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A Test of Ideal Free Distribution Predictions Using Targeted Survey and Excavation on California's Northern Channel Islands

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Abstract Using targeted survey, excavation, and radiocarbon dating, we assess the extent to which human settlement patterns on California's northern Channel Islands fit predictions arising from the ideal free distribution (IFD): (1) people first established and expanded permanent settlements in the regions ranked high for environmental resource suitability; (2) as population grew, they settled in progressively lower ranked habitats; and (3) changes in the archaeological record associated with high population levels such as increases in faunal diversity and evenness in high-ranked habitats are coincident with the expansion to other areas. On Santa Rosa Island, the early permanent settlements were located in both high- and middle-ranked locations, with the most extensive settlement at the highest ranked locations and only isolated sites elsewhere. Settlement at a low-ranked habitat was confined to the late Holocene (after 3600 cal BP). Drought influenced the relative rank of different locations, which is an example of climate adding a temporal dimension to the model that episodically stimulated population movement and habitat abandonment. Because the IFD includes a wide range of cultural and environmental variables, it has the potential to be a central model for guiding archaeological analysis and targeted field research.

Keywords Settlement patterns · Ideal free distribution · Coastal archaeology · Environmental archaeology · Shell midden analysis · Complexity

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Introduction

The settlement patterns of mobile hunter-gatherer populations can include ephemeral camps, seasonal residential bases, logistical sites and, in some cases, permanent settlement sites occupied annually or continuously (*e.g.*, Kelly 2013). The location of larger sites with permanent or semipermanent occupation usually takes into account a suite of environmental and socioeconomic factors. The ideal free distribution or IFD (Åström 1994; Fretwell and Lucas 1969; Fretwell 1972; Sutherland 1983, 1996; Treganza 1995) is used in behavioral ecology and increasingly in anthropology and archaeology to understand how such factors affect human settlement and broader patterns of decision-making and culture change (*e.g.*, Kennett 2005; Kennett *et al.* 2006, 2009; Kennett and Winterhalder 2008; McClure *et al.* 2009; Winterhalder *et al.* 2010; Culleton 2012; O'Connell and Allen 2012; Jazwa *et al.* 2013; Codding and Jones 2013; Giovas and Fitzpatrick 2014; Moritz *et al.* 2014; Codding and Bird 2015).

The IFD uses habitat suitability measures to generate predictions about regional population movement and distribution. It can be used to understand settlement patterns on both large (*e.g.*, Fitzhugh and Kennett 2010; Allen and O'Connell 2008) and small (*e.g.*, Kennett *et al.* 2006; Culleton 2012) scales. It is flexible enough to address questions about where people settled as they entered and expanded throughout California (Codding and Jones 2013) and which drainage on a small island people would choose to establish individual sites (Winterhalder *et al.* 2010).

The model is constructed by calculating the relative suitability of different habitats based on the spatial distribution of available environmental resources and cultural factors that influence their value. People should first settle the habitat with the highest overall base suitability. As population density increases, resource exploitation and interference competition cause a decrease in the effective suitability of that habitat, eventually making it advantageous to expand into and settle lower ranked habitats. A variety of more specific predictions and implications follow from this pattern (see Kennett *et al.* 2009; Winterhalder *et al.* 2010; Jazwa *et al.* 2013). In a variant of the IFD, the ideal despotic distribution (IDD), the inhabitants of a high-ranked habitat defend a disproportionate share of resources and impede in-migration, causing expansion of the overall population to more marginal habitats earlier than predicted by the IFD (Summers 2005; Kennett and Winterhalder 2008; Kennett *et al.* 2009, 2013; Culleton 2012; Bell and Winterhalder 2014).

We use the IFD and IDD to aid understanding of human settlement on Santa Rosa Island, one of California's four northern Channel Islands (NCI), located off the coast of Santa Barbara (Fig. 1). The NCI are particularly well suited to employ the IFD. First, there is a comprehensive archaeological record available for the islands that includes an existing database of radiocarbon dates and diagnostic artifacts, allowing a multi-island perspective that would not be feasible in a less-studied area (see Kennett 2005; Rick et al. 2005; Jazwa and Perry 2013). Second, the limited array of settlement options on the NCI allows for a model that is more inclusive of all potential settlement locations. Third, the islands have a relatively limited and thus manageable number of natural resources, facilitating accurate assessment of suitability. Finally, the islands were visited and used for thousands of years before permanent settlement (see Erlandson *et al.* 2011). When chosen, settlement locations were selected with a great deal of local
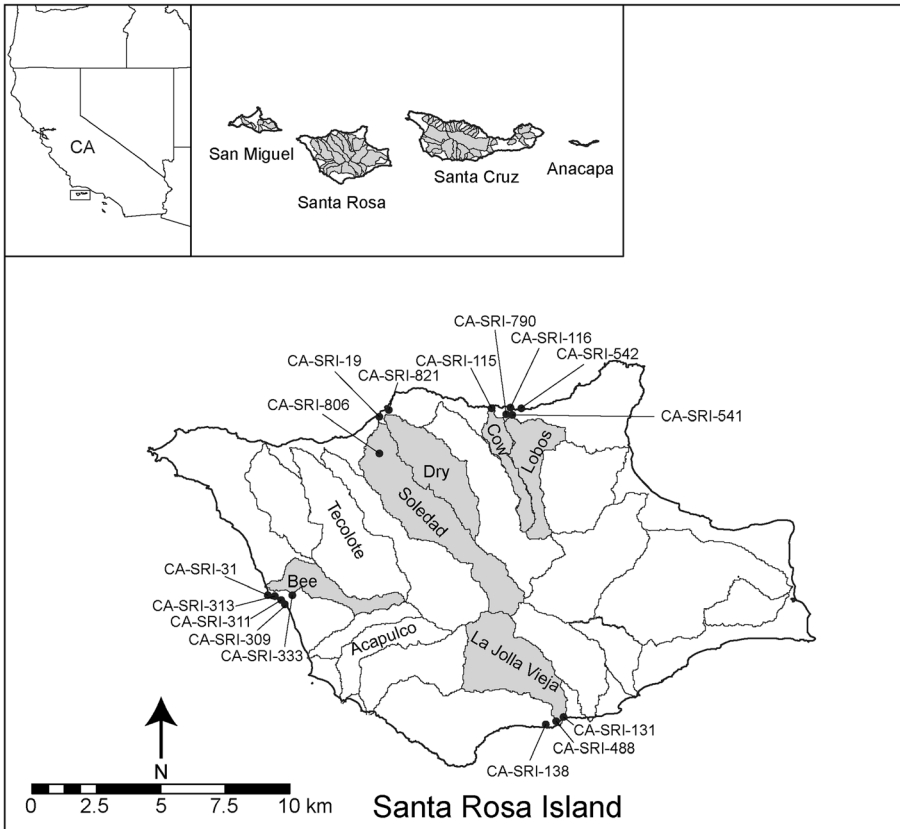
Fig. 1 Santa Rosa Island. The 19 major drainages are outlined and coastal sites indicated. Drainages with excavated habitats are highlighted in *gray*. Sites and drainages mentioned in the text are labeled

environmental experience and knowledge, increasing the likelihood that people made economically informed choices.

One of us (CSJ) surveyed and excavated coastal sites at four differently ranked drainage systems on Santa Rosa Island in 2012, 2013, and 2014: Soledad and Dry Canyons (high-ranked), Cow and Lobos Canyons (middle-ranked, adjacent to high-ranked areas), La Jolla Vieja Canyon (middle-ranked, isolated), and Bee Canyon (low-ranked), using the suitability rankings from Winterhalder *et al.* (2010). Based on these data, we assess a variety of hypotheses and find that the results largely conform to IFD predictions.

California's Northern Channel Islands

People visited and seasonally exploited environmental resources available on the NCI by at least 13,000 years ago (Erlandson *et al.* 2007, 2008, 2011; Johnson *et al.* 2002; Kennett 2005; Kennett *et al.* 2008). Sea levels were lower than at present (~70–75 m at 13,000 years ago) and the four islands were all connected to form one landmass, Santarosae (Kennett *et al.* 2008; Watts *et al.* 2011; Reeder-Myers *et al.* 2015), but they

were never connected to the mainland. With eustatic sea level rise, the islands had become separated by the time of the earliest evidence for their permanent settlement at approximately 8000 years ago (Winterhalder *et al.* 2010). This rise in sea level caused a 65 % decrease in land area and may have submerged evidence of early permanent settlement (Kennett *et al.* 2008). Thus, it is unclear whether early ephemeral sites on the island were culturally associated with submerged coastal sites or with more permanent sites on the mainland (Kennett 2005). Even if some early settlement sites have been lost, we can use the IFD to assess decisions about settlement location and persistence subsequent to the rise in sea level. Any patterns could then guide a search for submerged sites.

The productive environment of the Santa Barbara Channel region has prompted an emphasis among researchers on marine resources (*e.g.*, Kennett 2005; Rick *et al.* 2005; Erlandson *et al.* 2007, 2008, 2011). The earliest known occupants of these islands targeted fish, shellfish, and sea mammals such as pinnipeds and dolphins. During the middle Holocene (7550–3600 cal BP), a distinctive settlement system included large coastal settlement sites at the mouths of major streams, interior residential bases, and special purpose sites for collecting and shucking abalones (Clifford 2001; Kennett and Clifford 2004; Jazwa *et al.* 2015a). This system was primarily concentrated on the resource-rich north coast of Santa Rosa Island, with the exception of a series of abalone shucking sites on the west coast.

Throughout the Santa Barbara Channel region, there was a general increase in fishing and sea mammal hunting through time, which was accompanied at many sites by a decrease in shellfish collecting. This trend is particularly pronounced on the islands (Arnold 1992a; Braje *et al.* 2007; Colten 2001; Glassow 1977, 1993; Jazwa *et al.* 2012, 2013; Jazwa and Perry 2013; Kennett 2005; Kennett and Kennett 2000; Kennett and Conlee 2002; Raab *et al.* 1995; Rick 2007; Rick *et al.* 2008). Fish and sea mammals became particularly important during the late Holocene (after 3600 cal BP). Changes in diet like these can result from multiple causes, including resource depression, environmental change, sociocultural change, technological developments, and economic change. For example, a decrease in the size and abundance of high-ranked dietary items, coupled with an increase in dietary diversity, can reflect resource depression; opposite trends would be associated with resource recovery (see Braje *et al.* 2007; Jazwa *et al.* 2012 for NCI examples; more generally, see Bettinger 1991; Nagaoka 2002; Codding and Bird 2015; Singh and McKechnie 2015).

The relationship between environmental and sociopolitical change has been an important topic of research on the NCI (Arnold 1992a, 2001a; Arnold and Graesch 2004; Arnold and Tissot 1993; Braje *et al.* 2007; Erlandson and Jones 2002; Jazwa *et al.* 2012; Jazwa and Perry 2013; Kennett and Kennett 2000; Kennett *et al.* 2007, 2008; Raab and Larson 1997; Glassow *et al.* 2012). In parallel, there have been several attempts to generate high-resolution records for sea surface temperature (Arnold and Tissot 1993; Kennett 2005; Kennett and Kennett 2000; Pisias 1978) and drought (Raab and Larson 1997) in the Santa Barbara Channel region.

During the late Holocene, there were important environmental, technological, economic, and sociopolitical changes on the NCI (see Rick *et al.* 2005; Glassow *et al.* 2010). More intensive predation on fish and sea mammal populations during the late Holocene may be related in part to the development of the single-piece fishhook by 2500 cal BP (Strudwick 1986; Rick *et al.* 2002) and ocean going plank canoes (*tomol*)

after 1500 cal BP. The latter provided a more reliable form of marine transportation than was available previously. It allowed the occupants of the Santa Barbara Channel region to travel more quickly and farther from shore with larger amounts of cargo, and it provided a more stable platform for fishing and sea mammal hunting (Arnold 1992a, 1995, 2001a; Gamble 2002; Fagan 2004). Beginning around 1300 cal BP, the rate of population increase on the NCI accelerated and the number of permanent settlements increased dramatically (Arnold 2001a; Kennett 2005; Kennett and Conlee 2002; Winterhalder et al. 2010). The first signs of institutionalized status differences appeared after this time (e.g., Arnold 1992a, 2001a; Kennett et al. 2009).

The Middle to Late Period Transition (MLT; 800–650 cal BP) has also been associated with important changes (Arnold 1991, 1992a, 1997, 2001b; Arnold and Tissot 1993; Arnold et al. 1997; Jazwa et al. 2012; Jazwa and Perry 2013; Kennett 2005; Kennett and Conlee 2002; Perry and Jazwa 2010; Raab and Larson 1997). For example, the Callianax biplicata (purple olive) shell bead industry grew significantly, providing an important trade good (Arnold 1987, 1990, 1992a, b, 2001a; Arnold and Munns 1994; Munns and Arnold 2002, pp. 132–133; Kennett 2005; King 1990; Rick 2007). Many of the changes of this period can be related to environmental stress (Arnold 1991, 1992a, 1997, 2001b; Arnold and Tissot 1993; Arnold et al. 1997; Colten 2001; Jazwa et al. 2012; Jones et al. 1999; Jones and Schwitalla 2008; Lambert and Walker 1991; Lambert 1993, 1997; Kennett 2005; Kennett and Conlee 2002; Kennett and Kennett 2000; Kennett et al. 2007, 2008; Pisias 1978; Pletka 2001; Raab and Larson 1997; Stine 1994; Yatsko 2000).

The MLT occurred during a period of extreme droughts associated with the Medieval Climatic Anomaly (1150–600 cal BP; Kennett 2005; Jones et al. 1999; Jones and Schwitalla 2008; Raab and Larson 1997; Stine 1994; Yatsko 2000) that were felt throughout the American Southwest (Jones et al. 1999; Jones and Schwitalla 2008; Bocinsky and Kohler 2014). Osteological data from the Santa Barbara Channel region reveal peaks in health problems and violence (Lambert and Walker 1991; Walker 1989; Walker and Lambert 1989; Lambert 1993) associated with increasing sedentism and diminishing supplies of fresh water and terrestrial foods. Kennett (2005; also Jones and Schwitalla 2008) extends the period of drought and violence further back in time to 1500 cal BP. Population aggregation around wetter, more resource-rich areas may have been a stimulus for some of the changes that occurred during this period. However, there are relatively few well-documented and precisely dated sites that have been associated with the MLT (e.g., Arnold 1991, 1992a, b; Raab and Larson 1997; Yatsko 2000; Munns and Arnold 2002; Perry 2003; Kennett 2005; Rick et al. 2005; Rick 2007; Glassow et al. 2010; Jazwa et al. 2012).

The Channel Islands and the IFD

Kennett et al. (2009) generated an initial IFD model for the NCI, ranking suitability of potential coastal settlement locations based on weighted assessments of (1) length of accessible rocky intertidal coastline, (2) length of accessible sandy beach, (3) area of kelp forests within a 2-km radius, and (4) fresh water availability, estimated by watershed size. Watersheds were chosen as a unit of analysis for reasons given in Kennett (2005) and Kennett et al. (2009). Fresh water availability is watershed

dependent (Jazwa *et al.* 2015b; Winterhalder *et al.* 2010), and large primary NCI settlements are almost all along the coast at the mouths of major drainages (Kennett *et al.* 2009; Winterhalder *et al.* 2010; Jazwa *et al.* 2013). These suitability rankings were then compared with archaeological evidence for age of first permanent settlement and the persistence of use. However, evidence for environmental change, population change within sites, and human impacts on suitability (*i.e.*, cultural and technological changes) was not considered.

In a follow-up analysis that uses settlement order to assess environmental suitability, Winterhalder *et al.* (2010) found that watershed size, used as a proxy for fresh water availability, was the most important predictor of initial settlement and persistence. Kelp forest area and sandy beach length became more important through time, consistent with the increasing reliance on fish and sea mammals, the development of the *tomol*, and the expansion of the *C. biplicata* shell bead industry. In a second follow-up, Jazwa *et al.* (2013) examined archaeological collections from sites at the mouth of Old Ranch Canyon in eastern Santa Rosa Island to assess consequences for IFD predictions associated with closure of an estuary and the technological developments of the late Holocene. Both of these temporal changes in suitability are reflected in the archaeological assemblage from the site in a manner consistent with IFD predictions.

Here, we further adapt application of the IFD model using a regimen of targeted survey, excavation, and analysis of shell midden collections. We define permanent settlements as having substantial residential middens, cemeteries, or houses (Winterhalder *et al.* 2010), but do not require that these sites be inhabited year-round or without short hiatuses. Occupation of these sites indicates persistent settlement in a given location. We use watersheds as our unit of analysis, but refine the estimates of fresh water flow and drainage resilience using hydrological simulations (Jazwa *et al.* 2015b) to assess the assumption by Winterhalder *et al.* (2010) that watershed size is a good proxy for fresh water availability. We use weights of environmental contributions to suitability similar to those of Kennett *et al.* (2009). We assign weighted *z*-scores for drainage size (10 %), water flow (30 %), drainage resilience (10 %; percent water flow loss from a median to a dry century), length of rocky intertidal shoreline (30 %), length of sandy beach (5 %), and area of kelp beds (15 %; Table 1).

Model Expectations

Model predictions are similar to those outlined by Kennett *et al.* (2009), Winterhalder *et al.* (2010), and Jazwa *et al.* (2013): (1) the highest ranked locations should contain the earliest evidence for permanent settlement; (2) over time there should be evidence for resource depression at these locations, including decreases in the abundance and perhaps size of high-ranked resources along with evidence for dietary diversification to include lower ranked resources; (3) dates of settlement for lower ranked locations should coincide with periods of resource depression in nearby higher ranked locations; and (4) settlement at the highest ranked locations should persist even as settlement expands to other sites.

Two further predictions arise from the observation that habitat suitability can be affected by factors not directly related to population density: (5) extrinsic environmental change can depress suitability (Braje *et al.* 2007; Jazwa *et al.* 2012) and (6)

Table 1 Watershed rankings for Santa Rosa Island. z-scores are calculated for each of the primary variables and weighted by 10 % drainage size, 30 % water flow, 10 % resilience (percent flow lost is negative), 30 % rocky intertidal, 5 % sandy beach, and 15 % kelp bed density (see Jazwa et al. 2015b)

Drainage	Rank	Weighted score	Drainage size		Water flow		Resilience		Rocky intertidal		Sandy beach		Rocky headlands		Kelp bed density	
			km²	z-score	m³/day	z-score	% Flow	z-score	km	z-score	km	z-score	km	z-score	km²	z-score
Tecolote	1	1.27	12.14	0.96	338.36	1.92	2.83	−0.88	3.82	1.17	0.71	−1.00	0.00	−0.73	1.70	1.39
Arlington	2	0.85	11.93	0.92	303.70	1.38	2.63	−1.10	2.87	0.32	1.54	−0.14	0.00	−0.73	1.46	0.97
Trancion	3	0.54	7.36	−0.15	302.61	1.37	3.59	−0.02	2.73	0.19	2.10	0.45	0.00	−0.73	1.13	0.40
Verde	4	0.47	11.83	0.89	242.11	0.43	3.94	0.37	4.30	1.60	0.30	−1.43	0.56	−0.01	0.43	−0.81
Soledad	5	0.39	12.28	1.00	285.29	1.10	3.65	0.05	2.57	0.05	1.95	0.29	0.21	−0.46	0.67	−0.40
Garanon	6	0.13	6.83	−0.28	199.53	−0.22	3.40	−0.24	4.29	1.59	0.02	−1.72	0.00	−0.73	0.17	−1.26
Old Ranch House	7	0.10	4.17	−0.90	160.12	−0.83	3.97	0.40	3.79	1.14	2.51	0.87	0.11	−0.59	1.25	0.61
Dry	8	0.00	6.84	−0.28	227.67	0.21	3.56	−0.05	2.66	0.13	1.95	0.29	0.21	−0.46	0.55	−0.61
Acapulco	9	−0.07	4.83	−0.75	158.34	−0.86	2.98	−0.70	2.56	0.04	2.47	0.83	0.00	−0.73	1.44	0.94
Water	10	−0.08	12.28	1.00	277.14	0.97	3.62	0.01	0.57	−1.75	2.55	0.92	1.21	0.83	0.95	0.09
Cow	11	−0.08	2.73	−1.24	249.66	0.55	5.53	2.14	3.70	1.06	0.29	−1.44	1.03	0.60	0.29	−1.06
Old Ranch	12	−0.10	18.59	2.47	193.50	−0.32	2.09	−1.70	1.46	−0.95	2.98	1.36	0.00	−0.73	0.12	−1.35
Bee	13	−0.11	3.79	−0.99	160.08	−0.83	2.69	−1.04	1.95	−0.51	2.49	0.85	0.00	−0.73	1.86	1.66
Cherry	14	−0.15	8.84	0.19	132.82	−1.26	3.12	−0.55	2.58	0.06	1.90	0.24	0.00	−0.73	1.38	0.83
Whetstone	15	−0.26	2.81	−1.22	184.87	−0.45	3.50	−0.13	1.34	−1.06	3.17	1.56	0.00	−0.73	1.77	1.51
San Augustin	16	−0.44	3.62	−1.03	215.09	0.02	3.60	−0.02	1.68	−0.75	1.72	0.05	1.48	1.17	0.43	−0.81
La Jolla Vieja	17	−0.74	9.31	0.30	167.98	−0.71	4.47	0.96	1.18	−1.20	1.43	−0.25	1.84	1.64	0.58	−0.55
Lobos	18	−0.75	4.74	−0.77	112.91	−1.56	3.78	0.19	2.66	0.13	0.30	−1.43	1.90	1.71	0.31	−1.02
Wreck	19	−0.98	7.44	−0.14	155.91	−0.90	5.67	2.30	1.14	−1.24	1.36	−0.32	2.21	2.11	0.61	−0.50

technological developments, such as the ocean-going plank canoe, can influence habitat suitability and settlement rankings (Jazwa *et al.* 2013). Prediction (6) may not be entirely density independent if, for instance, economic development is initiated in response to larger populations.

More specifically, we predict that the high-ranked habitat of Dry and Soledad Canyons should be settled first (prediction 1). The faunal record at this habitat should reflect increasing population density over time, increasing shellfish diversity, the incorporation into the diet of lower ranked shellfish species other than *Mytilus californianus* and *Haliotis* spp. (see Braje *et al.* 2007: Table 1 for shellfish rankings and their justification) and evidence of an expansion of fishing and sea mammal hunting (prediction 2). Settlement should expand from the high-ranked habitat progressively to lower ranked Cow/Lobos, La Jolla Vieja, and Bee Canyons (prediction 3). These locations should then experience a similar pattern of resource depression as population density increases. Higher ranked drainages should exhibit evidence of resource depression before lower ranked drainages. Once settled, occupation is persistent unless environmental, cultural, or technological factors alter suitability sufficiently that it falls below the equilibrium level (predictions 4–6).

Methods

Strategic Approach

Previous IFD studies on the NCI compared regional settlement patterns to model predictions (see Kennett *et al.* 2009; Winterhalder *et al.* 2010). Here we focus specifically on four locations on Santa Rosa Island: the high-ranked Dry and Soledad Canyons, middle-ranked locations adjacent to high-ranked ones (Cow and Lobos Canyons), and two middle-low-ranked habitats (La Jolla Vieja and Bee Canyons), which invert their relative position depending on the ranking system (compare Table 1 with Kennett *et al.* 2009; Winterhalder *et al.* 2010). The topography and geology of Santa Rosa Island combined with resource-rich nearshore kelp forests ensure that even the lowest ranked habitat on Santa Rosa is 28th out of the 46 ranked habitats across all four islands (Winterhalder *et al.* 2010; Table 1).

We surveyed interior drainages to complement the excavation work done at the drainage mouths where permanent settlements typically are located. During the summers of 2012, 2013, and 2014, CSJ led a survey of the drainage bottoms and walls of Soledad, Dry, Cow, Lobos, Bee, Acapulco, and Tecolote Canyons. La Jolla Vieja Canyon had previously been surveyed as part of a National Park Service cultural resources project in 1995. The team recorded all observed sites in these drainages, covering 100 % of the survey area. Survey crews walked 10-m transect lines in all flat areas (<20° slope) of the drainage bottoms, performing light surface scrapes at 10-m intervals to clear vegetation and look for surface exposures of sites. All erosional banks along stream cuts and all accessible rockshelters along the drainages were inspected. Because of erosion and vegetation, sites in canyon bottoms were most readily discovered on the floors of rockshelters and the walls of cut banks.

Excavation targeted drainage mouths because they feature the most extensive and persistent permanent settlements on the NCI (Kennett 2005; Kennett *et al.* 2009;

Winterhalder *et al.* 2010). During the summer of 2013, CSJ and his field crew excavated 25-cm×25-cm column samples from sites within each of the four primary habitats included in this study (Table 2). All were from low coastal terraces, locations protected from the ocean tides and floods in the adjacent canyons but offering easy access to the coast and its marine resources. Nearly all large NCI coastal sites are found on these landforms. The number of samples from each site was set based on site size and number of distinct components. At least one column sample was placed in each locus of larger sites to better represent the range of occupation at each of the four locations. The 25×25-cm size of the column samples accommodates the directive of the National Park Service for preservation of cultural and natural resources and allows us to generate faunal assemblages from a broad variety of sites. Samples were excavated from eroding banks to minimize impacts.

From Dry and Soledad Canyons, we excavated three units from CA-SRI-19 and one from CA-SRI-821. The mouths of these two drainages are approximately 300 m apart; the preferred landscape for habitation is entirely encompassed by these two sites. CA-SRI-19 is a very large site ($\sim$56,000 m^2) and has evidence for several distinct phases of occupation. From Cow and Lobos Canyons, we excavated two units from CA-SRI-115 and one unit from CA-SRI-541. These two drainages, the mouths of which are approximately 700 m apart, also have a densely occupied cultural landscape connecting them. In 1996, Kennett and Morris excavated one 25×25-cm column sample from CA-SRI-116, which we incorporate into this analysis. From La Jolla Vieja Canyon, we excavated two units from CA-SRI-138 and one unit from CA-SRI-131. And from Bee Canyon, we excavated two units from CA-SRI-313 and one unit from CA-SRI-333. In 1996, Kennett and Morris excavated two 25×25-cm column samples from CA-SRI-31, which we also include (Kennett 1998). This approach includes samples from both the large, primary settlement sites in each of these drainages and the smaller adjacent sites. Together, they provide a more complete perspective of persistent occupation in each location. Our discussion of settlement focuses on the sites that are the best candidates for permanent habitation at each location (Table 2).

Chronology

We obtained at least two radiocarbon dates from each excavated column sample except for the thin deposit at CA-SRI-31, unit 2. We selected samples from the top and bottom strata with datable material for each unit to represent the beginning and end of occupation of that unit. We later dated intermediate levels from those units with a long occupation history, targeting strata with evidence for change in the faunal record. Column samples were placed strategically to try to encompass the full range of occupation at each site, increasing our confidence that the dates generated approximate initial and terminal occupation of each habitat. Kennett (1998, pp. 456, 458) obtained two standard radiometric dates from CA-SRI-116 and one each from CA-31 units 1 and 2 from Beta Analytic, Inc. From 2012 to 2014, we obtained 32 additional AMS radiocarbon dates to establish the chronology of the excavated sites and another 17 dates from other coastal locations and interior drainage bottoms (Tables 3 and 4; Fig. 2). All samples were tested at the Keck Carbon Cycle AMS Facility at the University of California, Irvine.

Table 2 Coastal sites included in this study, with indicators of potential permanent settlement and number of excavation units noted

Site	Drainage	Excavation units	Human remains	Midden density	Max midden thickness (cm)	House depressions	Likely primary habitation
CA-SRI-19	Soledad/Dry	3	Yes[a]	High	80	No	Yes
CA-SRI-806	Soledad/Dry	0	No	Low	Unknown	Maybe	No
CA-SRI-821	Soledad/Dry	1	Yes	High	56	No	Yes
CA-SRI-115	Cow/Lobos	2	No	High	64	No	Yes
CA-SRI-116	Cow/Lobos	1	Yes[a]	High	92	No	Yes
CA-SRI-541	Cow/Lobos	1	Yes	High	43	No	No
CA-SRI-542	Cow/Lobos	1	No	Low	10	No	No
CA-SRI-790	Cow/Lobos	0	Yes	Medium	66	No	Yes
CA-SRI-131	La Jolla Vieja	1	No	High	95	Yes	Yes
CA-SRI-138	La Jolla Vieja	2	Yes[b]	High	85	No	Yes[c]
CA-SRI-488	La Jolla Vieja	1	No	Medium	40	No	No
CA-SRI-31	Bee	3	Yes[a]	High	40	Yes	Yes
CA-SRI-309	Bee	0	No	High	65	No	No
CA-SRI-311	Bee	0	No	High	52	No	No
CA-SRI-313	Bee	2	No	High	42	No	Yes
CA-SRI-333	Bee	1	No	High	65	No	No

[a] Noted in the original site record but not currently visible

[b] Unclear if human remains are associated with early or late deposits. Not currently visible

[c] Large site with vegetation cover. Unclear how much is associated with early vs. late deposits

Table 3 Radiocarbon dates from the coastal sites in this study, including all excavated sites. All dates were calibrated in OxCal 4.1 (Bronk Ramsey 2009) using the most recent marine calibration curve, Marine13 (Reimer et al. 2013). We used a variable ΔR value for the Santa Barbara Channel region for samples with dates of less than 2600 ^{14}C BP. Variable ΔR values were calculated by Brendan Culleton (personal communication, 2015) using AMS radiocarbon dates from paired organic and planktonic marine foraminiferal carbonate in laminated varves published by Hendy et al. (2013) from a sediment core from Santa Barbara Basin. For older samples, we used an updated ΔR value for the Santa Barbara Channel region (261 ± 21 ^{14}C year; Brendan Culleton, personal communication 2012; Jazwa et al. 2012)

Site	Lab no.	Drainage	Provenience	Species	Conventional ^{14}C age (BP)	ΔR	2σ cal BP	Reference
CA-SRI-19	UCIAMS-130882	Soledad/Dry	Unit 1, 58–70 cmbs	*Chlorostoma funebralis*	4995±20[a]	261±21	5075–4845[a]	This study
CA-SRI-19	UCIAMS-137953	Soledad/Dry	Unit 1, 70–80 cmbs	*Mytilus californianus*	2980±20	261±21	2510–2325	This study
CA-SRI-19	UCIAMS-130881	Soledad/Dry	Unit 1, 83 cmbs	*Mytilus californianus*	3015±15	261±21	2600–2355	This study
CA-SRI-19	UCIAMS-130883	Soledad/Dry	Unit 2, 3 cmbs	*Mytilus californianus*	4620±15	261±21	4580–4405	Jazwa et al. (2015a)
CA-SRI-19	UCIAMS-130884	Soledad/Dry	Unit 2, 77 cmbs	*Mytilus californianus*	5220±20	261±21	5425–5240	Jazwa et al. (2015a)
CA-SRI-19	UCIAMS-130885	Soledad/Dry	Unit 3, 26 cmbs	*Septifer bifurcatus*	1880±15	139±44	1395–1195	This study
CA-SRI-19	UCIAMS-130886	Soledad/Dry	Unit 3, 66 cmbs	*Septifer bifurcatus*	2760±20	261±21	2280–2060	This study
CA-SRI-19	UCIAMS-116210	Soledad/Dry	Locus A, 89 cmbs	*Mytilus californianus*	4765±15	261±21	4805–4600	This study
CA-SRI-19	UCIAMS-147339	Soledad/Dry	Fish lens, surface	*Mytilus californianus*	1875±20	139±44	1260–1090	This study
CA-SRI-806	UCIAMS-147343	Soledad/Dry	Erosional cut	*Septifer bifurcatus*	2205±20	85±44	1825–1565	This study
CA-SRI-821	UCIAMS-130879	Soledad/Dry	Unit 1, 34 cmbs	*Mytilus californianus*	3700±15	261±21	3390–3220	Jazwa et al. (2015a)
CA-SRI-821	UCIAMS-147338	Soledad/Dry	Unit 1, 54 cmbs	*Mytilus californianus*	5355±25	261±21	5560–5330	Jazwa et al. (2015a)
CA-SRI-821	UCIAMS-130880	Soledad/Dry	Unit 1, 77.5 cmbs	*Haliotis cracherodii*	5755±20	261±21	5945–5760	Jazwa et al. (2015a)
CA-SRI-115	UCIAMS-136088	Cow/Lobos	Unit 1, 13 cmbs	*Septifer bifurcatus*	2645±25	261±21	2115–1915	This study
CA-SRI-115	UCIAMS-136089	Cow/Lobos	Unit 1, 57 cmbs	*Mytilus californianus*	2975±25	261±21	2545–2315	This study
CA-SRI-115	UCIAMS-137947	Cow/Lobos	Unit 2, 21 cmbs	*Mytilus californianus*	3845±20	261±21	3565–3385	This study
CA-SRI-115	UCIAMS-137948	Cow/Lobos	Unit 2, 38 cmbs	*Septifer bifurcatus*	4205±20	261±21	4045–3835	This study
CA-SRI-115	UCIAMS-116211	Cow/Lobos	Locus A, 53 cmbs	*Mytilus californianus*	4320±20	261±21	4205–3975	This study

Table 3 (continued)

Site	Lab no.	Drainage	Provenience	Species	Conventional ^{14}C age (BP)	ΔR	2σ cal BP	Reference
CA-SRI-116	Beta-107051	Cow/Lobos	Unit 1, 10–20 cmbs	*Mytilus californianus*	5110±80	261±21	5380–4870	Kennett (1998, p. 458)
CA-SRI-116	Beta-92291	Cow/Lobos	Unit 1, 60–65 cmbs	*Haliotis rufescens*	6060±70	261±21	6380–6020	Kennett (1998, p. 458)
CA-SRI-541	UCIAMS-136085	Cow/Lobos	Unit 1, 8 cmbs	*Mytilus californianus*	1365±25	280±43	730–545	This study
CA-SRI-541	UCIAMS-136086	Cow/Lobos	Unit 1, 32 cmbs	*Mytilus californianus*	1840±25	144±44	1355–1145	This study
CA-SRI-542	UCIAMS-136087	Cow/Lobos	Unit 1, 40–50 cmbs	*Mytilus californianus*	2985±25	261±21	2575–2325	This study
CA-SRI-790	UCIAMS-125192	Cow/Lobos	22 cmbs	*Mytilus californianus*	4585±20	261±21	4505–4345	This study
CA-SRI-790	UCIAMS-125191	Cow/Lobos	65 cmbs	*Mytilus californianus*	4545±20	261±21	4520–4365	This study
CA-SRI-131	UCIAMS-137949	La Jolla Vieja	Unit 1, 21 cmbs	*Mytilus californianus*	2990±20	261±21	2575–2330	This study
CA-SRI-131	UCIAMS-137950	La Jolla Vieja	Unit 1, 88 cmbs	*Septifer bifurcatus*	3865±20	261±21	3585–3405	This study
CA-SRI-138	UCIAMS-130888	La Jolla Vieja	Unit 1, 9.5 cmbs	*Mytilus californianus*	5695±20[a]	261±21	5890–5725[a]	This study
CA-SRI-138	UCIAMS-147341	La Jolla Vieja	Unit 1, 49 cmbs	*Mytilus californianus*	4820±20	261±21	4845–4655	This study
CA-SRI-138	UCIAMS-130889	La Jolla Vieja	Unit 1, 73 cmbs	*Mytilus californianus*	7235±20	261±21	7545–7415	This study
CA-SRI-138	UCIAMS-137951	La Jolla Vieja	Unit 2, 14 cmbs	*Mytilus californianus*	1270±20	305±43	645–530	This study
CA-SRI-138	UCIAMS-147342	La Jolla Vieja	Unit 2, 39 cmbs	*Mytilus californianus*	3210±20	261±21	2790–2675	This study
CA-SRI-138	UCIAMS-137952	La Jolla Vieja	Unit 2, 67 cmbs	*Haliotis cracherodii*	3465±20	261±21	3130–2900	This study
CA-SRI-488	UCIAMS-137946	La Jolla Vieja	Unit 1, 29 cmbs	*Mytilus californianus*	2585±20	148±44	2125–1930	This study
CA-SRI-488	UCIAMS-130887	La Jolla Vieja	Unit 1, 48 cmbs	*Mytilus californianus*	2525±15	132±43	2160–1960	This study
CA-SRI-31	UCIAMS-147340	Bee	Unit 1, 0–12 cmbs	*Mytilus californianus*	2085±20	94±44	1615–1350	Jazwa (2015)
CA-SRI-31	Beta-95455	Bee	Unit 1, 28–40 cmbs	*Haliotis rufescens*	2050±60	97±44	1680–1440	Kennett (1998, p. 456)
CA-SRI-31	Beta-96959	Bee	Unit 2, 10–25 cmbs	*Haliotis rufescens*	3470±80	261±21	3240–2790	Kennett (1998, p. 456)
CA-SRI-313	UCIAMS-130891	Bee	Unit 1, 3.5 cmbs	*Mytilus californianus*	1390±15	277±44	775–565	Jazwa (2015)
CA-SRI-313	UCIAMS-130890	Bee	Unit 1, 34.5 cmbs	*Haliotis cracherodii*	1790±15	155±44	1280–1070	Jazwa (2015)

Table 3 (continued)

Site	Lab no.	Drainage	Provenience	Species	Conventional ^{14}C age (BP)	ΔR	2σ cal BP	Reference
CA-SRI-313	UCIAMS-130892	Bee	Unit 2, 12 cmbs	*Haliotis rufescens*	1705±15	191±44	1170–965	This study
CA-SRI-313	UCIAMS-130893	Bee	Unit 2, 41 cmbs	*Septifer bifurcatus*	1750±15	170±44	1240–1040	This study
CA-SRI-333	UCIAMS-130894	Bee	Unit 1, 5 cmbs	*Mytilus californianus*	925±15	347±42	315–140	Jazwa (2015)
CA-SRI-333	UCIAMS-147337	Bee	Unit 1, 25 cmbs	*Mytilus californianus*	935±20	347±42	380–170	Jazwa (2015)
CA-SRI-333	UCIAMS-130895	Bee	Unit 1, 55–65 cmbs	*Mytilus californianus*	1825±15	147±44	1325–1120	Jazwa (2015)
CA-SRI-309	UCIAMS-125186	Bee	65 cmbs	*Mytilus californianus*	3235±20	261±21	2825–2695	This study
CA-SRI-311	UCIAMS-125187	Bee	52 cmbs	*Mytilus californianus*	1800±20	153±44	1295–1085	This study

[a] Date associated with a reversal in the record. It is likely that this sample eroded into the top stratigraphic layer from elsewhere in the site after occupation

Table 4 Other radiocarbon dates, including ephemeral early sites near the mouth of Bee Canyon and those from the interior of Cow, Lobos, and Tecolote Canyons. All dates were calibrated in OxCal 4.1 (Bronk Ramsey 2009) using the most recent marine calibration curve, Marine13 (Reimer et al. 2013), and ΔR values as in Table 3

| Site	Lab no.	Drainage	Provenience	Species	Conventional ^{14}C age (BP)	ΔR	2σ cal BP	Reference
CA-SRI-331	UCIAMS-125188	Bee	66 cmbs	*Lottia gigantea*	8500±25	261±21	8925–8625	This study
CA-SRI-338	UCIAMS-130896	Bee	Unit 1, 4 cmbs	*Haliotis rufescens*	5670±20	261±21	5880–5695	Jazwa et al. (2015a)
CA-SRI-338	UCIAMS-130897	Bee	Unit 1, 20–24 cmbs	*Haliotis rufescens*	5720±15	261±21	5905–5745	Jazwa et al. (2015a)
CA-SRI-338	UCIAMS-116212	Bee	52 cmbs	*Haliotis rufescens*	5665±15	261±21	5875–5695	Jazwa et al. (2015a)
CA-SRI-768	UCIAMS-116213	Cow	34 cmbs (cutbank)	*Mytilus californianus*	1090±15	330±42	480–300	This study
CA-SRI-770	UCIAMS-113214	Cow	64 cmbs	*Mytilus californianus*	1685±15	194±44	1160–935	This study
CA-SRI-772	UCIAMS-116215	Cow	8 cmbs	*Mytilus californianus*	770±15	294±42	245–0	This study
CA-SRI-773	UCIAMS-115031	Cow	79 cmbs	*Mytilus californianus*	1245±20	308±43	630–475	This study
CA-SRI-778	UCIAMS-116216	Tecolote	~8 mbs (cutbank)	*Haliotis rufescens*	7025±20	261±21	7385–7225	This study
CA-SRI-780	UCIAMS-116217	Tecolote	197 cmbs, locus A (sinkhole)	*Mytilus californianus*	8145±20	261±21	8410–8285	This study
CA-SRI-786	UCIAMS-115033	Tecolote	36 cmbs	*Mytilus californianus*	1670±15	202±44	1140–915	This study
CA-SRI-787	UCIAMS-116218	Lobos	31 cmbs	*Mytilus californianus*	1175±15	316±43	555–395	This study
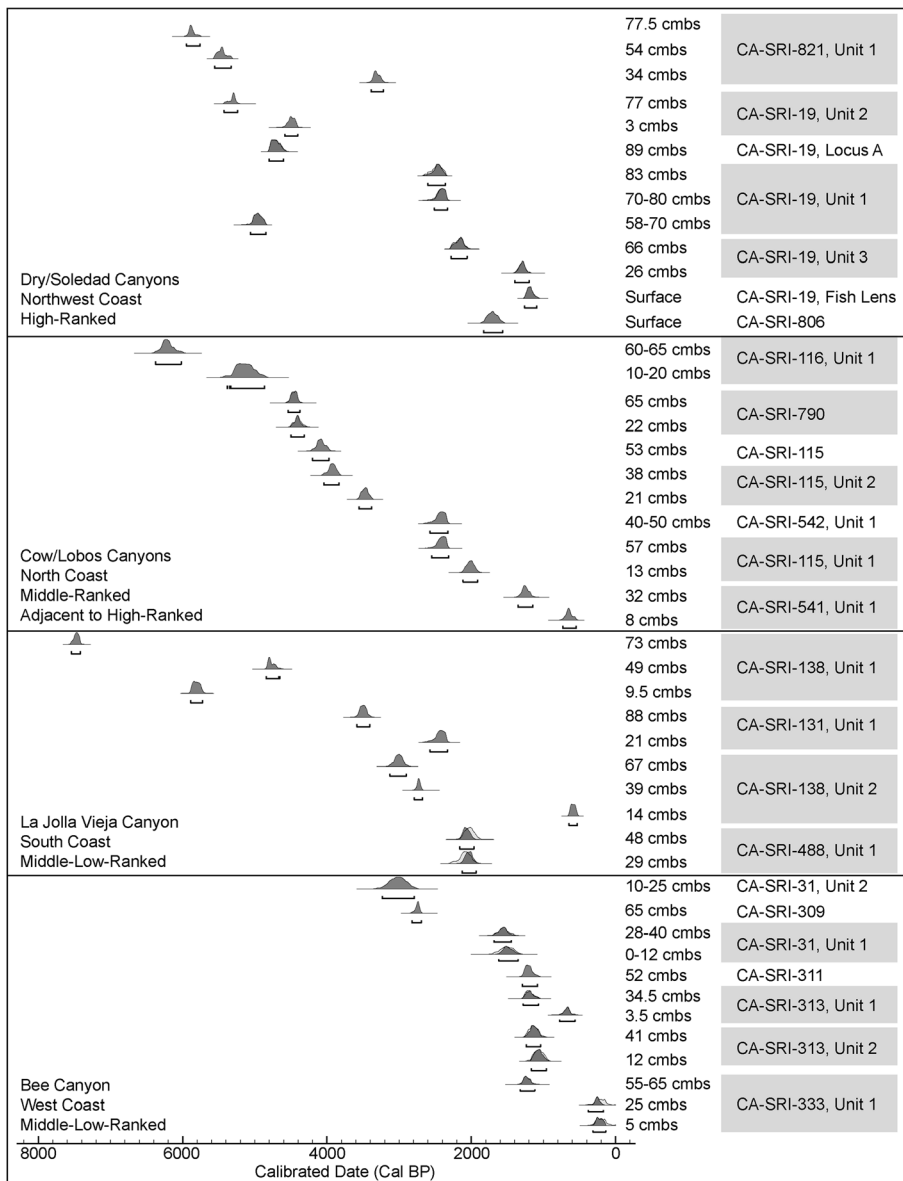
Fig. 2 2σ ranges for the radiocarbon dates from all of the coastal sites in this analysis. All dates were calibrated in OxCal 4.1 (Bronk Ramsey 2009) using the most recent marine calibration curve, Marine13 (Reimer *et al.* 2013) and modeled in OxCal to account for stratigraphy within excavation units

We calibrated all of the dates in OxCal 4.1 (Bronk Ramsey 2009) using the most recent marine calibration curve, Marine13 (Reimer *et al.* 2013). We used a variable ΔR value for the Santa Barbara Channel region for samples with dates of less than 2600 ^{14}C BP (Tables 3 and 4; Brendan Culleton, personal communication, 2015; Hendy *et al.* 2013) and an updated ΔR value for the Santa Barbara Channel region for older samples (261±21 ^{14}C year; Brendan

Culleton, personal communication 2012; Jazwa *et al.* 2012). Application of the Bayesian statistical model in OxCal further constrained the error ranges on dates based on the relative stratigraphic position of the radiocarbon samples within each of the units.

Faunal Analysis

We excavated eroding natural exposures from the surface to the base of the deposit in arbitrary 10-cm levels, with materials from different stratigraphic levels kept separate. All excavated materials were size sorted using 1/2-, 1/4-, and 1/8-in. mesh and identified at the Penn State University Zooarchaeology Lab. The lead author (CSJ) and trained undergraduate and graduate students sorted all shellfish, other faunal constituents, and cultural materials (see Jazwa *et al.* 2012, 2013) for methodology. Meat weights were calculated for dietary constituents using the multipliers compiled and summarized by Rick (2004, p. 79). Data are combined from individual excavation units for intersite comparisons. In units with deep deposits and clear changes in the faunal record, we separated the data into two distinct cultural components between the strata that best exemplified this change. Shell and meat weight data are normalized to a volume of 1 m^3 for comparison.

We analyze shellfish and other faunal materials by weight rather than minimum number of individuals because of the fragmentary nature of the midden and the difficulty of assigning meaningful counts to the species present in low densities (see Glassow 2000; Giovas 2009; *contra* Mason *et al.* 1998, 2000). We used the Shannon-Weaver function (Shannon and Weaver 1949) to calculate the taxonomic diversity of the assemblages from both shell and meat weights of all dietary shellfish species recovered. We also calculated shellfish species richness and evenness for both shell and meat weights. In all calculations, abalone and turban snail fragments that were indistinguishable to species (*i.e.*, *Haliotis* spp., *Chlorostoma* spp.) were apportioned to species by weight using the relative weights of individual species (red and black abalone, brown and black turban snails) for each unit or deposit.

Lastly, we estimated the size of *M. californianus* shells using the equation relating umbo thickness to shell length presented in Singh and McKechnie (2015; Singh *et al.* 2015; see also Campbell and Braje 2015):

$$\text{Total Length} = 15.312x + 7.1701 \qquad (1)$$

Singh and McKechnie demonstrate that this method has an R^2 value of 0.80 and average error of 10.2±1.9 mm. The only site for which this method was not employed was CA-SRI-31. These assemblages are not currently available and mussel sizes from this site were estimated using the template from White (1989). We do not include mussels less than 20 mm in length in average mussel size because we assume that they were too small to be targeted for consumption, and were instead inadvertently collected because they were attached to larger individuals. A high proportion of these small individuals could reflect mussel collection through stripping rather than plucking (see Bettinger *et al.* 1997).

Results

Radiocarbon Chronology

The sites excavated and reported encompass the entire known range of permanent occupation on the NCI from 7545–7415 cal BP (CA-SRI-138, unit 1, 73 cm below surface) through 315–140 cal BP (CA-SRI-333, unit 1, 5 cmbs; Table 3; Fig. 2). The highest ranked drainages along the northwest coast are the location of the earliest intensive permanent occupation on Santa Rosa Island. Once settled, it appears that these habitats were occupied consistently throughout the Holocene. The earliest available evidence for persistent settlement anywhere on the island is at the mouth of Tecolote Canyon, dating to 7890–7520 cal BP (Kennett 1998, p. 456; Winterhalder *et al.* 2010; Jazwa 2015). During our survey, we recorded a midden lens at CA-SRI-780 that we date to 8410–8285 2σ cal BP on the flat canyon bottom approximately 1 km from the drainage mouth (Table 4). It is difficult to determine whether these deposits could be associated with permanent occupation because they were only visible in a small sinkhole. There is also evidence for early settlement at the high-ranked habitat at the mouth of Old Ranch and Old Ranch House Canyons dating to 8050–7840 cal BP, but this habitat was apparently depopulated following the closure of a productive estuary there (Kennett 1998; Jazwa *et al.* 2013).

The earliest date from an excavation unit was from unit 1 of CA-SRI-138 (7545–7415 2σ cal BP; 73 cmbs). This site is located at the mouth of La Jolla Vieja Canyon, a middle-low-ranked habitat. One of the deepest levels of CA-SRI-116, in a middle-ranked habitat, Lobos and Cow Canyons, dates to 6380–6020 cal BP. The earliest date from the highest ranked habitat in this study, 5945–5760 cal BP, comes from 77.5 cmbs at unit 1 of CA-SRI-821 at the mouth of Dry Canyon (Fig. 2). The early dates from the other habitats appear not to be consistent with the predictions of the IFD (Table 5), a point that we take up in the discussion.

At the mouth of Dry and Soledad Canyons, there is evidence that the large site of CA-SRI-19 was occupied from 5425–5420 2σ cal BP through at least 1260–1090 2σ cal BP. Between that site and CA-SRI-821, the entire coastal plain within this habitat was occupied throughout much of the middle Holocene, like the nearby high-ranked habitat at the mouth of Tecolote and Arlington Canyons (CA-SRI-3, CA-SRI-4, CA-SRI-5, and CA-SRI-6) (Kennett 1998, pp. 456–457; Winterhalder *et al.* 2010). The radiocarbon record also shows that the mouths of Cow and Lobos Canyons likely were occupied nearly continuously from their initial occupation at CA-SRI-116 through at least 730–545 2σ cal BP (CA-SRI-541, 8 cmbs). However, there is no evidence of more than one site being inhabited contemporaneously until both CA-SRI-542 (2575–2325 2σ cal BP, 40–50 cmbs) and CA-SRI-115, unit 1 (2545–2315 2σ cal BP, 57 cmbs), were occupied.

La Jolla Vieja Canyon is ranked lower in the IFD and it is on the south coast of the island, isolated from the higher ranked drainages. The initial occupation at this habitat (CA-SRI-138, unit 1) is earlier than expected (7545–7415 2σ cal BP), but there is no evidence of any other coastal occupation of the area until 3585–3405 2σ cal BP (CA-SRI-131, 88 cmbs). It is unclear how continuously CA-SRI-138 was occupied. The latest date from unit 1 is 4845–4655 2σ cal BP, but it is from 49 cmbs. There is a major stratigraphic change immediately above where the sample was collected, but the sample

Table 5 Comparison of drainage ranking from this analysis with rankings from Kennett et al. (2009) and Winterhalder et al. (2010) along with radiocarbon dates for the initial settlement of each drainage. All dates were calibrated in OxCal 4.1 (Bronk Ramsey 2009) using the most recent marine calibration curves, Marine13 (Reimer et al. 2013) and IntCal13 (Reimer et al. 2013; where noted), and ΔR values as in Table 3. Sites from drainages targeted in this study are in bold

	New rank	Kennett rank	Winterhalder rank	Conventional		2σ cal BP	Material	Site	Reference
				¹⁴C age (BP)	ΔR				
Tecolote	1	1	2	7480±90	261±21	7890–7520	*Haliotis rufescens*	CA-SRI-3	Winterhalder et al. (2010)
Arlington	2	2	4	6980±120	261±21	7470–6960	*Haliotis* spp.	CA-SRI-4	Winterhalder et al. (2010)
Trancion	3	6	7	–	–	–	–	–	–
Verde	4	3	1	4260±90[a]	–	5210–4530	Charcoal	CA-SRI-41	Winterhalder et al. (2010)
Soledad	**5**	**4**	**5**	**5220±20**	**261±21**	**5425–5240**	***Mytilus californianus***	**CA-SRI-19**	Jazwa et al. (2015a)
Garanon	6	NR	NR	2250±90	88±44	1990–1520	*Mytilus californianus*	CA-SRI-2	Kennett (1998)
Old Ranch House	7	NR	NR	7750±40	261±21	8050–7840[b]	Marine shell	CA-SRI-187	Kennett (1998), Jazwa et al. (2013)
Dry	**8**	**8**	**8**	**5755±20**	**261±21**	**5945–5760**	***Haliotis cracherodii***	**CA-SRI-821**	Jazwa et al. (2015a)
Acapulco	9	10	12	2090±60	92±44	1770–1390	*Mytilus californianus*	CA-SRI-28	Winterhalder et al. (2010)
Water	10	9	9	1800±30	153±44	1300–1070	Marine shell	CA-SRI-77	Winterhalder et al. (2010)
Cow	**11**	**NR**	**NR**	**4320±20**	**261±21**	**4205–3975**	***Mytilus californianus***	**CA-SRI-115**	**This study**
Old Ranch	12	7	3	7750±40	261±21	8050–7840[b]	Marine shell	CA-SRI-187	Kennett (1998), Jazwa et al. (2013)
Bee	**13**	**12**	**14**	**3470±80**	**261±21**	**3240–2790**	***Haliotis rufescens***	**CA-SRI-31**	Kennett (1998)
Cherry	14	5	6	–	–	1500–1100	Artifact	CA-SRI-60	Winterhalder et al. (2010)
Whetstone	15	15	16	2410±50	109±44	2100–1750	*Haliotis rufescens*	CA-SRI-96	Kennett (1998)
San Augustin	16	16	15	2280±80	92±44	2010–1560	Marine shell	CA-SRI-432	Winterhalder et al. (2010)
La Jolla Vieja	**17**	**11**	**10**	**7235±20**	**261±21**	**7545–7415**	***Mytilus californianus***	**CA-SRI-138**	**This study**
Lobos	**18**	**14**	**11**	**6060±70**	**261±21**	**6380–6020**	***Haliotis rufescens***	**CA-SRI-116**	Kennett (1998)
Wreck	19	13	13	–	–	–	–	–	–

NR not reported

[a] Calibrated with IntCal13

[b] Old Ranch and Old Ranch House Canyons have adjacent mouths near CA-SRI-187. There is a gap in occupation at CA-SRI-187 from 6470–6315 to 3325–3145 cal BP (Jazwa et al. 2013)

from 9 cmbs (5890–5725 2σ cal BP) is anomalously early and was likely eroded from uphill. Therefore, it is unclear how late in time the upper strata at this unit continued to be occupied, and whether it overlapped with the lowest strata at CA-SRI-131. Beginning with the occupation of CA-SRI-131, there is evidence for continuous occupation at the mouth of La Jolla Vieja Canyon at least until 645–530 2σ cal BP (CA-SRI-138, unit 2, 14 cmbs). The rockshelter/valley bottom site CA-SRI-147 in the interior of La Jolla Vieja Canyon, more than 2 km from the coast, has evidence for intensive occupation from 7300 to 350 cal BP (Braje *et al.* 2007). This suggests that permanent occupation of this drainage was not isolated to a single site.

The habitat with the latest evidence for initial permanent settlement is Bee Canyon. The earliest dates from permanent settlement sites are from CA-SRI-31, unit 2 (10–25 cmbs; 3240–2790 2σ cal BP), and CA-SRI-309 (65 cmbs; 2825–2695 2σ cal BP). After these dates, the next evidence for occupation of this habitat is not until 1680–1440 2σ cal BP (CA-SRI-31, unit 1, 28–40 cmbs). Beginning around this date, the mouth of Bee Canyon was occupied until historic contact (CA-SRI-333, 5 cmbs). Despite the fact that Bee Canyon does not have evidence of permanent occupation until relatively late, people were there for short periods of time during the middle Holocene. CA-SRI-338 is a special purpose red abalone shucking site dating to ~5900–5700 cal BP (Jazwa *et al.* 2015a). Several other similar red abalone middens are located farther to the south near the mouth of Acapulco Canyon. There is also an early date from ephemeral deposits from CA-SRI-331 (8925–8625 2σ cal BP). Rick *et al.* (2013) noted the presence of several nonpermanent Paleocoastal (before 9000 cal BP) sites along the higher marine terrace on the west coast of the island.

Although middle Holocene sites are present along interior ridgelines (Kennett 1998, 2005; Jazwa *et al.* 2015a), most evidence from the bottom of drainages suggests recent occupation. There are two notable exceptions. There are thin lenses of red abalone shell in erosional banks in Tecolote Canyon, one of which we have dated to 7385–7225 2σ cal BP (CA-SRI-778). These may be secondary deposits eroded into the drainage. CA-SRI-147, the rockshelter/valley bottom site in La Jolla Vieja Canyon, has evidence for occupation from approximately 7300 to 350 cal BP (Braje *et al.* 2007). Most other rockshelters have initial dates of occupation during the late Holocene, within the last 1200 years (Table 4). All radiocarbon samples from these sites were taken from the deepest stratum exposed by erosion, in most cases directly overlying sterile soil. The earliest dates are from CA-SRI-786 (1140–915 cal BP) near the head of Tecolote Canyon and CA-SRI-770 (1160–935 cal BP), approximately 2 km from the mouth of Cow Canyon. Other rockshelters from throughout Cow and Lobos Canyon all date to the Late Period (650–168 cal BP), when people were clustered in large coastal villages and rockshelters were largely used as temporary camps to access interior resources (Kennett 2005).

Excavation Results

As discussed earlier, consistent with data from elsewhere on the NCI, shellfish is the dominant component prior to the late Holocene, when fish and sea mammal increased in importance. This is clearly evident in the middle and late Holocene deposits from the mouth of Dry and Soledad Canyons (Table 6; Fig. 3). The middle Holocene faunal record from both CA-SRI-821 and CA-SRI-19, unit 2, are strongly dominated by

Table 6 Measured faunal weight, meat weight density, and percent of total meat weight by major faunal component for all excavated sites

| Site	Unit	Level (cmbs)	Drainage	Shell Faunal wt. (g)	Meat wt. (g/m^3)	%	Fish Faunal wt. (g)	Meat wt. (g/m^3)	%	Sea mammal Faunal wt. (g)	Meat wt. (g/m^3)	%	Bird Faunal wt. (g)	Meat wt. (g/m^3)	%	Total meat wt. (g/m^3)
CA-SRI-19	1	70–92	Dry/Soledad	475.4	25,030.6	38.2	15.3	30,862.8	47.1	5.1	9011.2	13.8	0.6	621.8	0.9	65,526.4
CA-SRI-19	2	0–80	Dry/Soledad	8904.1	128,931.0	65.7	9.0	4997.1	2.5	123.0	59,522.3	30.3	9.1	2742.0	1.4	196,192.4
CA-SRI-19	3	22–71	Dry/Soledad	2119.7	50,112.2	18.6	99.7	90,186.7	33.4	163.9	129,498.6	47.9	0.7	342.9	0.1	270,140.4
CA-SRI-821	1	29–85	Dry/Soledad	2532.2	52,380.3	67.0	19.3	15,274.6	19.6	15.2	10,475.1	13.4	0.0	0.0	0.0	78,130.0
CA-SRI-115	1	10–64	Cow/Lobos	4281.0	91,835.0	67.6	16.6	13,607.9	10.0	42.4	30,366.5	22.4	0.0	0.0	0.0	135,809.4
CA-SRI-115	2	12–45	Cow/Lobos	1480.2	51,958.1	81.8	5.7	7668.7	12.1	3.2	3742.9	5.9	0.3	181.8	0.3	63,551.6
CA-SRI-116	1	10–102	Cow/Lobos	14,647.6	184,430.1	83.1	47.3	22,781.4	10.3	31.8	13,396.3	6.0	5.2	1346.1	0.6	221,953.9
CA-SRI-541	1	0–40	Cow/Lobos	5082.4	147,186.7	68.3	17.4	19,279.2	8.9	50.3	48,710.1	22.6	0.4	258.0	0.1	215,434.0
CA-SRI-131	1	10–60	La Jolla Vieja	6447.1	153,080.7	89.3	6.7	5912.3	3.4	7.9	6117.8	3.6	13.1	6297.6	3.7	171,408.3
CA-SRI-131	1	60–95	La Jolla Vieja	2681.1	90,943.2	63.9	29.6	37,418.7	26.3	11.5	12,667.0	8.9	1.8	1227.4	0.9	142,256.4
CA-SRI-138	1	0–50	La Jolla Vieja	7301.9	169,170.2	98.3	0.2	177.3	0.1	3.6	2756.9	1.6	0.0	0.0	0.0	172,104.3
CA-SRI-138	1	50–85	La Jolla Vieja	6639.4	225,207.3	93.2	2.6	3330.3	1.4	11.0	12,124.9	5.0	1.6	1069.7	0.4	241,732.3
CA-SRI-138	2	10–40	La Jolla Vieja	6210.7	245,779.3	63.1	12.7	18,747.4	4.8	96.7	124,859.1	32.1	0.0	0.0	0.0	389,385.7
CA-SRI-138	2	40–77	La Jolla Vieja	5860.1	188,029.9	50.8	137.6	164,858.4	44.6	16.1	16,869.4	4.6	0.1	32.4	0.0	369,790.2
CA-SRI-313	1	0–42	Bee	5489.5	173,789.8	41.5	203.0	239,942.6	57.2	5.3	5503.4	1.3	0.0	0.0	0.0	419,235.8
CA-SRI-313	2	14–46	Bee	2248.8	83,432.2	45.0	64.5	89,277.1	48.2	9.7	11,737.0	6.3	1.0	765.0	0.4	185,211.3
CA-SRI-333	1	0–50	Bee	3707.9	88,041.5	39.5	152.4	135,122.8	60.5	0.0	0.0	0.0	0.0	0.0	0.0	223,164.3
CA-SRI-31	1	0–40	Bee	5561.6	161,064.6	35.5	184.1	203,971.7	45.0	95.5	86,674.7	19.1	3.3	1956.0	0.4	453,667.0
CA-SRI-31	2	0–25	Bee	1519.1	70,388.4	44.3	43.8	77,577.7	48.9	6.8	10,593.8	6.7	0.2	163.2	0.1	158,723.1
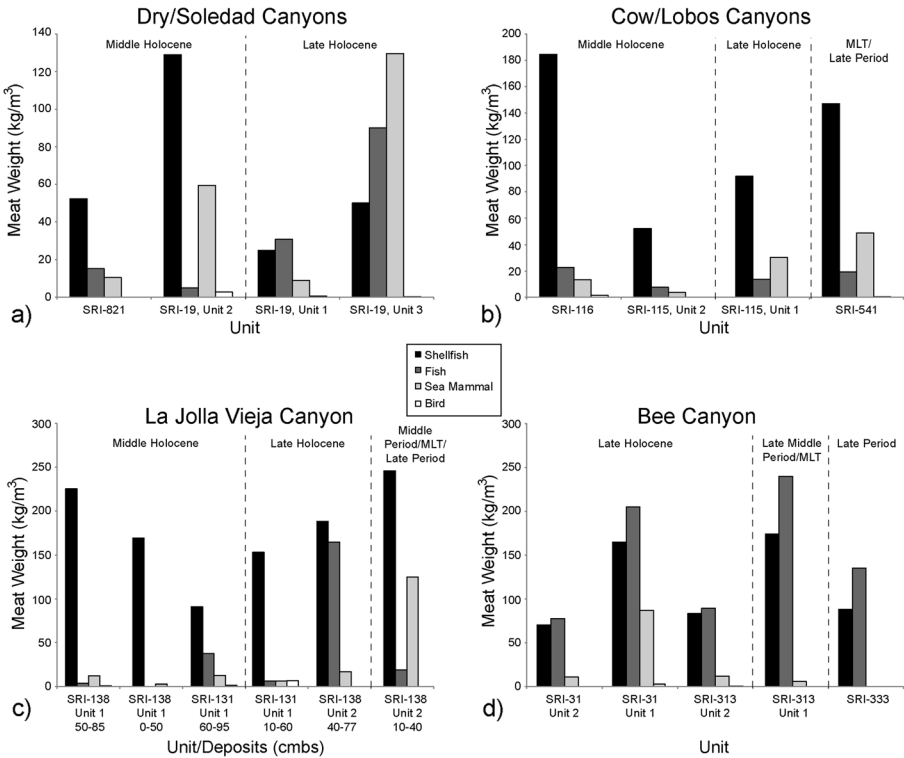
Fig. 3 a–d Meat weight density of the different faunal components of each excavation unit, separated by habitat

shellfish, 67 % and 66 %, respectively. Fish (20 %) is the second largest contributor at CA-SRI-821 and sea mammal (13 %) is third. This is reversed at CA-SRI-19, at which sea mammal (30 %) is more prominent than fish (3 %). During the late Holocene, fish and sea mammal are more prominent. At CA-SRI-19, unit 1, fish (47 %) overtakes shellfish (38 %) in importance. In the assemblage from CA-SRI-19, unit 3, both sea mammal (48 %) and fish (33 %) were more prominent contributors to meat weight than shellfish (19 %). This unit also had the greatest amount of meat weight represented by the assemblage, at 270.1 kg/m^3. CA-SRI-19, unit 2, is second with 196.2 kg/m^3.

Similar patterns are evident in the other habitats. At both Cow/Lobos and La Jolla Vieja Canyons, shellfish are the dominant meat weight component of all excavation units. Both CA-SRI-116 and CA-SRI-115, unit 2, are more than 80 % shellfish; fish is 10 % and 12 %, respectively. During the late Holocene, fish become slightly more important, at 17 % early in this period (CA-SRI-115, unit 1) and during the MLT and Late Period (CA-SRI-541). Sea mammal also increases in importance through time. At La Jolla Vieja Canyon, the dominance of shellfish during the middle Holocene is even more prominent, accounting for more than 93 % of the meat weight throughout CA-SRI-138, unit 1. Toward the end of the middle Holocene, this drops to 64 % (CA-SRI-131, 60–95 cmbs), with fish increasing to 26 %. During the late Holocene, fish become much more important, making up 45 % of the meat weight from CA-SRI-138, unit 2, 40–77 cmbs (*vs.* 51 % for shellfish). During the Late Middle Period and MLT (CA-SRI-138, unit 2, 0–40 cmbs), fish (5 %) decreases in importance compared to shellfish

(63 %) and sea mammal (32 %). The mouth of Bee Canyon was not settled until the late Holocene, and fish is the dominant contributor to meat weight at all times (between 48 % and 61 %). Shellfish is second (between 36 % and 45 %), and sea mammal only accounts for more than 7 % of the total in one unit (CA-SRI-31, unit 1; 19 %).

Overall, meat weight density from excavation units in all habitats generally tends to increase through time. The exception is Cow/Lobos Canyons, where CA-SRI-116 is the earliest unit and has the highest total meat weight (222 kg/m^3). In all other cases, the latest excavation units have the highest meat weight density, perhaps suggesting increased population density in all habitats through time.

The relative proportions of shellfish species in the faunal record from different excavation units are more strongly associated with their particular drainages than with the age of the site (Table 7; Fig. 4). California mussel (*M. californianus*) is the primary species in all excavation units except CA-SRI-333, but its prominence varies between drainages (Table 8). With the exception of the later deposits at Bee Canyon, the highest shellfish diversity is at the mouth of Dry and Soledad Canyons (Table 9; Fig. 5). It is consistent in these units over time, with a Shannon-Weaver diversity index between 1.7 and 1.9 (Shannon and Weaver 1949). Diversity of meat weight is higher, ranging from 1.9 to 2.1. This is because mussel makes up a high proportion of the meat weight but has a relatively low ratio of meat to shell. Evenness values are also among the highest at Dry and Soledad Canyons (Fig. 6). During the middle Holocene, the second most prominent contributor to the shellfish assemblage is black turban snails (*Chlorostoma funebralis*), which is 26 % of the shell at CA-SRI-19, unit 2, and 14.5 % of the shell at CA-SRI-821. This is followed by abalone (*Haliotis cracherodii* and *Haliotis rufescens*), chiton (*Ischnochiton conspicuus* and *Cryptochiton stelleri*), and crab (*Cancer* spp.).

During the late Holocene, chiton and crab are the second and third most prominent shell species. However, the shell meat weight densities at CA-SRI-19, unit 1 (25 kg/m^3) and unit 3 (50.1 kg/m^3) are substantially less than the middle Holocene unit 2 (128.9 kg/m^3). This reflects the increasing importance of fish and sea mammal. From the perspective of the IFD, it makes sense that there is high species diversity at the highest ranked habitat. Population increase there caused a depression of the highest ranked species (California mussel; see Braje *et al.* 2007), eventually prompting a population expansion to lower ranked habitats. This is also reflected in average mussel size data (Table 8, Fig. 7). There is a slight increase in mussel size throughout the middle Holocene, but there is a clear decrease in size during the late Holocene, suggesting overexploitation. The high average from CA-SRI-19, unit 1, is from only 22 individuals and therefore is not a reliable indicator.

The middle-ranked habitat at Cow and Lobos Canyons has the lowest species diversity overall, with a Shannon-Weaver diversity index between 0.7 and 1.1 for shell weight and 1.1 and 1.6 for meat weight. Evenness is also lower here overall than at any of the other habitats. This is because California mussel contributes more than 73 % of all shell assemblages. The only other species to make up significant proportions of the assemblage were turban snails (9 % of CA-SRI-116) and sea urchin (*Strongylocentrotus purpuratus*; 13 % of CA-SRI-541). The highest density shell deposits occur at CA-SRI-116 (187.4 kg/m^3), with the second highest at the MLT/Late Period deposits from CA-SRI-541 (157.6 kg/m^3). Mussel size is relatively consistent over time, with a slight decrease during the late Holocene. There is a

Table 7 Measured shell weight and shell weight density of major species for all excavated sites

Site	Unit	Level (cmbs)	M. californianus		H. cracherodii		H. rufescens		Haliotis spp.		S. purpuratus	
			(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)
CA-SRI-19	1	70–92	171.4	12,463.0	0.0	0.0	0.0	0.0	4.4	319.2	11.4	827.0
CA-SRI-19	2	0–80	3523.4	70,467.4	40.6	812.9	623.4	12,468.6	99.2	1983.4	93.7	1874.3
CA-SRI-19	3	22–71	882.2	28,807.6	17.7	577.2	0.0	0.0	31.8	1039.9	120.8	3943.7
CA-SRI-821	1	29–85	989.1	28,259.0	0.0	0.0	128.2	3662.8	97.6	2789.4	96.0	2744.0
CA-SRI-115	1	10–64	3574.3	105,904.4	13.1	389.5	4.1	122.8	0.0	0.0	103.8	3075.3
CA-SRI-115	2	12–45	1168.4	56,651.9	6.3	305.2	2.7	131.4	2.7	128.7	17.2	834.4
CA-SRI-116	1	10–102	10,773.4	187,363.1	4.8	83.9	339.7	5907.4	52.9	920.5	233.3	4058.2
CA-SRI-541	1	0–40	3941.0	157,641.2	46.4	1855.5	6.1	242.8	2.0	79.7	661.8	26,472.2
CA-SRI-131	1	10–60	4822.7	154,327.0	26.4	845.9	4.52	144.6	22.4	716.8	349.4	11,180.3
CA-SRI-131	1	60–95	1659.5	75,860.9	42.0	1920.8	48.4	2212.2	33.4	1527.8	430.1	19,663.3
CA-SRI-138	1	0–50	5141.1	164,515.8	33.4	1068.0	276.7	8853.4	107.3	3434.5	483.9	15,483.3
CA-SRI-138	1	50–85	3599.8	164,563.1	390.2	17,837.6	84.1	3845.2	43.1	1970.9	465.9	21,298.0
CA-SRI-138	2	10–40	5281.8	281,697.1	0.5	26.7	40.0	2134.1	0.9	45.4	158.5	8452.0
CA-SRI-138	2	40–77	4511.5	195,093.7	35.3	1528.2	37.4	1616.0	2.4	102.8	395.7	17,111.5
CA-SRI-313	1	0–42	2320.6	99,012.8	79.6	3396.8	29.0	1236.3	95.2	4060.8	928.1	39,600.1
CA-SRI-313	2	14–46	784.5	39,225.7	83.2	4161.8	16.6	827.9	6.2	310.2	287.4	14,368.9
CA-SRI-333	1	0–50	265.6	8500.8	90.2	2887.9	134.1	4291.2	57.3	1833.6	1072.1	34,306.7
CA-SRI-31	1	0–40	2724.3	108,971.7	265.7	10,626.6	0.0	0.0	1.7	67.3	1287.2	51,487.6
CA-SRI-31	2	0–25	636.8	40,752.6	44.4	2839.8	5.6	358.4	0.0	0.0	60.2	3852.7

Table 7 (continued)

| Site	Unit	Level (cmbs)	C. funebralis		C. biplicata		Chiton		Balanus spp.		Cancer spp.		S. bifurcatus	
			(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)	(g)	(g/m³)
CA-SRI-19	1	70–92	24.9	1808.7	1.1	81.5	71.3	5186.0	2.1	153.5	47.8	3478.6	110.6	8047.2
CA-SRI-19	2	0–80	2330.8	46,615.5	15.8	316.6	570.0	11,400.1	175.7	3514.3	377.9	7558.5	564.5	11,289.7
CA-SRI-19	3	22–71	82.3	2687.4	10.6	346.1	240.0	7835.4	21.8	711.9	112.6	3676.8	461.3	15,063.1
CA-SRI-821	1	29–85	372.0	10,628.4	0.0	0.0	282.9	8083.5	77.1	2203.4	249.8	7137.1	129.3	3695.1
CA-SRI-115	1	10–64	111.6	3306.7	9.3	275.6	63.8	1889.6	52.0	1540.4	21.0	623.2	307.2	9103.0
CA-SRI-115	2	12–45	32.5	1574.2	0.7	32.0	30.8	1491.4	55.3	2681.7	15.2	736.4	135.4	6565.1
CA-SRI-116	1	10–102	1342.7	23,351.8	33.7	586.6	184.0	3199.6	507.0	8816.8	130.9	2276.8	668.0	11,618.0
CA-SRI-541	1	0–40	30.7	1229.0	0.8	33.2	55.6	2225.2	29.3	1172.7	18.1	722.6	239.2	9569.0
CA-SRI-131	1	10–60	237.9	7613.6	9.08	290.6	121.3	3881.4	148.1	4739.0	64.8	2073.7	598.3	19,145.3
CA-SRI-131	1	60–95	68.0	3107.4	5.0	229.9	62.0	2836.4	42.8	1955.7	60.9	2782.4	215.3	9842.8
CA-SRI-138	1	0–50	568.2	18,181.0	5.8	185.6	88.7	2837.3	104.2	3333.6	71.4	2284.3	376.1	12,034.5
CA-SRI-138	1	50–85	407.5	18,629.5	2.5	115.2	86.9	3971.7	81.1	3706.2	53.4	2441.3	1339.4	61,228.0
CA-SRI-138	2	10–40	149.0	7947.7	11.2	598.9	21.1	1127.7	167.7	8943.7	42.8	2281.9	213.8	11,403.7
CA-SRI-138	2	40–77	71.7	3100.6	8.7	377.5	91.9	3975.3	276.0	11,936.6	24.3	1048.9	345.8	14,955.6
CA-SRI-313	1	0–42	667.3	28,470.3	5.5	233.8	524.8	22,390.8	421.2	17,972.8	17.9	764.4	107.3	4577.5
CA-SRI-313	2	14–46	484.4	24,221.3	0.0	0.0	283.6	14,178.4	110.2	5510.8	22.6	1128.8	68.8	3439.7
CA-SRI-333	1	0–50	1176.0	37,633.3	107.7	3445.4	226.8	7256.1	13.1	420.6	149.3	4776.2	108.0	5759.3
CA-SRI-31	1	0–40	115.5	4619.6	17.6	703.2	144.9	5795.8	319.3	12,771.9	133.3	5331.4	249.6	9984.0
CA-SRI-31	2	0–25	25.4	1625.8	2.1	137.0	527.8	33,777.7	68.8	4402.2	5.4	348.4	15.5	994.0
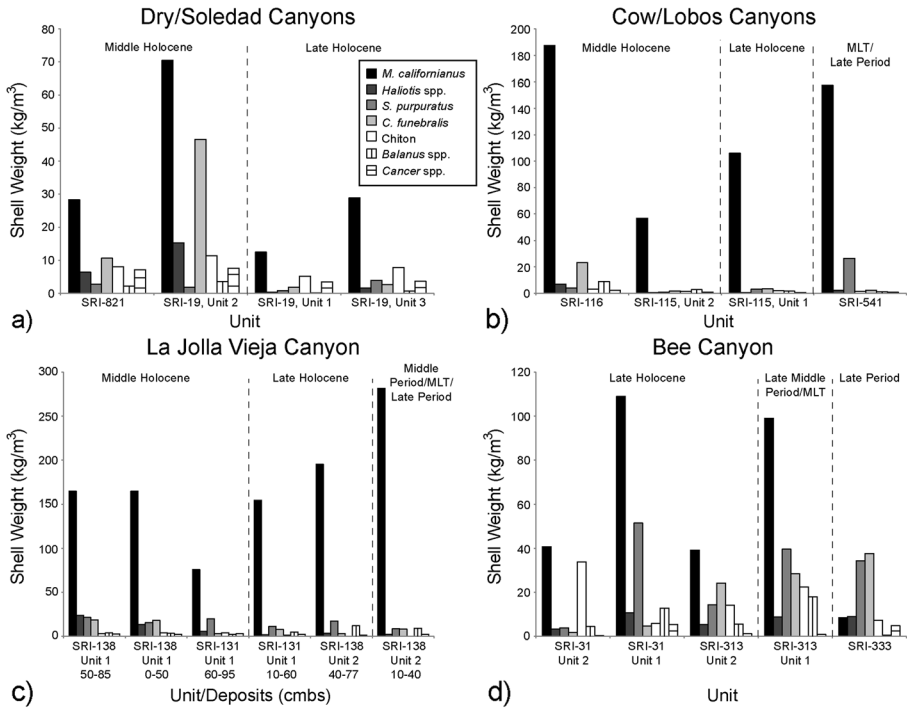
Fig. 4 **a–d** Shell weight density of the seven most important dietary components, separated by habitat

relatively high proportion of small individuals at CA-SRI-115, unit 1, suggesting that people may have increasingly employed stripping as a strategy as the overall availability of large mussels decreased.

The shell deposits from La Jolla Vieja Canyon exhibit a similar pattern. Diversity is low overall, although higher than at Cow and Lobos Canyons, with a Shannon-Weaver index ranging from 0.7 to 1.4 for shell weight and 1.4 to 1.8 for meat weight. California mussel is again the dominant component, at least 54 % of the shell weight in all cultural components of the excavation units. Abalone is more important early in time, particularly in the middle Holocene deposits from CA-SRI-138, unit 1 (8 %, 50–85 cmbs; 6 %, 0–50 cmbs), as are sea urchin (8 %, 50–85 cmbs; 7 %, 0–50 cmbs) and turban snails (6 %, 50–85 cmbs; 8 %, 0–50 cmbs). There is a general trend toward decreasing diversity and evenness through time. The Late Middle Period/MLT deposits from CA-SRI-138, unit 2, 10–40 cmbs, are more than 84 % California mussel.

One possible explanation for this pattern is that it was coincident with the establishment of the nearby site of CA-SRI-130, which has high-density midden deposits and clear house depressions (Kennett 1998). CA-SRI-138 may have become a specialized mussel collection and shucking site; many of the shells there were unbroken. The decreased diversity and increased focus on mussels over time at the expense of other shellfish species in these habitats could be a result of increased interest in collecting fish and sea mammals in the overall diet breadth. Rather than collecting a suite of shellfish, occupants of the region at the mouth of La Jolla Vieja Canyon may have focused only on mussels to complement the fish in their diet. This part of the island has the clearest pattern in mussel size over time, with a gradual decrease in size and proportion of small

Table 8 Mussel size, estimated using Eq. (1) for the relationship between umbo size and shell length given in Singh and McKechnie (2015). MNI of *Mytilus californianus* and the percentage of small (<20 mm) mussels are also included

Site	Unit	Level (cmbs)	Average mussel size (mm)	*Mytilus californianus*		Small mussels (<20 mm)	
				MNI	MNI/m^3	MNI	% of total MNI
CA-SRI-19	1	70–92	54.0	22	1600.0	5	22.7
CA-SRI-19	2	0–80	50.8	386	7720.0	62	16.1
CA-SRI-19	3	22–71	43.3	154	5028.6	9	5.8
CA-SRI-821	1	29–85	45.1	157	4485.7	22	14.0
CA-SRI-115	1	10–64	40.0	1226	36,325.9	296	24.1
CA-SRI-115	2	12–45	45.2	193	9357.6	13	6.7
CA-SRI-116	1	10–102	44.1	1915	33,304.3	230	12.0
CA-SRI-541	1	0–40	39.8	885	35,400.0	71	8.0
CA-SRI-131	1	10–60	43.1	933	29,856.0	47	5.0
CA-SRI-131	1	60–95	43.5	285	13,028.6	22	7.7
CA-SRI-138	1	0–50	49.9	472	15,104.0	20	4.2
CA-SRI-138	1	50–85	49.8	325	14,857.1	7	2.2
CA-SRI-138	2	10–40	40.0	1587	84,640.0	232	14.6
CA-SRI-138	2	40–77	40.9	1162	50,248.6	122	10.5
CA-SRI-313	1	0–42	62.7	131	5589.3	12	9.2
CA-SRI-313	2	14–46	59.4	54	2700.0	1	1.9
CA-SRI-333	1	0–50	51.1	21	672.0	3	14.3
CA-SRI-31	1	0–40	49.6	381	15,240.0	134	35.2
CA-SRI-31	2	0–25	55.1	92	5888.0	17	18.5

individuals, suggesting a similar pattern to Cow and Lobos Canyon. CA-SRI-138, unit 2, also has by far the greatest density of mussel MNI, further supporting the interpretation of overpredation of mussels (Table 8).

The shellfish assemblages from Bee Canyon are among the most diverse overall, with a Shannon-Weaver index ranging from 1.6 to 1.9 for shell weight and 1.9 to 2.2 for meat weight. These values increase over time. Values for evenness are similarly high. Overall, Bee Canyon is the drainage in which California mussel is the least important component. Sea urchin is one of the dominant species in all units except CA-SRI-31, unit 2. In the other units, it is between 12 % (CA-SRI-313, unit 2) and 33 % (CA-SRI-333) of the total. Turban snails, chiton, and barnacles (*Balanus* spp.) are also important contributors to the assemblage. Overall, shellfish meat weight is lower than at either Cow/Lobos or La Jolla Vieja Canyons. Occupation of these sites occurred only during the late Holocene when fishing and sea mammal hunting were more important than earlier. The increased diversity of shellfish over time may be related to an increased human population density. Mussel size is largest at Bee Canyon of all areas that we tested, which may be related to the fact that it was settled for only a short time. CA-SRI-31, unit 1, has unusually small mussels and a high proportion of small

Table 9 The Shannon-Weaver diversity index, richness, and evenness values for shell and meat weight for all excavated sites

Site	Unit	Level (cmbs)	Richness	Shell weight		Meat weight	
				Diversity	Evenness	Diversity	Evenness
CA-SRI-19	1	70–92	13	1.8	0.7	2.0	0.8
CA-SRI-19	2	0–80	22	1.8	0.6	2.1	0.7
CA-SRI-19	3	22–71	14	1.7	0.7	1.9	0.7
CA-SRI-821	1	29–85	19	1.9	0.6	2.0	0.7
CA-SRI-115	1	10–64	17	0.7	0.3	1.1	0.4
CA-SRI-115	2	12–45	16	0.9	0.3	1.4	0.5
CA-SRI-116	1	10–102	26	1.1	0.3	1.6	0.5
CA-SRI-541	1	0–40	16	0.8	0.3	1.2	0.4
CA-SRI-131	1	10–60	11	1.0	0.4	1.4	0.6
CA-SRI-131	1	60–95	16	1.3	0.5	1.7	0.6
CA-SRI-138	1	0–50	15	1.2	0.4	1.6	0.6
CA-SRI-138	1	50–85	14	1.4	0.5	1.8	0.7
CA-SRI-138	2	10–40	15	0.7	0.3	1.1	0.4
CA-SRI-138	2	40–77	14	1.0	0.4	1.4	0.5
CA-SRI-313	1	0–42	20	1.8	0.6	2.2	0.7
CA-SRI-313	2	14–46	16	1.9	0.7	2.2	0.8
CA-SRI-333	1	0–50	23	1.9	0.6	2.0	0.6
CA-SRI-31	1	0–40	20	1.6	0.5	1.9	0.6
CA-SRI-31	2	0–25	15	1.7	0.6	1.9	0.7

individuals, which may reflect overpredation, but could also be because sizes were estimated using a less reliable method than the other units. By the beginning of the MLT, there were permanent settlements at the mouths of all of the major drainages on the island, limiting the possibilities for expansion to new settlement locations. Because opportunities for further expansion would have been limited, it would have been more difficult for population movement to alleviate resource stress.

Discussion

Kennett *et al.* (2009) and Winterhalder *et al.* (2010) have shown that the existing radiocarbon chronology for permanent coastal settlement across the four NCI supports IFD predictions of initial occupation and persistence. Jazwa *et al.* (2013) added a temporal dimension by demonstrating how suitability rises or falls with environmental or technological change independent of population density. Fieldwork reported in this study goes a step further, targeting not only the chronology of initial occupation of different habitats but also the timing of changes in the faunal record as a proxy for population density and changing habitat suitability (Fig. 8).
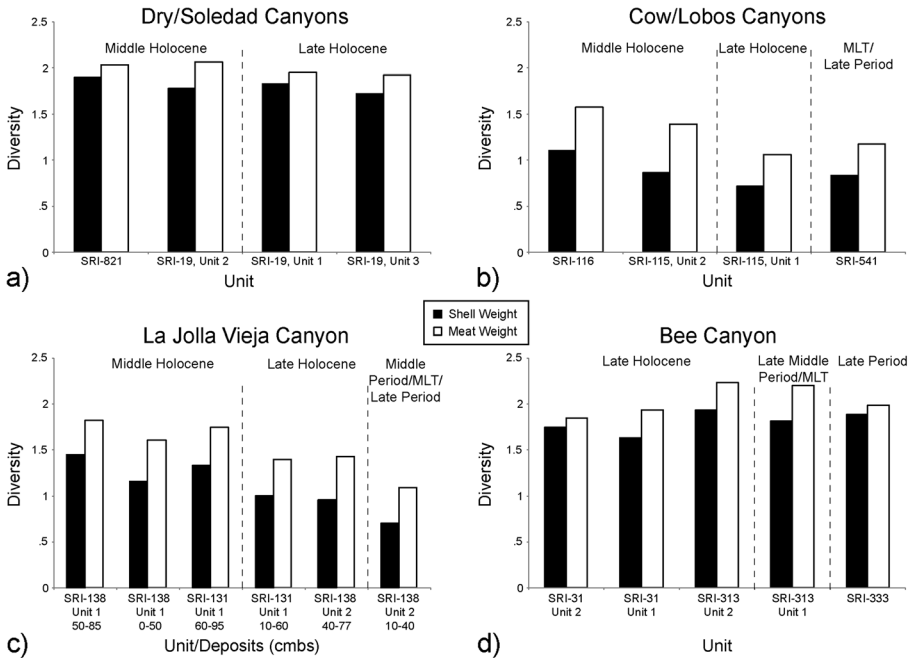
Fig. 5 a–d Shannon-Weaver diversity function for each site examined in this study, divided by habitat
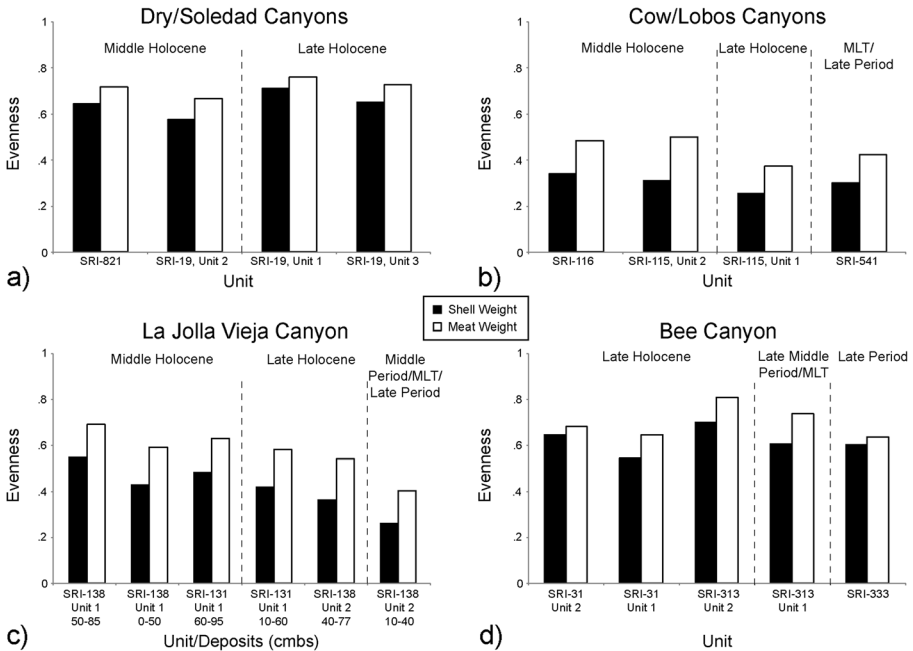
Fig. 6 a–d Evenness values for each site examined in this study, separated by habitat
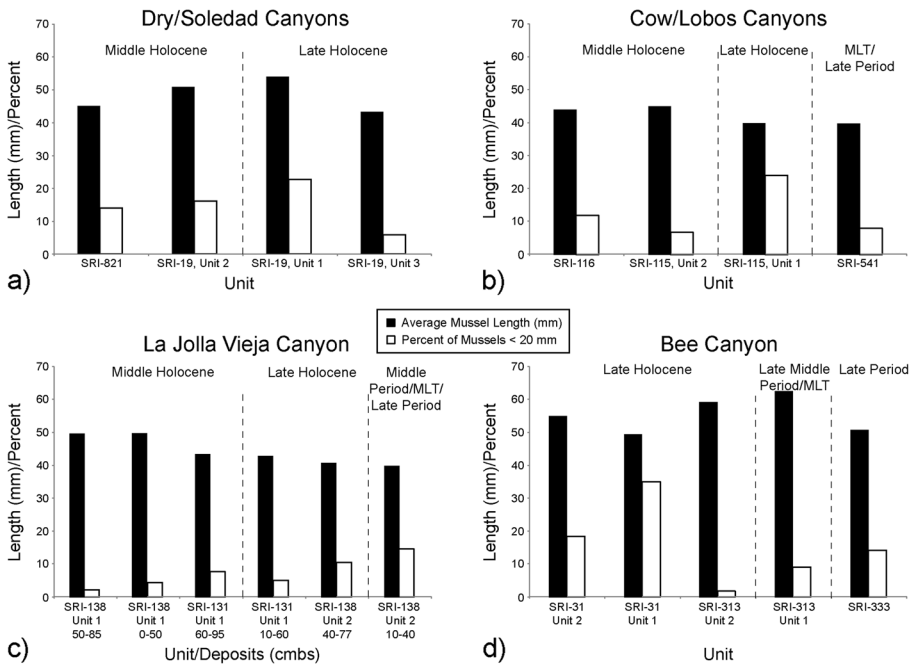
Fig. 7 **a–d** Average mussel size and percent of small (<20 mm) mussels, separated by habitat. Note that the y-axis represents both average mussel length (mm) and percent of small mussels (%)

According to the IFD, the earliest permanent settlement should occur at the highest ranked locales. The earliest dates available from permanent settlements on Santa Rosa are from Old Ranch and Tecolote Canyons, both high-ranked habitats. CA-SRI-187, at the mouth of Old Ranch Canyon and Old Ranch House Canyons, has been dated to 8050–7840 cal BP (Kennett 1998; Jazwa *et al.* 2013). The suitability of this site was increased by the presence of a productive estuary at the mouth of those drainages during the middle Holocene (Jazwa *et al.* 2013). CA-SRI-3, at the mouth of Tecolote Canyon, dates to 7890–7520 cal BP (Kennett 1998, p. 456; Winterhalder *et al.* 2010). It is uncertain if the midden lens at nearby (~1 km up canyon) CA-SRI-780, dated to 8410–8285 2σ cal BP, can push this date further back in time because only a small part of the site is exposed and it is unclear whether it meets the criteria of a permanent settlement. However, permanent early settlements on the island are not confined to the highest ranking habitats, but also can be associated with middle-ranked habitats like Lobos Canyon (CA-SRI-116) and La Jolla Vieja Canyon (CA-SRI-138, unit 2).

Expansion of settlement sites during the middle Holocene is consistent with the predictions of the IFD. High-ranked habitats along the northwest coast of Santa Rosa Island are the first to experience clear evidence of more intensive occupation (prediction 1; Table 10). There is an important difference between these habitats and the others with early settlement (Fig. 2). In the high-ranking habitats, there are multiple locales that were occupied contemporaneously. At Dry and Soledad Canyons, this includes units at CA-SRI-19 and CA-SRI-821. Similarly, CA-SRI-3 and CA-SRI-5 at the mouth of Tecolote and Arlington Canyons were both occupied during the middle Holocene (Kennett 1998; Winterhalder *et al.* 2010; Jazwa *et al.* 2015a). Intensive settlement persists at both of these locations through the late Holocene (prediction 4).
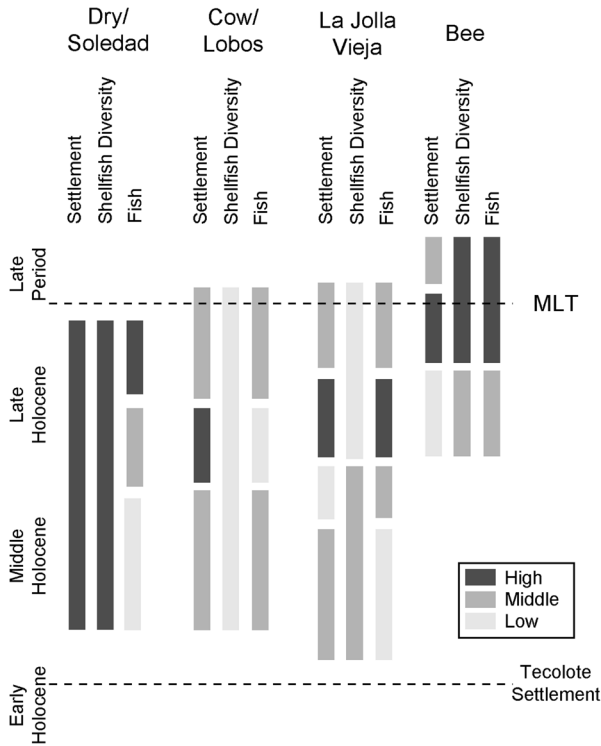
Fig. 8 Idealized summary of settlement patterns at the excavated habitats through time. Settlement intensity is inferred from the number and size of occupied sites. Shellfish diversity is used to determine resource stress. The increase in fishing suggests that population at individual sites is larger

Table 10 IFD model predictions and assessments following the targeted sampling of habitats of high, middle, and low predicted suitabilities

Prediction	Description	Result	Notes
1	Highest ranked locations settled first	Partially supported	Middle-ranked habitats also settled early, but high-ranked habitats most intensively
2	Evidence for resource depression	Partially supported	Evident between habitats, but not over time within habitats
3	Expansion associated with resource depression	Partially supported	Temporal resolution prevents precision
4	Settlement persistence following expansion	Supported	Except the Late Period (few high population villages)
5	Environmental change can depress or increase suitability	Supported	Middle Holocene fresh water scarcity
6	Technological developments can influence suitability	Supported	Fishhook and *tomol* development

There is a continuous record of occupation through the middle Holocene at the nearby middle-ranked habitat of Cow and Lobos Canyon, but there is no evidence of contemporaneous occupation of multiple sites in this habitat until the late Holocene. At La Jolla Vieja Canyon, evidence for permanent coastal settlement is sparse and limited to a single locus of CA-SRI-138 until the very end of the middle Holocene (prediction 3).

Dry conditions during the middle Holocene enhanced the suitability of drainages along the northwest coast relative to other locales. These drainages are among the most resilient to drought on the island (prediction 5). Climate records suggest that the middle Holocene, particularly the period from about 6500 to 3800 cal BP, was a dry interval dominated by drought conditions (*e.g.*, Antevs 1948, 1952, 1955; LaMarche 1973, 1974; Lindström 1990; Morgan *et al.* 1991; Thompson 1992; Cole and Liu 2004; Quade *et al.* 1998; Hughes and Graumlich 2000; Benson *et al.* 2002; Erlandson *et al.* 2005; Kennett 2005; Kennett *et al.* 2007). To examine the local effects of this climate change, Jazwa *et al.* (2015b) modeled fresh water flow and drainage resilience at the mouth of the 19 major drainages on Santa Rosa Island (Table 1). We use these results to generate several different sets of drainage rankings by altering the weights given to the different environmental variables (Table 11). Across our weightings, Tecolote and Arlington Canyons are always the top two ranked drainages. Soledad and Dry Canyons fall by 7 and 5 ranking spots, respectively, when water is ignored and gain 2 and 5 spots when taking only water into account. This reflects the important contribution of water availability to habitat suitability along the northwest coast.

At the start of the late Holocene, permanent settlement density increased at locations that had previously been occupied and settlement expanded to new drainages (predictions 3 and 5; Fig. 8). Increasingly wet conditions in California at the end of the middle Holocene (Antevs 1955; Lindström 1990; Davis 1992; Thompson 1992; Quade *et al.* 1998; Benson *et al.* 2002; Kennett 2005; Kennett *et al.* 2007) increased the suitability of multiple drainages, including Bee Canyon. Climate change lowered the premium on drought-resistant drainages. Dry and Soledad Canyons maintained a high settlement density at this time, as did the other high-ranked drainages along the northwest coast of the island like Tecolote and Arlington Canyons (Fig. 2; Kennett 1998). Apparently, continuous occupation persists at Cow and Lobos Canyons through the middle and late Holocene.

There was a clear increase in settlement at La Jolla Vieja Canyon, with evidence for contemporaneous occupation at CA-SRI-131, CA-SRI-138, and CA-SRI-488 during the late Holocene. This matches IFD predictions (4), as increasing population led to an increase in population density at all occupied habitats. The late Holocene is also when lower ranked or more isolated habitats like Bee Canyon first experienced permanent settlement. Jazwa *et al.* (2013) show that Old Ranch Canyon was reoccupied at the end of the middle Holocene following a gap of at least 1500 years after the closure of the estuary that was present there. This pattern is consistent with the model discussed here. After about 1300 cal BP, the number of settlement sites on the NCI reaches its maximum and there is evidence for permanent settlement at all of the major drainages on Santa Rosa Island (Winterhalder *et al.* 2010), including all four of the locations investigated here. The population expansion that occurred during this period makes this pattern consistent with the IFD.

There are two periods during which the settlement chronology of Santa Rosa Island does not fully conform to IFD predictions: initial permanent occupation (*contra*

Table 11 Drainage rankings with environmental variables weighted in different ways

Drainage	Standard rank	No water 0.6 RI, 0.1 SB, 0.3 KA		High resilience 0.2 WF, 0.3 DR, 0.3 RI, 0.05 SB, 0.15 KA		No resilience 0.5 WF, 0.3 RI, 0.05 SB, 0.15 KA		Only water 0.2 DS, 0.6 WF, 0.2 DR		Fish 0.1 DS, 0.3 WF, 0.1 RI, 0.25 SB, 0.25 KA	
		Rank	Change	Rank	Change	Rank	Change	Rank	Change	Rank	Change
Tecolote	1	1	0	1	0	1	0	1	0	1	0
Arlington	2	4	−2	2	0	2	0	2	0	2	0
Trancion	3	8	−5	3	0	3	0	4	−1	3	0
Verde	4	3	1	5	−1	5	−1	7	−3	13	−9
Soledad	5	12	−7	9	−4	4	1	3	2	5	0
Garanon	6	5	1	7	−1	7	−1	9	−3	18	−12
Old Ranch House	7	2	5	8	−1	9	−2	17	−10	8	−1
Dry	8	13	−5	12	−4	8	0	8	0	11	−3
Acapulco	9	6	3	6	3	11	−2	14	−5	9	0
Water	10	19	−9	14	−4	10	0	5	5	4	6
Cow	11	10	1	16	−5	6	5	11	0	15	−4
Old Ranch	12	16	−4	11	1	16	−4	6	6	10	2
Bee	13	9	4	4	9	13	0	13	0	7	6
Cherry	14	7	7	10	4	15	−1	16	−2	12	2
Whetstone	15	11	4	13	2	12	3	12	3	6	9
San Augustin	16	15	1	15	1	14	2	10	6	14	2
La Jolla Vieja	17	17	0	18	−1	17	0	15	2	16	1
Lobos	18	14	4	17	1	19	−1	19	−1	19	−1
Wreck	19	18	1	19	0	18	1	18	1	17	2

DS drainage size; *WF* water flow, *DR* drainage resilience, *RI* length of rocky intertidal shoreline, *SB* length of sandy beach, *KA* kelp forest area

prediction 1) and just before historic contact (*contra* prediction 4). The available evidence for earliest permanent settlement is not confined to the highest ranked drainages, but is distributed throughout high- and middle-ranked habitats. Excavation units from middle-ranked habitats examined here predate the earliest deposits from high-ranked Dry and Soledad Canyons (CA-SRI-821) by approximately 1000–1500 years (La Jolla Vieja) and 100–500 years (Lobos). We propose several potential explanations. First, at especially low overall population densities, any of the better locations on Santa Rosa Island would have provided adequate resources, allowing sociocultural factors to play a larger role in the population distribution. Occupants of the high-ranked northwest coast may have acted despotically, dissuading nearby settlement and prompting new groups to locate on the south side of the island or along the east coast. Likewise, factors like weather could have drawn small populations to the south coast of the island, which is sunnier and more protected from wind. It also is possible that this anomaly is an artifact of rising sea levels, which may have obscured the evidence of earliest occupation in the highest ranking habitats. If that is the case, the truncated evidence available to us at present will conform to a pattern of contemporaneous settlement across the *upper end* of the suitability range, similar to what we see (Fig. 9). Unfortunately, we do not currently have evidence to sort out these possibilities.

In the second apparent exception to the IFD, despotism is more clearly present during the latest occupation on the islands, particularly during and after the MLT. Despite the fact that population continued to increase (Glassow 1999; Kennett 2005) after the MLT, permanent settlement condenses to a smaller number of large villages rather than continuing to expand to new settlement locations. By Spanish contact, residents of Santa Rosa Island occupied only eight large coastal villages (Johnson 1982, 1993, 2001; Kennett 1998, 2005; Glassow *et al.* 2010). There is no evidence for occupation of the mouth of Dry and Soledad Canyons after 1260–1090 2σ cal BP (CA-SRI-19), La Jolla Vieja Canyon after 645–530 2σ cal BP (CA-SRI-138, unit 2), and Cow and Lobos Canyons after 730–545 2σ cal BP (CA-SRI-541). In fact, the only
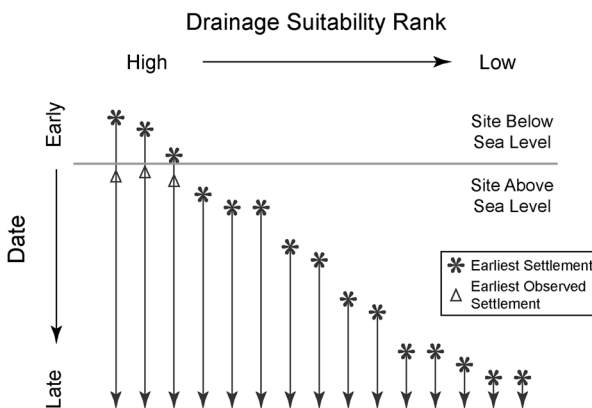
Fig. 9 Potential effect of sea level rise on evidence for the IFD. We show idealized dates for initial settlement as would be predicted by the IFD. Habitats are settled in order of suitability and settlement persists through time. However, if sea level rise submerges evidence for early coastal settlement at the mouths of the highest ranked drainages, all habitats with submerged cultural components will appear to have their initial evidence of occupation at approximately the same time (*triangles*) and across the upper end range of suitabilities, not only in the highest ranked drainages

site examined intensively in this study with clear evidence of occupation until historic contact is CA-SRI-333, which is relatively small and perhaps subsidiary to the large village of Nawani (CA-SRI-97) at the mouth of Acapulco Canyon to the south (Jazwa 2015). The Late Period population aggregated into larger villages partially in response to environmental stress and conflict (*e.g.*, Walker 1989; Walker and Lambert 1989; Lambert and Walker 1991; Lambert 1993, 1997; Raab and Larson 1997; Jones *et al.* 1999; Kennett and Kennett 2000; Kennett 2005; Kennett *et al.* 2013). Associated changes included the increase of institutionalized differences in social status (Kennett 2005; Kennett *et al.* 2009) and more rigid territorial boundaries (Kennett 2005; Jazwa 2015).

The end of the Middle Period and the MLT are coincident with the Medieval Climatic Anomaly, a period of extreme drought conditions throughout the western USA (1150–600 cal BP; Kennett 2005; Jones *et al.* 1999; Jones and Schwitalla 2008; Raab and Larson 1997; Stine 1994; Yatsko 2000). In the Santa Barbara Channel region, Lambert and Walker (1991; Walker 1989; Walker and Lambert 1989; Lambert 1993, 1997) document declining health and increased violence based on skeletal samples from the MLT, which they associate with increasing sedentism and diminishing supplies of fresh water and terrestrial foods. Resource shortfalls could have prompted people to move to villages at the mouths of larger, more reliable watersheds. These locations were also typically near large, protected sandy beaches where plank canoes could be launched, increasing access to offshore resources like sea mammals and kelp forest fish species. These canoes provided greater connectivity with the mainland, allowing people to more efficiently obtain subsistence and nonsubsistence resources. Sandy beaches are also the habitat of *C. biplicata* snails, the shells of which were used to create shell beads traded for external resources (prediction 6; *e.g.*, Arnold 1987, 1990, 1992a, b, 2001a; Arnold and Munns 1994; Munns and Arnold 2002; Kennett 2005; King 1990; Rick 2007).

The settlement pattern that emerged during the Late Period is consistent with an IDD at the regional scale. Despotic behavior by groups (*i.e.*, territoriality imposed by violence or the threat of violence) may have emptied locations that were otherwise suitable, high-ranked habitats like Dry and Soledad Canyon. Within these territories, a more centralized, defendable village was established at the highest ranked location, as predicted by the IFD. On Santa Rosa, these locations were often positioned on promontories along the coastline that offered clear views to monitor approaching *tomols* or potential attackers. Population aggregation is also consistent with the idea that increased conflict led to buffer zones between villages (Kennett 2005).

Implications of the Faunal Record

The faunal record from Santa Rosa Island is also consistent with the IFD and IDD (Fig. 8). The highest diversity of middle Holocene shellfish in our excavation units comes from the highest ranked habitat at Dry and Soledad Canyons (CA-SRI-821 and CA-SRI-19, unit 2). We hypothesize that this represents the incorporation of more low-ranked shellfish species like crab, chiton, and platform mussels (*Septifer bifurcatus*) into the diet (see Braje *et al.* 2007). This is a manifestation of resource depression and decrease in the basic habitat suitability that comes with increased population density (prediction 2). Dry and Soledad Canyons are especially attractive because of their

relatively abundant and dependable water sources. Water is sufficiently important that it might have held increasing population there despite depressed shellfish resources, delaying expansion into lower ranked habitats.

The middle Holocene occupation at the mouth of Cow/Lobos and La Jolla Vieja Canyons appears to be different from that at Dry/Soledad Canyons. These drainages do not have the same fresh water flow nor are they as resilient to drought as the high-ranking drainages along the northwest coast (Jazwa *et al.* 2015b). The middle Holocene occupation at Cow/Lobos Canyons is more extensive than that at La Jolla Vieja Canyon, perhaps because of their relative locations. Cow and Lobos Canyons are along the north coast of the island, adjacent (along with Cañada Verde) to high-ranking drainages. This offered benefits including the potential for social or marriage relationships with nearby communities. La Jolla Vieja is more isolated and without such benefits. The shellfish assemblages from the middle Holocene deposits at the middle-ranked habitats are less diverse and perhaps reflective of less stress on shellfish resources than at the high-ranked habitats. Nonetheless, high densities of shellfish at CA-SRI-116 and CA-SRI-138, unit 1, do suggest that the populations at these sites were substantial.

At the end of the middle and beginning of the late Holocene, the number of settlement locations and sites expands and there is a general increase in the intensity of occupation of permanent settlements (Fig. 8). There is also a general trend toward smaller mussels at those locations that continued to be occupied from the middle Holocene, further supporting the interpretation of resource stress. With the exception of the relatively sparse deposits at CA-SRI-19, unit 1, there is an increase in total meat weight between the final middle Holocene deposits and initial late Holocene deposits (Table 6; Fig. 3), including an increase in fish and sea mammal in all cases and an increase in shellfish in all except Dry/Soledad Canyons. This presumably reflects an increase in population density in these habitats and, thus, an impetus for a geographic expansion to lower ranked settlement sites. In addition, there is a clear increase in fishing from the middle to late Holocene (Figs. 3 and 8). Fishing requires more technological investment than collecting shellfish, but it also is more easily intensified and therefore a more flexible strategy for supporting larger population densities and sedentism (Raab 1992; Glassow 1993). The decrease in shellfish diversity and evenness between the middle and late Holocene could also reflect the increased focus on fishing, a shift that continues into the Late Period, at which time fishing, particularly offshore, increases even more at village sites at the expense of shellfish (Jazwa 2015).

CA-SRI-333 and the Late Period rockshelter sites in Cow, Lobos, and Tecolote Canyon (Table 4) suggest that population was not entirely condensed at large villages late in time. A seasonality study at CA-SRI-333 indicates that people were there to some degree in all seasons except winter (Jazwa 2015). Because our investigation of rockshelter sites is limited to a single date for initial occupation and observations of surface deposits and erosional cuts, it is difficult to determine the extent to which those sites were used. Given their location and superficial deposits, it seems likely that they were short-term or seasonal sites, used to get out of the wind or to stay while collecting terrestrial resources from the island interior. Plant resources were likely the primary objective (Timbrook 2007; Gill 2013, 2014), but low quality chalcedony, which outcrops near the head of Cow and Lobos Canyon, may have also been important.

Caveats and Future Directions

Limitations potentially affecting our conclusions include the issue of sample size. We include excavation materials from the mouths of only 6 of the 19 major drainages on Santa Rosa Island. Within sites, we did our best to sample different settlement loci, but we cannot guarantee that we have sampled all periods of settlement in each location. We excavated relatively small 25×25-cm column samples to minimize site disruption and because of the time and resources required to sort the high density of midden. The comparative nature of our study design favored sampling a broad range of locations rather than intensively excavating a small number of them. While there is always bias in subsampling a site, the density of shell and fish bone were high in all units, increasing confidence that they are representative of the faunal assemblage, at least in the immediate area (see Kennett 2005; Joslin 2012). Given their much larger size, sea mammal remains are distributed more unevenly, making extrapolations from small column samples less trustworthy than for fish or shellfish.

We trace habitat and settlement on Santa Rosa in much greater detail than previous IFD applications (cf., Kennett et al. 2009; Winterhalder et al. 2010). There is more to settlement mobility than such an island-wide approach can take into account, including movement to smaller seasonal and special purpose sites (see Kennett 2005; Jazwa et al. 2015a). Finally, we note that Santa Rosa Island includes only relatively high-ranked settlements. We predict that the low-ranked settlements along the northwest coast of Santa Cruz Island will have late initial settlement, if any, and have limited evidence for continuous occupation. Further studies will include survey and excavation there.

Conclusion

Field studies in four NCI drainages including targeted survey and excavation of sites differing in basic suitability provide partial support for predictions of the IFD (Table 10). In general, the high-ranked locations were settled early at the beginning of the middle Holocene and were persistently occupied through the late Holocene. However, we observe early permanent settlement distributed across high- and middle-ranked locations. We offer several potential explanations for this pattern, including the possibility that it is the product of early despotic behavior, that low population densities allowed people to value factors not included in the model, or because of submergence of early settlement sites by rising sea levels (Fig. 9).

Dry and Soledad Canyons, our high-ranked habitat, were the first to experience intensive settlement that persisted throughout the middle and late Holocene. The middle-ranked drainages at Cow/Lobos and La Jolla Vieja Canyons were occupied through the middle Holocene, but less intensively. The lowest ranked habitat in this study, Bee Canyon, was not a site of permanent settlement until the late Holocene. All of the four drainages on Santa Rosa examined in detail in this study are in the top 2 quartiles of suitability for drainages on all of the NCI (Winterhalder et al. 2010), and therefore, all were settled before even lower ranked habitats on Santa Cruz and San Miguel Islands.

During the middle Holocene, the assemblages with the highest shellfish diversity were from the high-ranked habitats, which also would have had the highest population

densities. During the late Holocene, population expansion was supported in part from an increase in fishing and sea mammal hunting, which could readily be intensified using new technologies. After the MLT, the population of the island condensed to relatively few large coastal villages, following a settlement pattern more consistent with the IDD. Populations likely congregated at villages to secure access to scarce resources and to seek protection from competing factions. Despotism in the form of territoriality expanded as previously occupied drainages were abandoned, a process that may also have been affected by economies of scale offered by the new technologies available in the more aggregated sites (see Winterhalder *et al.* 2010). Across the occupation of the NCI, we find good support for the IFD model, now applied with much more explicit attention to temporal dynamics of habitat suitability (Jazwa *et al.* 2013) arising from population-independent environmental change in habitat suitability. These temporal dynamics are related to fresh water availability, diet breadth change, technology, and changes in political economy.

The use of the IFD and IDD is becoming more prominent in anthropology (see Codding and Bird 2015). Perhaps the greatest benefit of these models is their ability to represent in one formulation economic relationships among variables considered critical by human ecologists: population density and growth, migration, settlement, resource selection and exploitation, environmental change, subsistence efficiency and economic returns, hierarchy, and competition. The IFD/IDD subsumes several other well-established archaeological models (see Jazwa 2015). The models adapt well to changing scale, from single sites through time (Jazwa *et al.* 2013), to detailed data-driven comparisons of multiple habitats (this paper), to regional settlement (Kennett *et al.* 2009; Winterhalder *et al.* 2010), to settlement of broader regions such as California (Codding and Jones 2013) or the Pacific (Kennett *et al.* 2006) and Australia (O'Connell and Allen 2012). Confirmed from several angles using data from the Channel Islands, the IFD/IDD provides an example for understanding human settlement patterns among other hunter-gatherer populations and can be expanded to model human decision-making among larger, more complex populations throughout the world.

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