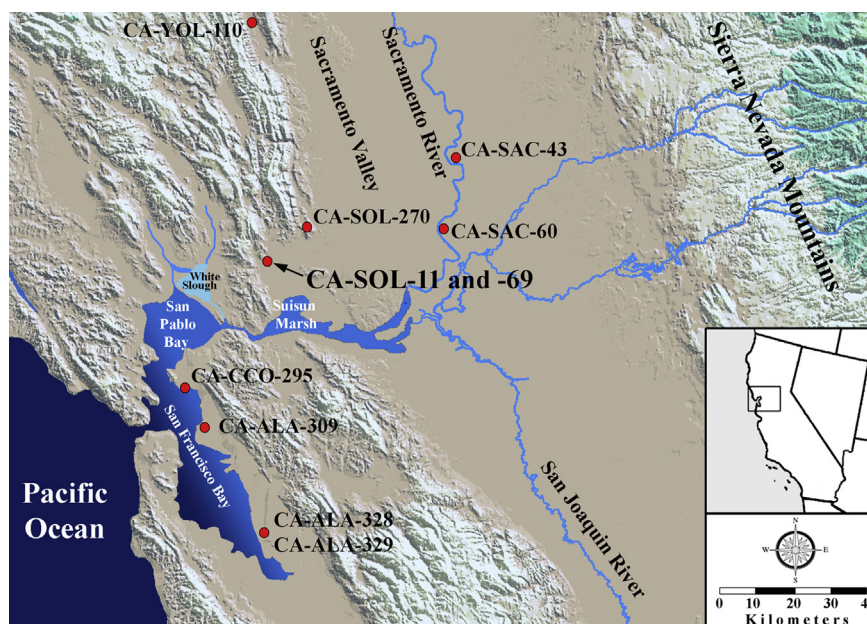


**Fig. 1.** Map of study area, showing locations of important water bodies, ecological zones, other archaeological sites, and CA-SOL-11 and -69.
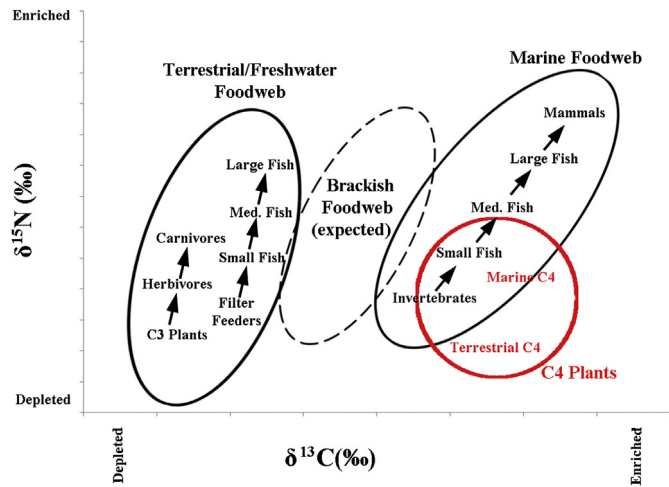
**Fig. 2.** Expected $\delta^{15}$N and $\delta^{13}$C in different foraging environments.

carbon that generally follows salinity gradients (Fry, 2002). The amount of ocean water generally varies over space. For example, salinity varies from fully marine just outside the mouth of San Francisco Bay to fully freshwater near Sacramento. Further, the importance of marine vs. terrestrial carbon in brackish waters will fluctuate with the seasons, with greater marine input during the dry season and greater terrestrial input during the rainy season. In Central California summer and early fall are generally dry, while winter and spring are wet. As a result, the incorporation of carbon from brackish environments into biological tissues will result in intermediary $\delta^{13}$C values, between those expected for C3 and marine consumers, depending slightly on local salinity values and the intensity of foraging in dry vs. wet seasons.

While $\delta^{13}$C reflects C4/marine vs. C3 input, nitrogen isotopes ($^{15}$N/$^{14}$N, expressed as $\delta^{15}$N, see below) reflect the general trophic level of consumed foods. Nitrogen fractionates during the synthesis

of biological tissues, favoring the retention of the heavier $^{15}$N. As a result, $\delta^{15}$N increases by about 3–4‰ with each trophic level. In terrestrial systems, there are essentially three trophic levels—plants, herbivores, and carnivores. By contrast, in marine and freshwater aquatic environments there are more trophic levels, resulting in greater enrichment of $\delta^{15}$N at the top of the food chain (typically large fish, predatory birds, and aquatic mammals).

Foragers in coastal environments gain much of their protein from marine resources, and therefore, tend to have elevated $\delta^{13}$C. Because nitrogen isotopes fractionate with each trophic level and marine environments tend to have more trophic levels, $\delta^{15}$N also tends to be enriched (elevated) in bone collagen in coastal settings. Even plants in marine and coastal environments tend to be enriched in $\delta^{15}$N relative to plants growing in terrestrial environments (Heaton, 1987; Howe and Simenstad, 2011). By contrast, foragers in terrestrial environments typically display very different ranges of C and N isotopes. Where C4 plants dominate local landscapes, $\delta^{13}$C values in collagen can overlap values for coastal foragers, but $\delta^{15}$N will typically be depleted due to the lower trophic level of plants. In terrestrial landscapes where C3 plants dominate, both $\delta^{13}$C and $\delta^{15}$N are depleted (i.e., lower, or more negative in the case of $\delta^{13}$C) relative to coastal foragers. In lacustrine or riverine settings, where there is no marine carbon but there are many trophic levels, foragers display enriched $\delta^{15}$N but depleted $\delta^{13}$C. Again, we expect brackish-water environments to be intermediate between marine and lacustrine/riverine environments. Fig. 2 shows these expected differences.

### 2.2. Modern foods near Suisun Marsh

Fig. 3 plots data from modern plant and animal samples amalgamated from a wide range of studies in and around Suisun Marsh, including San Francisco Bay and the California Delta (data assembled from Bartelink, 2006; Canuel et al., 1995; Cloern et al., 2002; Goldberg, 1993; Greenfield et al., 2002; Grenier et al., 2002; Howard et al., 2005; Howe and Simenstad, 2011; Kleckner et al.,
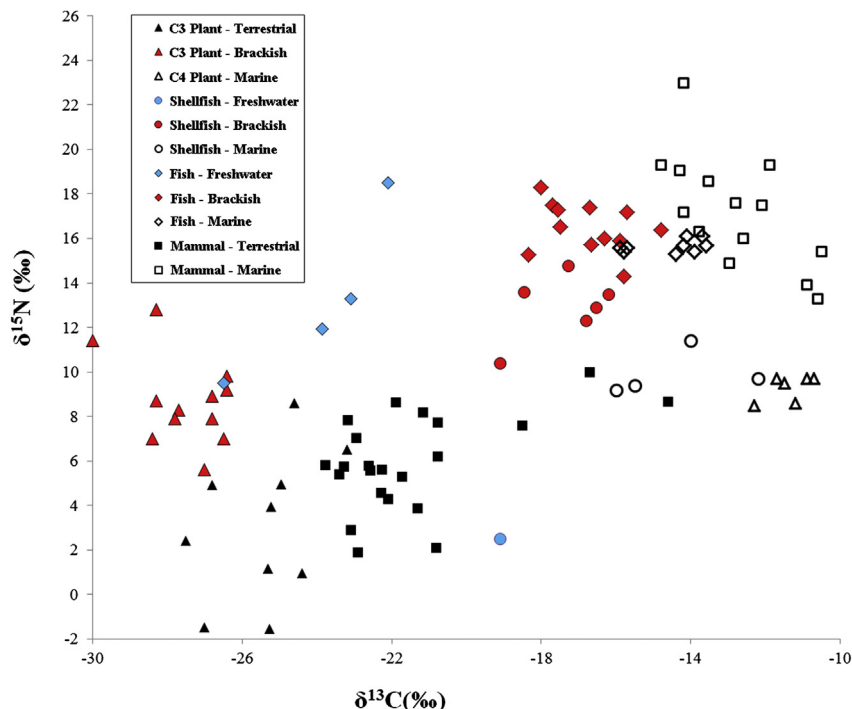


**Fig. 3.** $\delta^{13}$C and $\delta^{15}$N for plant and animal species in Central California.

2010; Newsome et al., 2009, 2012; Rast, 1989; Sarakinos et al., 2002; Sydeman et al., 1997). Given large inputs of fertilizer and sewage into modern waterways, and extreme changes to the local ecology, especially the effects of invasive species, it is difficult to estimate how applicable modern data are to reconstructing ancient foodwebs in Central California (Wankel et al., 2006). Many of the species exploited by prehistoric foragers are either locally extirpated, legally protected, or are otherwise not considered economically important, and are not analyzed by modern researchers. Furthermore, the studies are not systematic by ecological zone or the types of species collected, and often focus on issues unrelated or only tangential to human foraging. In spite of these shortcomings, we attempt to outline general features of the modern data that have implications for human foraging.

Fig. 3 only includes species reported to have been exploited by native groups, or recent invasive species that essentially replaced those previously exploited by native groups (such as striped bass which replaced high trophic level feeders in the Sacramento River and Delta region). Following Bartelink (2006), δ13C values have been transformed by adding 1.5‰, to account for the Suess effect (recent contributions of depleted carbon into the atmosphere due to the burning of fossil fuels; Keeling, 1979). This brings the values closer to what would be expected for prehistoric foragers, making archaeological data more directly comparable to the values presented in the figure.

Fig. 3 separates the data points by environmental zone, focusing on fully marine (Pacific coast), estuarine (San Francisco Bay), and freshwater (Sacramento River), and by biological category (e.g., plant vs. invertebrate vs. mammal vs. fish). Unfortunately, Suisun Marsh itself has seen fewer studies than adjacent San Francisco Bay or the Pacific Coast, thus, many of our interpretations of Fig. 3 rely on interpolating between freshwater, San Francisco Bay, and marine environments. As well, the sample size of native Central California freshwater shellfish and fish is small ($n = 4$), due mainly to the severe decline of native fish populations, and a valuable contribution for future work would be to increase the number of native species studied.

Fig. 3 generally conforms to expectations from Fig. 2. C3 plants, terrestrial foraging animals, and freshwater fish and shellfish, are depleted in δ13C and occur on the left side of the figure, with δ13C less than −18‰ (excepting a few land mammals such as raccoon that consume large amounts of urban garbage, and bobcat). Marine animals, including shellfish, fish, and sea mammals, and C4 plants, all fall on the far right of the figure, with enriched δ13C generally greater than −15‰. Estuarine shellfish and fish fall between these extremes. As expected, δ15N increases with higher trophic levels in terrestrial (e.g., plant vs. herbivore vs. carnivore), freshwater (shellfish vs. fish), estuarine (plant vs. shellfish vs. fish), and marine (plant and shellfish vs. fish vs. mammal) ecosystems. As well, holding general trophic level constant, δ15N is higher in marine and estuarine species relative to terrestrial and freshwater ones.

### 2.3. A bioapatite model

In humans, consumed protein is differentially routed to collagen. A recent model (Fernandes et al., 2012) suggests that 74% of the carbon in bone collagen is derived from dietary protein, with the remainder coming from carbohydrates and fats. By contrast, bone apatite is more reflective of the whole diet (Ambrose and Norr, 1993; Kellner and Schoeninger, 2007; Tieszen and Fagre, 1993). The difference between collagen and apatite (collagen–apatite spacing) to a large degree reflects differences between the sources of dietary protein, on the one hand, and dietary carbohydrates and fats, on the other. To try to tease these dietary components apart, we also measured δ13C in bone apatite and compared it to δ13C in bone collagen.

A recent model by Froehle et al. (2010) based on results of controlled diets in non-human mammals maps the effects of C3 vs. C4/marine foods on bone collagen and apatite isotope values. Their model is reproduced in Fig. 4 with one alteration: we have added 1.5‰ from all their isotope values to correct for the Suess effect (Keeling, 1979). As with the modern plant and animal data, this alteration makes the isotopic values more comparable to pre-industrial archaeological samples.

Fig. 4 shows the range of observed isotopic values, or potential isotopic space, as a rhomboid. There is a linear and positive relationship between δ13C in collagen and apatite overall, as seen by the upward slope of the rhomboidal space. This linear relationship holds because protein, carbohydrates, and fats are all used to some
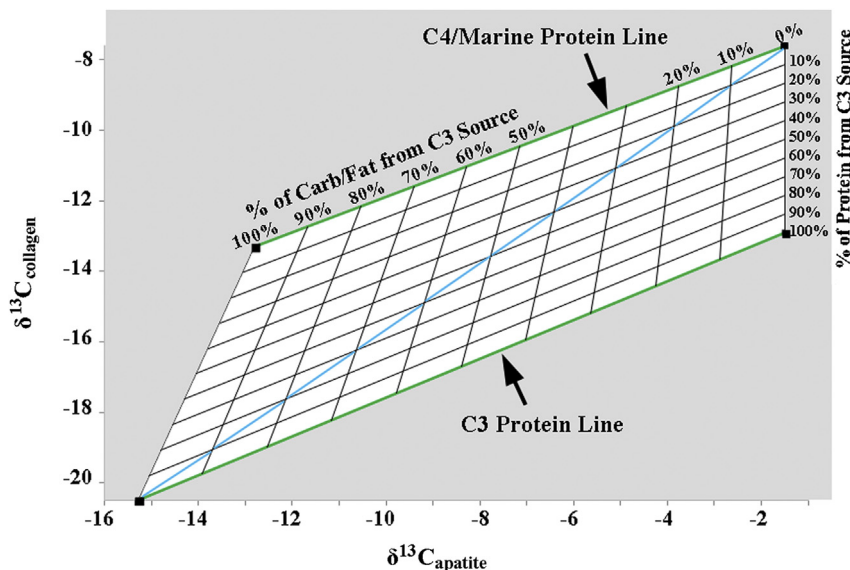


**Fig. 4.** Relationships between δ13C values in bone collagen vs. apatite based on the model by Froehle et al. (2010), with 10% isobars for C3 vs. C4/marine composition of the protein vs. carbohydrate/fat components of the diet added.

degree to synthesize collagen and apatite, and hence $\delta^{13}C$ in collagen and apatite are not independent of one another. Yet, within the rhomboid there is significant room for variation, reflecting a range of different potential diets. This is because collagen and apatite draw on protein, carbohydrates, and fats in different proportions, and importantly, organisms can gain these nutrients from sources with different $\delta^{13}C$ values.

The controlled dietary studies vary the contribution of C3 and C4/marine sources to both protein and carbohydrate/fat components of the diet. In Fig. 4, the lower left corner of the rhomboid represents observed collagen and apatite values when all macronutrients are composed solely of C3 sources. The upper left corner represents a diet where protein is composed solely of C4/marine sources but C3 sources contribute 100% of the carbohydrates and fats. Likewise, the right-hand corners represent 100% C4/marine for all macronutrients (top right) and 100% C3 protein paired with 100% C4/marine carbohydrate and fat (bottom right).

To the Froehle model, we have added isobars between these extremes, in increments of 10%, along the protein and carbohydrate/fat axes. We recognize this is an approximation, as controlled dietary studies with mixed proportions of C3 vs C4/marine in various dietary macronutrients are lacking. Thus, it is possible that the isobars we have added to Fig. 4 do not in reality shift linearly across the isotopic space (i.e., even spacing between each 10% isobar), but change in a non-linear fashion (e.g., exponential or Poisson). Additional research is necessary to address this issue. Assuming 1) foragers within a population consume similar proportions of protein, carbohydrate, and fats, and 2) linear relationships between the isotopic composition of different food mixtures and resulting bone isotope values, we suggest Fig. 4 represents a first approximation of expected collagen–apatite isotope values given the $\delta^{13}C$ of dietary protein and dietary carbohydrates and fats. Note, in particular, that the percent of C3 carbon in protein and the percent of C3 carbon in carbohydrates/fats do not have to add to 100%. Thus, a forager can fall anywhere within the rhomboid.

In Fig. 4, a diagonal line from the lower left to the upper right corner of the rhomboid indicates diets where particular carbon sources (e.g., C3 vs. C4/marine) contribute equal proportions of protein vs. carbohydrate/fat to the diet. For example, a forager consuming 10% C4/marine-based protein paired with 10% C4/marine-based carbohydrate/fat, or 80% C4/marine protein and 80% C4/marine carbohydrate/fat, is expected to fall on this diagonal. At a population level, if samples fall mainly along this diagonal it would suggest individual-level variation in the overall exploitation of particular environments for *all* of their nutrients (e.g., some were gaining 30% and others 40% or 50% of *all* nutrients from C4/marine sources). In other words, a population falling along this diagonal is using the same carbon source in equal proportions for both protein and carbohydrate/fat components of the diet.

By contrast, a "diagonal" from the top left to the bottom right of the rhomboid represents diets where foragers access multiple carbon sources simultaneously, but in inverse proportions for different nutrients. For example, a forager pairing C4/marine-derived protein with terrestrial C3-derived carbohydrates and fats (e.g., 90% of protein from C4/marine sources but 10% of carbohydrates and fats from C4/marine sources, or 20% C3 terrestrial protein with 80% C3 terrestrial carbohydrate/fat), is expected to fall on this diagonal. This would be expected if certain carbon sources are particularly rich in just one of the macronutrients but poor in the other. For example, if marine-derived foods are rich in protein but poor in carbohydrates and fats, a forager would be expected to make up the deficiency by harvesting carbohydrates and fats from terrestrial environments which should be high in C3 sources of carbon (provided C4 plants are not important in the diet). In Fig. 4,

such "diagonals" would appear as roughly horizontal lines in $\delta^{13}C_{apa}$–$\delta^{13}C_{col}$ isotopic space (i.e., they run diagonally through protein–carbohydrate/fat space, but horizontally through apatite–collagen space).

Together collagen and apatite analyses provide a better estimate of aggregate diet and permit greater differentiation between the diets of individuals and populations (Froehle et al., 2010, 2012). Combined, $\delta^{13}C_{apa}$, $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ can be used to estimate exploitation of different environments for different macronutrients, provided the isoscape is sufficiently partitioned across environmental zones.

## 3. CA-SOL-11 and CA-SOL-69

CA-SOL-11 is located in Green Valley just outside Fairfield, California (see Fig. 1). The site was originally excavated from 1965 to 1966 by the UC Davis Archaeology Field School Class. The only analysis of these materials is a Master's thesis written in 1967 by James Snoke that focuses on the associated artifacts (Snoke, 1967). Unfortunately, since that time the ecofacts and artifacts from the site have been missing from the UC Davis Museum of Anthropology, and only the human skeletal materials are curated. While the missing faunal and botanical remains are unfortunate, Snoke did make cursory observations about these remains, and more importantly, as we show below, we can use stable isotope analysis to fill in such a gap.

CA-SOL-11 is located in an inland setting, on the ecotone between fresh- and brackish-water marsh and grasslands. The site sits at 15 m elevation above sea level in Green Valley, on the east banks of Green Valley Creek. In the immediate vicinity of the site, Green Valley Creek provided access to a range of riparian plant foods, including berries, bulbs, and some seed resources, as well as freshwater fish and shellfish. Adjoining grasslands produced high quantities of small seeds, an important staple in Central California diets (Wohlgemuth, 1996), as well as access to small mammals and large game (primarily deer). Hills rise rapidly to the east, north, and west of the site, and would have provided access to a range of additional terrestrial resources, including hunting grounds for deer, as well as groves of oaks providing acorn (another important Central California staple), manzanita, buckeye and other plants. Although analysis of faunal remains was not the focus of Snoke's research at SOL-11, he notes that elk, deer, and pronghorn remains were most common among the identifiable faunal remains, especially in the deeper levels of the midden deposit.

Aquatic foods, particularly fish and shellfish, could have been acquired at slightly further distances from CA-SOL-11. Green Valley Creek flows into Suisun Marsh, a brackish water estuary located approximately 10 km to the southeast. Likewise, San Pablo Bay is 20 km to the southwest and White Slough (which spills into San Pablo Bay) is 15 km to the west. Anadromous fish (salmon and sturgeon) would have been available both in Green Valley Creek and in the nearby brackish and marine estuaries. Sturgeon scutes were recovered during excavations at nearby sites in Green Valley such as SOL-315 and SOL-355 (Wiberg, 1992, 1993).

Snoke (1967:14) noted that unmodified shell was prominent in the midden deposit at SOL-11, but unfortunately he did not differentiate shell as belonging to either mussel or clam. Shellfish could be either brackish water (e.g., bay mussel; *Mytilus trossulus*) or freshwater (e.g., *Anodonta californiensis*, *Gonidea angulata*, *Margaritifera falcata*) in origin. Other nearby Middle Period sites such as SOL-355 contain significant numbers of Bay mussel (Wiberg, 1993), thus, it is likely that at least some of the shell Snoke describes is *M. trossulus*. In any case, Snoke noted that the ratio of shell to bone was higher in the shallower levels of the site, which he interpreted as representing a shift from hunting-

focused economies early to more shellfishing-focused subsistence economies later in time.

Based on descriptions in Snoke (1967), artifacts at SOL-11 include a range of flaked stone, ground stone, shell, and bone artifacts. Although the artifacts are not available for reanalysis, Snoke presents sketches and photos of a range of these items in his thesis. The types of artifacts depicted are consistent with what is known for Middle Period sites in Central California (Beardsley, 1948; Bennyhoff and Fredrickson, 1994; Chartkoff and Chartkoff, 1984; Fredrickson, 1994; Moratto, 1984).

CA-SOL-69 is located approximately 1.3 km to the SE of CA-SOL-11. The site was excavated in 1990 as part of an urban development project (Wiberg, 1992), with additional monitoring and excavation in 1997 and 1998 (Reynolds and Wiberg, 1999). The samples in this study come from the latter monitoring work. Obsidian hydration data, interment style (all flexed burials), and temporally diagnostic artifacts indicate a single-component occupation during the Middle Period, ca. 2500–1500 BP, contemporaneous with CA-SOL-11. The discovery of one large house floor, the presence of many burials, and seasonality data on faunal and floral remains indicated year-round occupation of the site to the excavators.

Faunal analysis was minimal, and included examination of just 135 elements, only 20 identified to family level. However, these remains include the remains of migratory waterfowl (geese; MNI = 2), sturgeon (MNI = 1) and minnow (MNI = 1), in addition to deer (MNI = 1), pocket gopher (MNI = 2), coyote (MNI = 1), gray fox (MNI = 1) and snake (MNI = 1). Small amounts of freshwater mussel (Anodonta sp.) and bay mussel were also recovered. Paleobotanical remains include a high proportion of grass seeds, especially fescue (Vulpia sp.) and maygrass (Phalaris sp.), in addition to acorn (Quercus sp.), manzanita (Arctostaphylos sp.), and wild cucumber (Marah sp.). The majority of these plant species are found in higher densities away from the marsh, in more terrestrial locations. Together, the faunal data indicate exploitation of both estuarine and terrestrial environments, while the paleobotanical data indicate exploitation of terrestrial environments only for nuts and seeds (i.e., no C4 or brackish water plants present).

## 4. Sample selected and methods

This study includes bone samples from 67 individuals recovered from 47 different graves at CA-SOL-11, and three individuals from three graves at CA-SOL-69. In some cases a nearly complete skeleton is present, allowing the estimation of age at death, and for adults, sex. In others, only a single bone fragment is present and we are unable to estimate age or sex. Given the archaeological context (location of unit and depth of sample) and demographic data (e.g., age and sex), we are confident that these samples represent 67 different individuals. The majority of these are adults ($n = 48$), with only two infants, eleven children below the age of 14, and five adolescents (age 14–20). Of the adults, 9 were confidently identified as female and 19 as male, with the remaining indeterminate for sex. Although the remainder of our analysis focuses on population-level interpretations, Table 1 provides a breakdown of the sample by age and sex.

To isolate collagen for analysis a modified Longin procedure was followed (Longin, 1971). Approximately 1–2 g of cortical bone was cleaned of any surface contamination by drilling exposed surfaces with a diamond bit and then sonicating the sample in deionized $H_2O$ (three five-minute baths, with the $dH_2O$ replaced after each bath). The sample was left in an open container until completely dry, weighed, and demineralized with a solution of 0.5M hydrochloric acid (HCl). HCl was changed every other day until the sample was completely demineralized (up to 2 weeks). The bone was then washed three times with $dH_2O$ and soaked in 0.125M

**Table 1**
Age and sex of individuals included in this study.

|        | Infant (0–2 yrs) | Child (2–14) | Adolescent (14–20) | Adult (20+) | Young Adult (20–39) | Old Adult (40+) | Indet. | Total |
|--------|------|------|------|------|------|------|------|------|
| Male   | 0 | 0 | 0 | 2 | 10 | 7 | 0 | 19 |
| Female | 0 | 0 | 0 | 3 | 4 | 2 | 0 | 9 |
| Indet. | 2 | 11 | 4 | 18 | 0 | 3 | 1 | 39 |
| Total  | 2 | 11 | 4 | 23 | 13 | 12 | 1 | 67 |

Notes: Indet. = Indeterminate.

NaOH (sodium hydroxide) for 24 h to remove humic acids. The sample was rinsed five times with $dH_2O$ to remove any residual NaOH.

Slightly acidic pH3 water was added to the vial and the sample placed in a 70–90 °C oven for approximately 24 h to solubilize collagen. After centrifuging the sample for 3–4 min the pH3 solution was pipetted into a clean vial. This process was repeated two additional times before freeze drying to remove the water, isolating the collagen fraction.

Collagen $^{13}C/^{12}C$ ($\delta^{13}C_{col}$) and nitrogen $^{15}N/^{14}N$ ($\delta^{15}N$) was measured by continuous-flow mass spectrometry (PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer) at the Stable Isotope Facility, University of California Davis. Carbon isotopes ratios, $\delta^{13}C_{col}$, are reported expressed in permil notation (parts per thousand) relative to the Pee Dee Belemnite standard (arbitrarily set at 0‰), while N isotope ratios, $\delta^{15}N$, are expressed against $N_2$ in modern atmospheric air (also arbitrarily set to 0‰).

We extracted and analyzed bone collagen from four burials twice to check for internal consistency. Differences between these repeat samples in $\delta^{13}C_{col}$ averaged 0.07‰ (maximum of 0.14‰) and in $\delta^{15}N$ averaged 0.12‰ (maximum 0.14‰). These repeat samples indicate our overall precision, including bone preparation and instrument error, is less than 0.2‰.

Apatite preparation started with the same cleaned bone, which was powdered in an agate mortar and pestle. Approximately 0.04 g of bone powder was placed in a weighed centrifuge vial. Organics were removed by adding a 1.5% sodium hypochlorite at a ratio of 0.04 ml solution/mg sample. After 24 h the sample was centrifuged and the solution replaced. After a second 24 h the solution was discarded and the sample was washed three times with $dH_2O$. For the next 8–12 h the sample was placed in a diagenetic wash composed of a 1M acetic acid solution (at the same ratio of 0.04 ml solution/mg sample) which was replaced after 12 h. The sample was then rinsed three times with $dH_2O$ and any remaining water pipetted off. The sample was left in the container with no cap until completely dry. Apatite samples were analyzed on a GVI Optima Stable Isotope Ratio Mass Spectrometer at the Stable Isotope Lab in the Geology Department at University of California, Davis. $\delta^{13}C$ and $\delta^{18}O$ are simultaneously measured from the carbonate component of bone apatite. Though our interpretations focus only on $\delta^{13}C_{apa}$, we do report $\delta^{18}O$ as well. Due to a lab error, the three CA-SOL-69 samples were unfortunately not run for apatite.

Finally, we submitted 11 collagen samples from CA-SOL-11 for radiocarbon dating to help establish better chronological control at the site.

## 5. Results

Table 2 shows the entire sample, including measured isotopic values from bone collagen and bone apatite. The generally depleted (i.e., more negative) $\delta^{13}C_{col}$ values suggest that terrestrial foods were the primary source of protein for most people, with 59 of the

**Table 2**
Results of collagen ($\delta^{13}C_{col}$, $\delta^{15}N$) and apatite ($\delta^{13}C_{apa}$, $\delta^{18}O$) analyses for 64 individuals from CA-SOL-11 and three individuals from CA-SOL-69.

| Site CA- | Burial # | Sex | Age at death | $\delta^{13}C_{col}$ | $\delta^{15}N$ | $\delta^{13}C_{apa}$ | $\delta^{18}O$ | $^{14}C$ age BP |
|---|---|---|---|---|---|---|---|---|
| SOL-11 | BB-1-1 | Female | Young Adult | −19.4 | 7.5 | −11.9 | −4.6 | 2220 ± 30 |
| SOL-11 | 43 #1 | Indet. | Child | −19.1 | 9.1 | −11.2 | −4.6 | |
| SOL-11 | E-8-3 | Female | Old Adult | −18.9 | 9.6 | −12.8 | −5.1 | |
| SOL-11 | F-7-5 #2 | Indet. | Adult | −19.3 | 8.2 | −12.7 | −3.7 | |
| SOL-11 | G-6-1 #1 | Indet. | Child | −19.1 | 9.0 | −14.1 | −4.6 | |
| SOL-11 | G-22-1 | Indet. | Adult | −19.6 | 7.7 | −14.0 | −5.1 | |
| SOL-11 | DD-9-1 #2 | Indet. | Old Adult | −17.3 | 13.4 | −11.5 | −4.1 | 1720 ± 25 |
| SOL-11 | E-7-5 | Female | Adult | −19.2 | 9.2 | −13.1 | −4.6 | |
| SOL-11 | G-10-5 | Indet. | Adult | −19.5 | 7.5 | −12.7 | −4.8 | |
| SOL-11 | E-7-4 | Indet. | Child | −18.9 | 9.3 | −13.0 | −4.1 | |
| SOL-11 | G-6-2 #1 | Male | Old Adult | −19.1 | 9.2 | −11.7 | −3.4 | |
| SOL-11 | G-9-1 | Female | Adult | −19.0 | 9.2 | −12.5 | −4.7 | |
| SOL-11 | A-2-1 | Indet. | Adolescent | −18.6 | 11.2 | −11.7 | −4.5 | |
| SOL-11 | G-8-2 #1 | Male | Young Adult | −19.2 | 8.9 | −12.5 | −2.9 | |
| SOL-11 | G-7-1a | Male | Young Adult | −18.7 | 9.7 | −14.5 | −5.2 | |
| SOL-11 | F-7-5 #3 | Indet. | Adult | −18.9 | 9.6 | −13.7 | −5.0 | |
| SOL-11 | F-6-1 #1 | Male | Old Adult | −19.4 | 9.1 | −12.7 | −5.1 | |
| SOL-11 | G-6-2 #2 | Indet. | Adolescent | −19.0 | 9.7 | −12.0 | −4.8 | |
| SOL-11 | F-6-5 #2 | Indet. | Infant | −19.0 | 9.7 | −12.5 | −4.6 | |
| SOL-11 | HH-5-1 | Male | Old Adult | −19.3 | 7.4 | −11.7 | −4.7 | |
| SOL-11 | E-9-1 | Indet. | Child | −19.4 | 9.7 | −12.6 | −4.0 | |
| SOL-11 | C-3-1 | Male | Young Adult | −19.5 | 8.3 | −13.3 | −5.0 | |
| SOL-11 | CC-9-1 | Male | Old Adult | −18.7 | 9.7 | −12.8 | −4.3 | |
| SOL-11 | 42 | Female | Adult | −19.3 | 8.5 | −12.8 | −3.2 | 2090 ± 35 |
| SOL-11 | F-7-6 #1 | Indet. | Old Adult | −19.1 | 9.0 | −14.2 | −4.6 | |
| SOL-11 | EE-9-1 #1 | Male | Old Adult | −17.7 | 13.0 | −11.7 | −4.6 | 1850 ± 40 |
| SOL-11 | HH-2-1 #1 | Male | Adult | −19.5 | 8.0 | −11.2 | −3.4 | 1990 ± 25 |
| SOL-11 | EE-9-1 #2 | Indet. | Unknown | −19.4 | 8.0 | −11.7 | −3.4 | |
| SOL-11 | CC-2-2 #1 | Male | Young Adult | −19.3 | 8.6 | −12.1 | −4.7 | 2200 ± 30 |
| SOL-11 | E-6-2 | Indet. | Adolescent | −18.6 | 10.0 | −11.7 | −4.0 | |
| SOL-11 | EE-5-1 | Indet. | Adult | −17.7 | 11.9 | −12.4 | −4.2 | 1390 ± 25 |
| SOL-11 | E-8-2 | Male | Young Adult | −19.1 | 9.6 | −14.4 | −4.9 | 2130 ± 25 |
| SOL-11 | E-7-3 #1 | Indet. | Child | −19.4 | 9.1 | −12.0 | −4.7 | |
| SOL-11 | F-9-1 | Indet. | Child | −19.8 | 7.8 | −12.4 | −4.9 | 2000 ± 25 |
| SOL-11 | AA-1-3 | Indet. | Adult | −19.2 | 7.5 | −11.6 | −4.6 | |
| SOL-11 | CC-2-2 #2 | Indet. | Child | −18.6 | 10.4 | −12.2 | −5.0 | |
| SOL-11 | AA-1-1 | Male | Old Adult | −18.6 | 11.2 | −12.5 | −4.3 | |
| SOL-11 | 43 #2 | Female | Young Adult | −19.1 | 8.8 | −12.2 | −4.4 | |
| SOL-11 | G-7-16 | Male | Young Adult | −19.1 | 9.8 | −11.1 | −2.1 | |
| SOL-11 | CC-9-2 | Indet. | Adult | −17.9 | 11.1 | −12.5 | −4.4 | 1990 ± 25 |
| SOL-11 | F-10-5 | Indet. | Adult | −19.7 | 7.5 | −12.6 | −4.0 | |
| SOL-11 | HH-2-1 #2 | Indet. | Adult | −19.3 | 7.7 | −11.9 | −4.3 | |
| SOL-11 | F-6-5 #1 | Male | Young Adult | −19.1 | 9.3 | −13.1 | −5.2 | |
| SOL-11 | F-6-1 #2 | Indet. | Child | −18.4 | 10.1 | −12.3 | −4.2 | |
| SOL-11 | DD7 | Indet. | Adult | −17.9 | 11.6 | −11.4 | −5.3 | |
| SOL-11 | E-6-7 | Indet. | Adult | −19.3 | 8.9 | −11.9 | −4.8 | |
| SOL-11 | F-7-2 #2 | Indet. | Child | −19.5 | 9.3 | −13.7 | −5.1 | |
| SOL-11 | E-9-2 | Female | Young Adult | −19.6 | 8.0 | −11.8 | −4.4 | |
| SOL-11 | E-8-1 | Male | Young Adult | −19.5 | 9.7 | −12.8 | −5.2 | |
| SOL-11 | G-9-2 | Male | Adult | −18.5 | 11.2 | −11.4 | −3.9 | |
| SOL-11 | DD-9-1 #1 | Male | Young Adult | −18.4 | 9.5 | −11.3 | −4.7 | |
| SOL-11 | G-8-2 #2 | Indet. | Adult | −19.4 | 7.6 | −12.6 | −5.1 | |
| SOL-11 | CC-9-3 | Indet. | Adolescent | −18.5 | 9.0 | −11.8 | −4.2 | |
| SOL-11 | F-7-1 | Female | Old Adult | −18.4 | 9.9 | −14.0 | −4.8 | |
| SOL-11 | AA-1-2 | Indet. | Adult | −18.7 | 10.1 | −12.3 | −5.0 | |
| SOL-11 | G-8-1 | Indet. | Child | −18.9 | 9.2 | −13.5 | −5.1 | |
| SOL-11 | E-8-4 #1 | Indet. | Child | −18.9 | 10.3 | −13.4 | −4.0 | |
| SOL-11 | E-7-3 #2 | Indet. | Adult | −18.9 | 9.0 | −13.2 | −5.0 | |
| SOL-11 | A-5-1 #1 | Female | Young Adult | −19.6 | 7.4 | −11.7 | −3.9 | |
| SOL-11 | F-7-5 | Indet. | Adult | −19.1 | 8.2 | −13.7 | −4.7 | |
| SOL-11 | E-6-5 | Indet. | Adult | −18.9 | 9.6 | −12.5 | −4.7 | 2100 ± 25 |
| SOL-11 | F-7-4 | Indet. | Infant | −19.0 | 10.5 | −13.2 | −4.0 | |
| SOL-11 | G-7-1b | Indet. | Adult | −18.4 | 9.9 | −13.9 | −4.5 | |
| SOL-11 | G-6-1 #2 | Indet. | Adult | −18.7 | 9.8 | −12.8 | −4.2 | |
| SOL-69 | B97-3 | Indet. | Old Adult | −19.3 | 8.4 | n/a | n/a | |
| SOL-69 | B98-2 | Male | Old Adult | −18.3 | 10.7 | n/a | n/a | |
| SOL-69 | B98-4 | Male | Young Adult | −19.5 | 9.3 | n/a | n/a | |

Notes: All isotopic values given in permil (‰) relative to standards (Air and Pee Dee Belemnite for N and C, respectively). Burial number indicates lot assigned by Snoke or Wiberg, #1 indicates first individual within burial lot, generally the main burial identified in the field, and #2 indicates an additional individual represented through subsequent laboratory analysis (e.g., a duplicating skeletal element). Radiocarbon dates given in uncalibrated years BP.

67 individuals (92%) falling in a narrow range between −19.8‰ and −18.4‰. These individuals are also relatively depleted (i.e., low) in $\delta^{15}N$. Indeed, the majority of the samples have $\delta^{15}N < 10‰$, indicative of consumption of low trophic level (and terrestrial, judging by $\delta^{13}C_{col}$) foods. However, a small number ($n = 6$; two male, four indeterminate sex) have $\delta^{13}C_{col}$ between −18.3 and −17.3‰, indicative of elevated levels of marine-derived carbon. These samples are simultaneously elevated in $\delta^{15}N$.

We compare the CA-SOL-11 and -69 data to $\delta^{13}C_{col}$ and $\delta^{15}N$ data from several other ecological regions in California where isotopic analyses have also been undertaken with human bone collagen. These samples include Late Holocene (3000−300 BP) burials from the Sacramento Valley/Plains (CA-SOL-270 and CA-YOL-110; unpublished data produced by Eerkens) and along the Sacramento River (CA-SAC-43 and -60; data from Bartelink, 2009; Bartelink and Yoder, 2008), San Francisco Bay (CA-ALA-309, -328, -329; Bartelink, 2009), Ellis Landing Shellmound (CA-CCO-295, also on San Francisco Bay; Beasley et al., 2013) and coastal foragers from Southern California Channel Islands (Rick et al., 2011), Central California (Jones, 1998), and Northern California (Bartelink, 2006). Fig. 1 shows the location for the Central California samples, while Fig. 5 shows the geographic location of these additional regional samples relative to Suisun Marsh (where CA-SOL-11 and -69 are located).

Table 3 gives the average and standard deviation of the three isotope ratios for each region, as well as the sample size. T-tests (2-tailed, assuming unequal variance) comparing means between the CA-SOL-11 and -69 samples and these other regional samples are less than 0.05 for nearly every comparison, the only exception being $\delta^{15}N$ with the Central Coast sample. This suggests that the isotope values for humans near Suisun Marsh are drawn from a different underlying sample than the other regions. In other words, humans in all these other regions are accessing protein from very different isoscapes than the Suisun Marsh foragers.
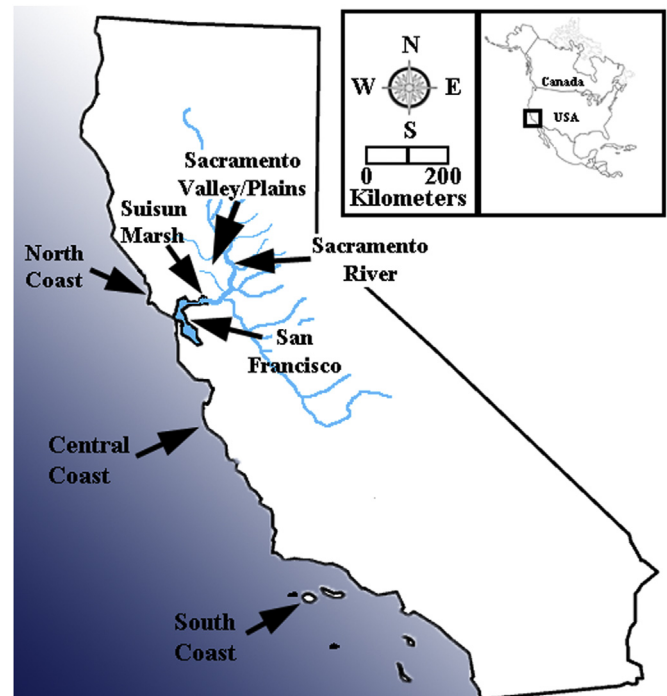


Fig. 5. Map showing locations of regional human bone isotope samples from Central California.

**Table 3**
Comparison of regional samples from California.

| Region | # samples | $\delta^{15}N$ avg | $\delta^{15}N$ stdev | $\delta^{13}C_{col}$ avg | $\delta^{13}C_{col}$ stdev | $\delta^{13}C_{apa}$ avg | $\delta^{13}C_{apa}$ stdev |
|---|---|---|---|---|---|---|---|
| CA-SOL-11 & -69 | 67 | 9.34 | 1.28 | −18.97 | 0.52 | −12.55 | 0.87 |
| Sacramento Valley | 74 | 7.94* | 1.22 | −19.73* | 0.45 | −12.73 | 1.28 |
| Sacramento River | 13 | 11.25* | 0.65 | −19.91* | 0.34 | −13.17 | 1.14 |
| San Francisco Bay | 21 | 10.17* | 1.64 | −17.57* | 1.12 | −13.23* | 0.99 |
| CA-CCO-295 | 65 | 14.70* | 1.63 | −14.34* | 1.31 | −10.84* | 1.02 |
| North Coast | 4 | 16.04* | 0.35 | −13.40* | 0.41 | −10.11* | 0.36 |
| Central Coast | 6 | 9.07 | 1.87 | −16.87* | 1.13 | n/a | n/a |
| South Coast | 15 | 17.40* | 1.79 | −13.56* | 0.81 | n/a | n/a |

Notes: n/a = data not available (apatite not run); * = T-test (2-tailed, unequal variance) $p < 0.05$ in comparison to CA-SOL-11 and -69 samples.

Fig. 6 shows $\delta^{13}C_{col}$ vs. $\delta^{15}N$ for all 67 individuals in our sample. As shown, the CA-SOL-11 and -69 samples occupy a distinctive region in the center of the bivariate plot. As the differing means in Table 3 also suggested, the partitioning by region suggests that local ecologies played an important role in the types of foods humans collected and consumed that are reflected in isotope values.

Overall, there is a linear and positive correlation between $\delta^{13}C_{col}$ and $\delta^{15}N$ in the CA-SOL-11 and -69 samples, resulting in an elongated cloud of points in Fig. 6. Samples at the lower left end of the CA-SOL-11 and -69 distribution overlap with some Sacramento Valley/Plains individuals. This suggests that lower-trophic protein consumers near Suisun Marsh may have been exploiting valley/plains-like environments to the north and east for much of their protein, especially relative to foragers in the upper right part of the point cloud, who appear to have accessed more brackish water protein. There is no isotopic overlap between the CA-SOL-11 and -69 foragers with individuals from any of the coastal regions (south, central, or north), nor from foragers living along the Sacramento River.

A similar elongated $\delta^{13}C_{col}-\delta^{15}N$ ellipse is also evident in burials from other marine-influenced environments in California, including individuals recovered in shell mounds on San Francisco Bay (Bartelink, 2009; Beasley et al., 2013), the central coast (Jones, 1998), the north coast near Tomales Bay (Bartelink, 2006), and Santa Rosa Island in southern California (Rick et al., 2011). The cloud

of points from San Francisco Bay and the Central Coast are shifted to the right of CA-SOL-11 and -69, and seem to have lower slopes. Holding trophic level constant (as measured by $\delta^{15}N$), this suggests that protein sources in San Francisco Bay and especially the Central Coast contain higher amounts of marine-derived carbon (i.e., enriched $\delta^{13}C_{col}$). This is consistent with the modern salinity data discussed above, where both these environments have much higher mean salinities than Suisun Marsh.

Likewise, protein sources from the Sacramento River and Sacramento Valley at the same trophic level are depleted in $\delta^{13}C_{col}$ relative to CA-SOL-11 and -69, consistent with freshwater foraging in the former. $\delta^{13}C_{col}$ and $\delta^{15}N$ are not obviously positively correlated for individuals from Sacramento River and Valley, resulting in more circular clouds of points for these two ecosystems. These results suggest different relationships for C and N fractionation in freshwater and terrestrial ecosystems, and more importantly, suggests the presence of distinctive diets, foodwebs and/or foraging strategies in the different ecosystems of Central California.

Data from all regions, especially CA-SOL-11 and -69 and San Francisco Bay, show considerable variation between individuals, especially in $\delta^{15}N$. This suggests that there is significant dietary variation, not only between regions as discussed above, but also *within* regions. We aim to explore the source of this variation in greater detail in future studies (e.g., by age, sex, and health). However, this result shows that there are many different but successful foraging strategies that individuals can pursue within a given region. We believe the implications of dietary heterogeneity on our understanding of human foraging patterns and longer-scale evolutionary trajectories in human behavior are important (but beyond the scope of this paper).

Fig. 7 plots $\delta^{13}C_{col}-\delta^{13}C_{apa}$ for the CA-SOL-11 and CA-SOL-69 individuals relative to the Froehle et al. (2010) dietary model. Also plotted are individuals from San Francisco Bay, Sacramento Valley, and Sacramento River. Note that nearly 50% of the CA-SOL-11 and -69 samples fall outside the endpoints of the controlled feeding experiments (points on the lower right in the gray area), as do nearly all of the Sacramento River and Valley samples. These samples have very high apatite−collagen spacing values, where $\delta^{13}C_{apa}$ apatite is over 8‰ lighter than $\delta^{13}C_{col}$, and as a result, they
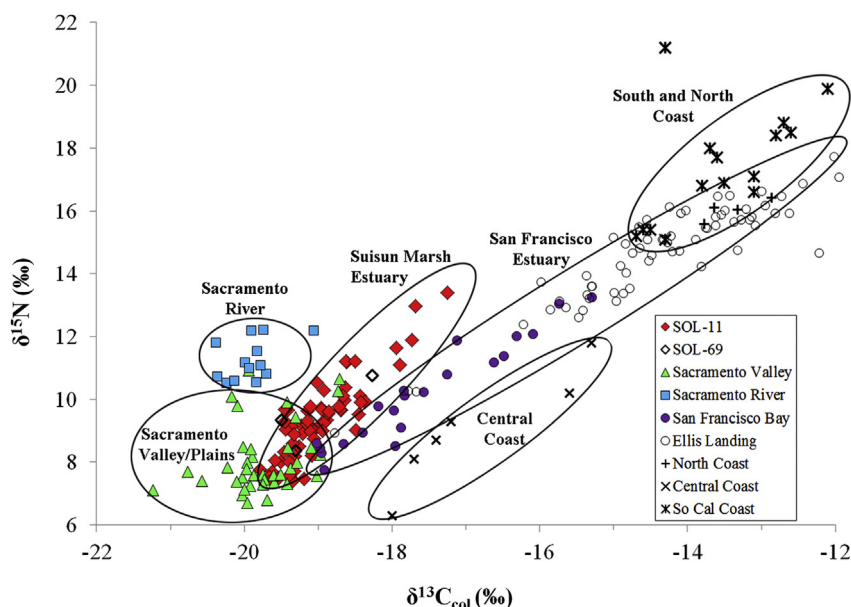


**Fig. 6.** $\delta^{13}C_{col}$ and $\delta^{15}N$ at CA-SOL-11 and CA-SOL-69 relative to nearby regions with distinctive foodwebs.
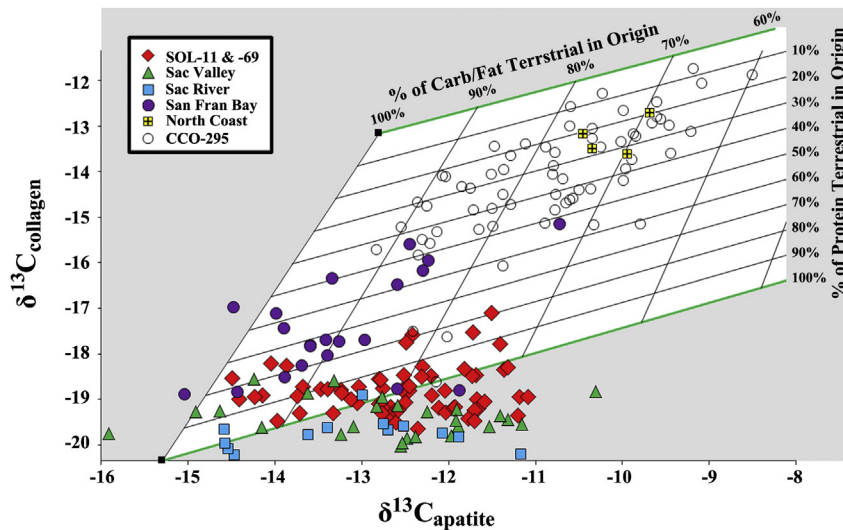
**Fig. 7.** $\delta^{13}C_{col}$ and $\delta^{13}C_{apa}$ at CA-SOL-11 relative to the Froehle et al. (2010) model.

fall below the 100% terrestrial protein line. The reason these samples fall outside the modeled isotopic space is not known, but may reflect a different isotopic pool of carbon available in freshwater aquatic systems, such as Sacramento River and its tributaries, versus C3 plants growing on nearby soils. Alternatively, it could indicate differences between how animals, such as pigs and rats, and humans route macronutrients to bone tissues. Additional controlled dietary experiments, preferably with humans, are clearly needed to address this issue. In any case, it is clear from Fig. 7 that the Froehle et al. (2010) model needs to be modified when applied to Central California foragers. Perhaps the C3 protein line needs to be lowered to include the samples below the "100% C3 protein" line. If so, the net effect on our estimates would be to lower slightly the contribution of terrestrial protein to the overall diet.

Leaving aside this issue, Fig. 7 suggests that carbohydrates and fats were predominantly from terrestrial environments for *all* Central and Northern California individuals. While the contribution of marine-derived protein varies across the full spectrum (0% for most Sacramento River and Valley people, to nearly 100% for some CA-CCO-295 individuals), no individual seems to have gained more than 40% of their carbohydrate and fat carbon from marine sources. This is consistent with the notion that marine foods are rich in protein but poor in fats and especially carbohydrates (e.g., shellfish, fish). Surprisingly, $\delta^{13}C_{apa}-\delta^{13}C_{col}$ values from the CA-SOL-11 and -69 samples using the Froehle model suggest that, although it was small, as a percentage, marine carbon actually contributed more to the carbohydrate/fat component of the diet (average 18%) than the protein component (average 2%). The reason for this is unclear, but is considered again below.

In any case, Fig. 7 shows that, together with the Sacramento River and Sacramento Valley samples, the CA-SOL-11 and -69 individuals have a different relationship between $\delta^{13}C_{apa}$ and $\delta^{13}C_{col}$ than San Francisco and coastal foragers. In particular, these point clouds seem to fall on an upper-left to lower-right diagonal through the isobars in Fig. 7. This suggests an inverse relationship between marine-derived protein and marine-derived carbohydrate and fat. In other words, individuals accessing greater amounts of marine-derived protein seem to be balancing their diet with greater amounts of terrestrial carbohydrate and fat, and vice versa. This relationship does not hold for the San Francisco Bay and CA-CCO-295 samples, where marine carbon is positively correlated in the protein and carbohydrate/fat components. That relationship indicates that coastal foragers used the bay (or coast) to increase yields of *all* their macronutrients simultaneously, not just protein or just carbohydrate/fat.

## 6. Discussion

As expected, individuals at CA-SOL-11 and -69 display a distinctive isotopic signature relative to foragers in other nearby environments. Although these foragers were accessing similar trophic levels as those in San Francisco Bay for dietary protein (outside of CA-CCO-295), as indicated by the identical range in collagen $\delta^{15}N$ values, carbon isotope ratios indicate the source of these foods was different. Likewise, carbon isotopes at CA-SOL-11 and -69 are unlike foragers living on the fully freshwater Sacramento River. Instead, the signature is consistent with the incorporation of significant amounts of brackish water resources into the diet, between the more marine San Francisco Bay and the fully fresh Sacramento River. This leads to the spatially distinctive cloud of points from the two sites in Fig. 6. Individuals at the upper right extreme were consuming more protein from these brackish-water marshes than the majority of individuals at the site, who fall in the lower left of the point cloud. The latter gained the majority of their protein from low trophic level terrestrial sources, such as plants and herbivorous mammals.

Brackish resources were likely gathered from the adjacent Suisun Marsh, or perhaps nearby White Slough, where isotopically heavy terrestrial and isotopically light marine sources of carbon mix. Salinity is a general indicator of the amount of marine-based carbon present and varies spatially and temporally in Suisun Marsh. For example, a hydrographic station maintained by the USGS in Suisun Marsh (see http://sfbay.wr.usgs.gov/access/wqdata, station 7) shows that modern salinity of near-surface water averages 8.5‰ psu throughout the year (minimum = 0‰, maximum = 22.3‰). Along the California Coast, salinity in seawater is more stable around 33‰, thus, Suisun Marsh averages about 25% seawater (and 75% freshwater). However, salinity in Suisun Marsh is highly variable from year to year depending on rainfall and runoff conditions, and more significantly, varies within a given year. Salinity is lowest during late winter and early spring when it averages just 4‰, and is highest during late summer and fall when it averages 13‰. It is likely that salinity in Suisun Marsh was slightly lower in prehistory due to modern diversions of water upstream for agriculture (Byrne et al., 2001; Peterson et al., 1989), though the period between 1600 and 1300 cal BP had notably

higher salinity in San Francisco Bay (Malamud-Roam and Ingram, 2004). Radiocarbon dates on CA-SOL-11 and -69 individuals indicate they pre-date this increase in salinity.

It is difficult to estimate the percent of the diet at CA-SOL-11 and -69 derived directly from Suisun Marsh (versus non-marsh terrestrial sources) for several reasons. First, Suisun Marsh has both terrestrial and marine carbon available in a range of forms that are not well documented (e.g., dissolved organic, dissolved inorganic, bicarbonate). Second, the percent of carbon from these two sources fluctuates seasonally and we do not know which season foragers would have emphasized the collection and consumption of marsh vs. non-marsh foods. Third, some marsh foods, such as salmon, carry fully marine carbon signatures with them into the interior (i.e., because they do not eat once they begin migrating inland to spawn). Likewise, other marsh foods bring fully terrestrial carbon signatures (e.g., fish migrating downstream during higher river flow in winter).

Indeed, in a broad study of plant samples taken from both San Francisco Bay and the Delta, Cloern et al. (2002) found it difficult to develop micro-habitat isotopic signatures for plants and microbiota (phytoplankton and diatoms). Instead, isotopic composition of plants varied significantly across the seasons and changed during the decomposition process. They did, however, find isotopic differences between freshwater-dominant and marine-water-dominant ecosystems, consistent with our comparison of humans foraging in these different environments. Likewise, Jassby et al. (1993) found that the quantity and source of organic content in Suisun Marsh waters varied significantly across the year, though the Sacramento River contributed the majority of available carbon in all seasons. These studies, and others, demonstrate the complexity of carbon cycling in Suisun Marsh and the San Francisco Bay estuary, and suggest our understanding of these processes is far from complete.

What we *can* say, however, is that marine carbon seems to have comprised a non-trivial fraction of total carbon in nearly all the CA-SOL-11 and -69 individuals. Based on our estimates using the Froehle et al. (2010) model, marine carbon contributed between 0% and 25% of protein and between 0% and 33% of carbohydrate and fat. We assume the majority of this marine carbon came from Suisun Marsh, and was not accessed directly on the coast, due to the lack of coastal remains (e.g., marine fish, shellfish) in the middens of these sites. Thus, we suggest marsh foods contributed a large fraction of total nutrition to the foragers at these sites.

Excavations at SOL-11 did not attempt to recover or identify fish bone. Likewise, although a small number of sturgeon scutes have been identified at several nearby sites, including CA-SOL-69 (Wiberg, 1992, 1993), and fish vertebrae have been recovered, there have been no attempts to identify salmon specifically in those assemblages. Thus, we cannot evaluate the role of anadromous or marsh fish in the diet from midden constituents. On the other hand, brackish-water foods such as bay mussels are a common component of Green Valley archaeological sites (Wiberg, 1992, 1993), likely including SOL-11 where Snoke (1967) specifically noted the high density of shell. Such shellfish were harvested from the brackish marshes and hauled back to these sites. The volume of shellfish at CA-SOL-11, -69, and other nearby sites, indicates that inhabitants must have made frequent visits to the marsh.

Given the protein-rich nature of many brackish-water resources, especially shellfish and anadromous fish, it is somewhat surprising that the marine carbon signal is actually stronger in the carbohydrate/fat component of the diet. Why this might be so is unclear to us, however, we offer three possibilities that should be explored in future research. First, it is possible that the Froehle model as shown in Figs. 4 and 7 is not suitable for application in Central California, and needs significant reworking. Second, it is possible that inhabitants of these sites were consuming higher quantities of C4 plants than is commonly assumed based on ethnographic reports and remains recovered in the archaeological record (which indicate virtually no consumption of them). Such C4 salt-marsh plants could have included cordgrass (*Spartina foliosa*) and salt grass (*Distichlis spicata*). Third, perhaps inhabitants of these sites differentially accessed fat-rich (vs. protein-rich) foods from Suisun Marsh with high amounts of marine carbon, such as small oily fishes or sturgeon, or waterfowl (and/or their eggs). If so, it is unclear why they would forego more protein-rich foods from the marsh only in favor of these other resources.

## 7. Conclusions

Stable isotope analyses of bone collagen and apatite from 67 individuals from CA-SOL-11 and -69 indicate that prehistoric inhabitants had a diet rich in brackish-water resources. Such resources were presumably harvested from nearby Suisun Marsh to the south (and perhaps White Marsh to the west). The majority appears to have come from relatively low trophic levels, suggesting a heavy component of plants in the diet (e.g., acorns, roots, small seeds). Significant brackish-water foraging created a distinctive population-level isotopic signature, unique relative to Late Holocene groups living on the California coast, San Francisco Bay, along the Sacramento River, and in the plains of the Sacramento Valley.

We believe this signature can be used to help identify recent immigrants and non-locals to archaeological sites both near the Suisun Marsh shore, if they fall within the range of other environments, or alternatively in other areas if they overlap with CA-SOL-11 and -69 samples. For example, a small number of the individuals from CA-CCO-295 and San Francisco Bay shore fall within the CA-SOL-11 and -69 point cloud. These may represent recent immigrants from the latter into the former sites. Additional isotopic data from other elements, such as Sr, burial style, or non-local artifact types could be used to corroborate such isotopic information.

In spite of the importance of the marsh in local diets, inhabitants did not establish their village directly on the shores of the marsh, but instead, placed it at an inland location some 10 km from the marsh edge. This implies that access to other resources in more inland locations must also have been important. Such resources could have included carbohydrate- and lipid-rich plants (e.g., grass seeds, acorns), but could also have included other resources such as freshwater, toolstone, and/or access to trading corridors.

Finally, we believe the data underscore the value of stable isotope analysis on human bone when faunal or paleobotanical remains are largely lacking, as is the case at CA-SOL-11, or minimal, as is the case at CA-SOL-69. In such a case, collagen and apatite isotope data can help fill in a significant gap in our understanding of ancient diet and nutrition.

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