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Ideal free settlement of California's Northern Channel Islands

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ABSTRACT

The prehistoric establishment and expansion of permanent settlements on the Northern Channel Islands of southern California generally follows a pattern predicted by the population ecology model, the ideal free distribution (IFD). We determine this by comparing the abundant archaeological record of these Islands against a careful quantification of habitat suitability using areal photography, satellite imagery, and field studies. We assess watershed area, length of rocky intertidal zone, length of sandy beach for plank canoe pull-outs and area of off-shore kelp beds, for 46 coastal locations. A simple descriptive analysis supports key IFD predictions. A Bayesian model fitted with the Gibbs sampler allows us to reconstruct the Native assessment of habitat that appears to underlie this process. Use of the Gibbs sampler mitigates the impact of missing data, censored variables, and uncertainty in radiocarbon dates; it allows us to predict where new settlements may yet be discovered. Theoretically, our results support a behavioral ecology interpretation of settlement history, human population expansion, and economic intensification in this region. They also demonstrate Bayesian analytical methods capable of making full use of the information available in archaeological datasets.

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Introduction and problem

The Native Americans who moved from the mainland to settle the Northern Channel Islands of southern California knew well the country they were settling. By first recorded permanent settlement (~8000–7000 cal. years BP) they had been exploring and seasonally exploiting the resources of the islands for as much as 5000 years (Erlandson et al., 2008; Kennett, 2005; Kennett et al., 2008). Subsequent to that first settlement further Island colonization of coastal sites at the mouths of major drainages drew on local knowledge gained through even more lengthy experience. Settlers were familiar with the suitability of the habitats they were about to occupy and, we might predict, they established residential sites in an orderly process of adaptive decision-making: Settle first in the most salubrious location. When, with growing exploitation or crowding, its resources were depressed and its value declined to match the next-ranked locale, establish a new settlement there. As population grew this process repeated, adding further new settlements in locations ordered by habitat suitability. In parallel, we expect overall quality of life in all occupied locales declined due to reductions in the availability of or access to critical resources.

This process is neatly captured in a behavioral ecology model: the ideal free distribution (IFD, Fretwell and Lucas, 1969). Analysis of environmental and archaeological data from the Northern Channel Islands indicates that colonization there follows IFD predictions. To demonstrate this, we first describe the prehistory of the Northern Channel Islands. We then introduce the IFD, with the goal of predicting how population growth, intensified use and declining suitability generate a predictable pattern of settlement and habitat infilling. We develop a comparative database of environmental and archaeological variables for 46 coastal locations on the four Northern Channel Islands (Fig. 1). A simple, preliminary analysis substantiates the key IFD hypothesis and fosters the development of a more complete, computationally intensive evaluation of the environmental features that figured most prominently in the settlement decisions of these prehistoric people. Thus, we substantiate our basic behavioral ecology prediction and we make use of statistical methods – the Gibbs sampler and Bayesian analysis – well-suited to the shortcomings and opportunities that occur in datasets drawn from the prehistoric record.

Island Chumash prehistory in brief

At the time of European contact (AD 1542), the people living on the Northern Channel Islands occupied relatively large coastal villages governed by chiefs. They depended heavily upon fishing,

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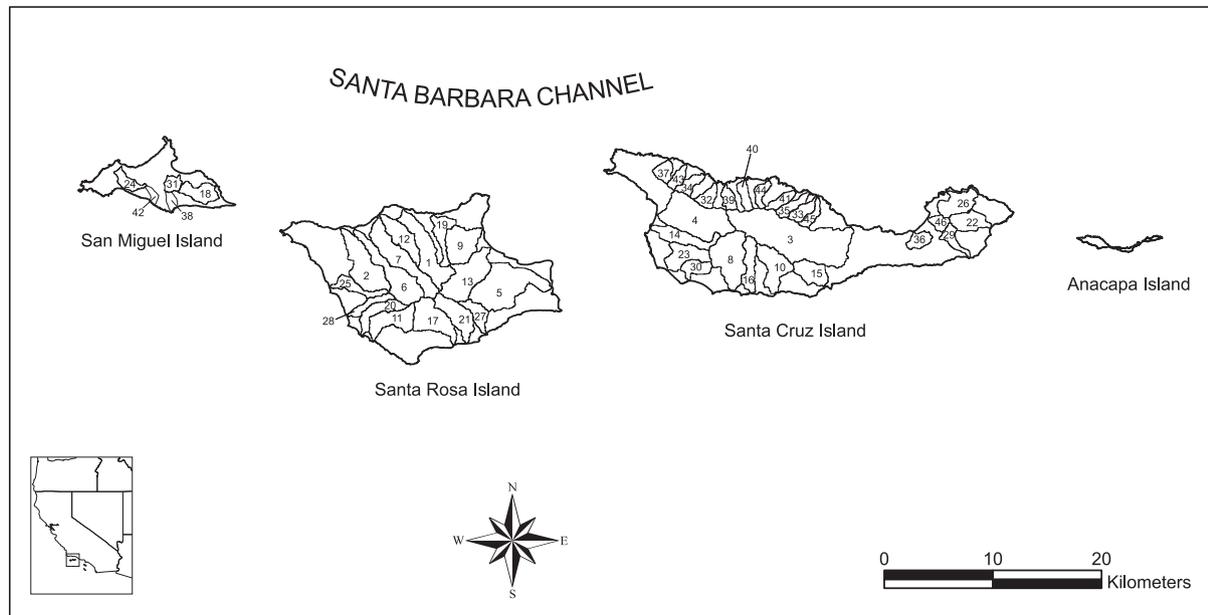
Fig. 1. Key drainages of the Northern Channel Islands, California. Numbers follow the order given in the first column of Table 1. They index a ranked ordering of watersheds by our preliminary analysis of environmental suitability for human habitation (see Kennett et al., 2009).

produced a variety of trade items and participated in an extensive inter-regional exchange network (Arnold, 2001, 2004; Johnson, 1982, 1988, 1993; Kennett, 2005; King, 1976). They spoke a dialect of the Chumash language (Cruzeño) distinct from the related languages on the mainland coast and interior. Chumash is an ancient language with no affinities with other languages in California (Klar et al., 1999). Although mainland and island languages were not mutually intelligible, there is strong evidence for intermarriage throughout Chumash territory, and for exchange of resources and ideas within the region and beyond (Arnold, 1995; Johnson, 1988; Kennett, 2005).

During the early contact period, population densities in the Santa Barbara Channel region were some of the highest in California (Moratto, 1984: 2) and among the highest for hunter–gatherers worldwide (Kelly, 1995). The largest Chumash populations were concentrated on the mainland coast, but significant numbers of people also lived off-shore, an estimated three thousand on Santa Cruz, Santa Rosa and San Miguel (Johnson, 1982). Chumash informants in the late 19th and early 20th century named 22 villages on these three islands (Johnson, 1982, 1993). Locational information for many of these villages is clear and historic artifacts substantiate their existence (Arnold, 1990a; Johnson, 1982, 1993). Baptismal records indicate that intermarriage among these island communities and mainland villages across the Santa Barbara Channel was extensive (Johnson, 1988). Archaeological evidence for the relative permanence of these villages comes from the large size and depth of midden deposits, the presence of substantial domestic features (e.g., house depressions and cemeteries) and diverse faunal and artifact assemblages (Kennett, 2005).

Human occupation of the Northern Channel Islands extends back into the late Pleistocene (Erlandson et al., 1996, 2007; Johnson et al., 2000; Kennett et al., 2008). A partial skeleton, Arlington Man, buried under 11 meters of sediment, provides the earliest evidence for a human presence. It dates to between 13,000 and 12,900 cal. years BP (Agenbroad et al., 2005; Johnson et al., 2000). Little is known about the subsistence and settlement activities of this individual because the archaeological record on the islands and adjacent mainland is essentially silent during this early interval, possibly because post-glacial sea-level rise has obscured or erased the record (Kennett et al., 2008). Regardless, the use of

watercraft and by extension an inferred maritime lifeway is suggested by the presence of Arlington Man on these off-shore islands (Erlandson et al., 2008).

Although the early date of Arlington Man is intriguing, persistent use of the Islands currently does not register in the record for another 600–800 years, at the end of the Younger Dryas cold interval (~12,200 cal. years BP, Kennett et al., 2008). The archaeological evidence occurs on the westernmost island of San Miguel, at Daisy Cave and Cardwell Bluff (Erlandson et al., 2008). The earliest deposits at Daisy Cave (~11,200 cal. years BP) contain only a small number of stone flakes (chert and silicous shale) in association with charcoal and the remains of shellfish from the nearby rocky intertidal zone (Erlandson et al., 1996), evidence for a visit of short duration. Cardwell Bluffs, on eastern San Miguel, is a low-density shell midden dating to 12,200 cal. years BP that appears to be associated with projectile points, stone crescents and other stone artifacts (Erlandson et al., 2008).

The oldest occupational level at Daisy Cave sits at the base of a well-stratified sequence of material, suggesting periodic short term visits to the cave that continue into the early Holocene and later. Early Holocene deposits at Daisy Cave are substantial and contain bone fish gorges, sea grass cordage (including a sandal fragment), stone projectile points and other cultural material associated with a diverse faunal assemblage (fish, shellfish, sea-mammal bone). Persistent and more intensive use of Daisy Cave parallels increases in the formation of low-density shell middens on the outer islands of Santa Rosa and San Miguel during the early Holocene. One of the open questions is whether these ephemeral shell middens represent periodic visitation and resource exploitation by people living more permanently on the mainland, or a resident population based somewhere on the islands (Kennett, 2005). If more permanent settlements existed on the islands they remain undiscovered, perhaps due to post-Glacial sea level rise (Erlandson et al., 2008).

The first evidence for persistent residential bases occurs on the north coast of Santa Rosa Island near the mouth of Tecolote Canyon (SRI-3). A large residential midden and associated cemetery have been identified at this location (Orr, 1968) and radiocarbon dated to between 8000 and 7000 years ago (Erlandson, 1994), the time when sea-level was beginning to stabilize and the coastline started to take its more modern form (Kennett et al., 2008). Identification

of SRI-3 as a permanent settlement is based on the identification of a cemetery at this location (Orr, 1968). Radiocarbon dates confirm that some of the burials date to this early interval, but Erlandson (1994) cautions that some of these burials date to the Middle Holocene. These data suggest settlement continuity at SRI-3 and this is consistent with the expansion of communities along the coast to the west (Skull Gulch, SRI-2) and into the mouth of nearby Arlington Canyon to the east (SRI-4, -5) during the Middle and Late Holocene. Evidence currently available points to the primacy of the Tecolote-Arlington region as an early node of island settlement and social life, but subsequent work should be designed to test this hypothesis. As Tecolote Canyon suggests, for purposes of this analysis we identify permanent settlements archaeologically by the presence of substantial residential middens, the presence of cemeteries, or houses (or some combination) as opposed to more ephemeral concentrations of material representing shorter-term use.

Increases in the number of archaeological sites after 7500 years ago point to a substantial amount of demographic expansion. Primary nodes of settlement extended to several locations along the north and east coasts of Santa Rosa Island (SRI-41, SRI-116, SRI-187) and the southern coast of Santa Cruz (SCrI-333, SCrI-109, Glassow et al., 2008; King, 1990; Wilcoxon, 1993). Substantial middens in the interiors of the islands dating to the Middle Holocene suggest periodic and likely seasonal residential movement to interior locations for the purpose of collecting and processing plant resources (Kennett, 2005; Kennett and Clifford, 2004; Perry, 2003). Midden constituent data indicate a strong focus on organisms from rocky intertidal habitats, but isotopic evidence suggests that higher trophic level organisms (sea-mammals and fish) were also being pursued and consumed (Goldberg, 1993). Although a large number of Middle Holocene archaeological sites have been documented on the islands, only a relatively small number of substantial coastal villages are known. Other sites are the residues of more logistical subsistence activities based in large foraging ranges and perhaps periodic and short term residential mobility (Kennett, 2005).

Major changes in subsistence and settlement occurred on the Northern Channel Islands during the Late Holocene (3000–200 cal. years BP). Populations increased substantially and the number of permanent residential sites expanded around the perimeters of the three largest islands, particularly after 1300 cal. years BP (Arnold, 2001; Kennett, 2005; Rick, 2004b). Periodic visitation to the smaller rocky islets of Anacapa were also more frequent in the late Holocene (Rick, 2006). It is during this time that the patterns of settled life, intensive fishing and extensive maritime trade documented at historic contact emerged (Kennett, 2005; Kennett et al., 2008; Walker and DeNiro, 1986). Skeletal material from Late Holocene cemeteries indicates that demographic expansion paralleled decreases in stature and increases in health stress indicators (e.g., cribra orbitalia, periosteal lesions, Lambert, 1994, 1997). This trend reverses after about 600 years ago. These demographic changes also paralleled increases in diet breadth (Braje, 2007), a greater focus on fishing and the development of new maritime technologies (Arnold and Bernard, 2005; Kennett and Kennett, 2000; Rick, 2004b), the development of the plank canoe (Arnold, 2007; Gamble, 2002), heightened production of trade items, particularly shell beads (Arnold, 1992, 2001, 2004; Arnold and Graesch, 2001; Munns and Arnold, 2002), increases in interpersonal violence (Lambert, 1994) and the emergence of social hierarchies (Arnold, 1992, 2001, 2004; Kennett et al., 2009).

The ideal free distribution

The IFD assumes a dispersive organism making the decision to settle in one of two or more habitats differing in their provision of living sites, resources and exposure to hazards or, in the aggregate, in their suitabilities. The organism makes the best choice available. We further assume that the suitability of each habitat is density dependent. Suitability can decline with increasing density of con-specifics, exhibiting *negative density dependence*. It can increase over low ranges of density, exhibiting *positive density dependence*, a phenomenon known as the Allee effect. Organisms locate or relocate until there is no advantage to further movement. Whether spread over one or more habitats, all organisms then experience the same marginal suitability. This establishes a stable equilibrium – the IFD – in which none has any further incentive to migrate. The IFD represents a seemingly simple process that leads to unexpected and interesting temporal and spatial results that can be tested against the archaeological record (Kennett et al., 2006b). The origin and applications of this model are reviewed in Tregenza (1995), Sutherland (1996).

We define a *habitat* as a bounded area of sufficient size for at least temporary settlement, with a particular suitability. It differs in suitability from other such regions. Suitability is measured in terms of a typical organism's survival and reproduction (fitness), and depends on such environmental features as food, shelter and predators, as well as interactions with con-specifics. Basic suitability (Fretwell, 1972: 83) is measured by the fitness of the first occupant of a habitat. Subsequent occupants come from two sources: migrants arriving from another region or internal growth from among the habitats under consideration, *immigration* and *reallocation*, respectively.

The IFD relies on these simplifying assumptions: (a) habitats generate the resources and other conditions that establish their suitabilities at a constant rate; (b) suitability can be measured on a common scale by characteristics that are basic to the survival and reproduction of the organism and common to all habitats being considered; (c) this measure establishes a unique ordering of suitabilities across habitats; (d) the function representing the relationship between suitability and density for a particular habit is well behaved; at minimum, it is monotonically increasing or decreasing; (e) all individuals in the population have similar needs and abilities; (f) individuals make the best, constrained-optimization habitat choice (the "ideal" of the IFD), meaning that they have the information and cognitive capacity to appraise and compare relative suitabilities; and (g) there are no impediments to an individual acting on a decision to enter and use a habitat. Movement is unconstrained and organisms take up residence on an equal basis with existing residents (the "free" of the IFD).

As with human behavioral ecology models generally, it takes experience and judgment to determine how stringently to interpret violations of these assumptions. Violations may or may not vitiate use of the model. For instance, assumption (a) does not preclude use of the model in environments affected by seasonality or even stochastic aspects of resource yield if, for instance, long-term averages over normal variability are the appropriate basis for analysis. Likewise, in many cases, mathematical variants of the IFD have assessed the impact of changing specific assumptions, for instance by examining the effects of unequal competitive abilities (relevant to assumption e), perceptual constraints (assumption f), and travel costs between habitats (assumption g) (review in Tregenza, 1995). Tests of a model's predictions are in part tests of its assumptions (Winterhalder, 2002).

The IFD adopts an individual-based, decision-making view of population-level phenomena such as colonization, habitat filling and subsistence intensification. It brings together individual behavior and broad ecological and sociological processes. It allows for the presence and density of con-specifics – benefactors and/or competitors – by treating them as a part of what makes a habitat desirable or undesirable. It incorporates population effects through the manner in which suitability is enhanced or depressed by

changes in con-specific density. For these reasons it should be useful to anthropologists and archaeologists interested in habitat selection and population ecology in relation to temporal trends in settlement patterns, range expansion, dispersal and colonization, and subsistence intensification.

Two classes of competitive mechanisms underlie formal representations of the IFD model (Sutherland, 1983; Tregenza, 1995). In *exploitation competition* each organism is viewed as consuming and thus subtracting a portion of a continuous resource stream. Following Tregenza (1995), if we define an individual payoff w_i for a population of n_i competitors sharing habitat i, then at equilibrium the density specific payoff will be constant across habitats: $w_i(n_i) = c$. If q_i is the total input to habitat i, then: $w_i(n_i) = c = q_i/n_i$. The payoff is the resource stream divided among its users. Rearranging terms gives, $n_i = q_i/c$, known as the *habitat matching rule*. At equilibrium, habitat-specific densities (n_i) are proportional to the habitat specific inputs (q_i), across all occupied habitats.

Competitors can also reduce each other's fitness indirectly, apart from the direct exploitation of resources. *Interference competition* can result from territoriality, wasteful contests, declines in foraging efficiency due to search path overlap, general disturbance which increases prey wariness, or density effects that differentially attract parasites or predators. All of these can make successful use of a habitat more costly as a function of con-specific density, even though con-specifics may not reduce the resource stream itself. Tregenza (1995) building on Sutherland (1983) suggests interference or resource waste can be added to the exploitation model through an exponent modifying the variable n. In this model, $w_i(n_i) = q_i/n_i^f$, with f scaled from 1 to infinity. If $f = 1$ we get exploitation competition without interference. Higher values of f signal greater waste through the interference effects of con-specifics on each other's foraging effectiveness.

Exploitation competition presumes that resource availability is density dependent, but not the difficulty or costs associated with harvest; interference assumes the reverse, and allows for a broader range of interactions than those concerned with subsistence.

Greene and Stamps (2001) propose a simple means of implementing the IFD, using a quadratic equation for the suitability of habitat i:

$$S_i(n_i) = Q_i - B_i(n_i - M_i)^2 \qquad (1)$$

in which the variable $n_i \geqslant 0$ is the density of con-specifics in habitat i; $M_i \geqslant 0$ is a parameter determining the density of con-specifics at which the suitability in habitat i is maximized; and Q_i, and B_i are scaling parameters. Suitabilities S_i are scaled relative to each other across habitats in a context-specific way (Greene and Stamps suggest a 0–1 scaling). We denote the *basic suitability* of habitat i as $S_i^* = S_i(1)$. And, we assume there is a suitability threshold S_{min}, common to all habitats, indicating con-specific densities which are unsupportable. Thus if $S_i^* \leqslant S_{min}$, habitat i remains unpopulated, as it would not support the first individual to arrive. Finally, we expect suitabilities to exhibit negative density dependence at large values of n_i, thus we assume $B_i > 0$.

Key features of Eq. (1) are evident upon inspection. If $M_i = 0$, then suitability declines monotonically as a function of con-specific density. $M_i = 0$ gives us the basic, negative density dependence form of the IFD. If $M_i > 0$, then suitability has an intermediate peak at $n_i = M_i$. This generates positive density dependence at low densities ($<M_i$) and thus an Allee effect. Q_i controls the height of the curve at its maximum; M_i controls the position of the apex; and, B_i controls the rate at which the curve falls to the side(s) of that apex. Larger values for B_i accelerate or steepen the curve's rise and fall.

Negative density dependence

We have built the Greene and Stamps (2001) formula into a computer program that populates habitats according to the assumptions of the IFD (Fig. 2). Looking initially at the top panel, the first individual in the population elects to settle in the best habitat, *a*. Subsequent newcomers also elect to occupy habitat *a*, until the marginal suitability in habitat *a* drops to that of habitat *b* (arrow #1). From this point, further endogenous population growth or immigration is divided among *a* and *b* in a pattern that equalizes their marginal suitabilities. Equal marginal suitability is an equilibrium property because no individual has an incentive to relocate. A similar response occurs at arrow #2, with new individuals now distributed over three habitats.

Population distribution among habitats as a function of overall population size is depicted in the lower panel. Individuals first colonize and begin to fill habitat *a*. At arrow #1 further growth is divided between habitats *a* and *b*, each of which fills at a slower rate. Subsequently (arrow #2), some individuals begin to distribute to habitat *c* while others continue to fill habitats *a* and *b*. Although lowest in basic suitability, habitat *c* ends up with the largest population,
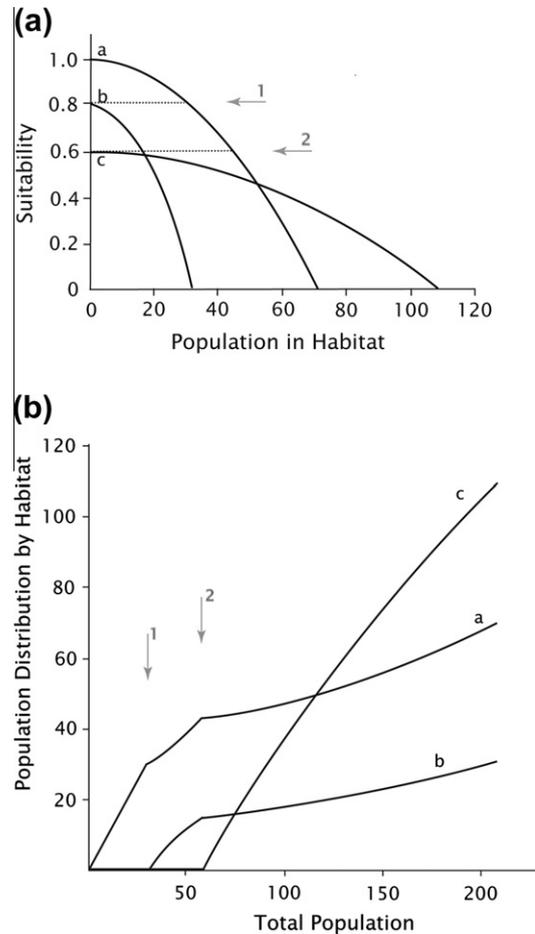
Fig. 2. Ideal free distribution, negative density dependence (without Allee effects). The upper panel shows suitability curves, on a normalized scale of 0–1, for three habitats – a, b, and c – as a function of the population density in that habitat. The habitats are ranked in alphabetical order by the suitability experienced by the initial occupant; in all cases suitability declines with population growth. The lowest ranked habitat, c, also experiences the lowest rate of declining suitability. The lower panel shows how population growth will be allocated among habitats given these suitabilities. See the text for further explanation. Note that the curves in the lower graph have been smoothed for ease of visualization; in actuality they would be jagged because individuals necessarily relocate in whole units. Suitabilities are given by Eq. (1) with: $Q_a = 1$, $B_a = 0.0002$, $M_a = 0$; $Q_b = 0.8$, $B_b = 0.0008$, $M_b = 0$; $Q_c = 0.6$, $B_c = 0.00005$, and $M_c = 0$.

experiencing faster growth over a longer period because its suitability in this example is significantly less sensitive to negative density effects. Total population size stops growing when all habitats reach their saturation densities (where in this example, $S_{min} = 0$).

From IFD graphics like this we can generate structural (or qualitative) predictions relating habitat suitability to population distribution and dynamics. If our data are sufficiently precise, we also can generate quantitative variants of these predictions:

(i) As total population grows, habitats will be settled in order of decreasing basic suitability S_i^*.

(ii) This process is cumulative in that high-ranking habitats will not be abandoned or see their numbers diminish as lesser ranking ones are occupied (provided there are no Allee effects; see below).

(iii) The habitat ranked second will not be settled until its basic suitability is matched by the (declining) suitability of the first-ranked habitat. This generalizes to habitats ranked $r + 1$ relative to r.

(iv) If more than one habitat is occupied, the relative numbers in each of them will be proportional to their relative suitabilities.

(v) Finally, a wide variety of more specific predictions are possible, depending on specific configurations of the suitability curves relative to one another. For instance, as we have noted, a habitat unspectacular in terms of basic suitability may fill more rapidly and expand to a larger size than its higher-ranked alternatives (Fig. 2).

Each of these predictions suggests a means of testing whether or not human settlement patterns conform to the IFD.

Positive density dependence

In his 1938 book, *The Social Life of Animals*, W.C. Allee argued that organisms at very low densities may suffer disproportionately from the problems of finding mates and resources. They may be less able to avoid or deter predators. Consequently, when population is sparse, increasing density might actually make a habitat *more* suitable to its residents. This vision of positive density dependence at low densities has since become known as the *Allee effect*; it has quite interesting implications for the IFD.

Graphically, the Allee effect is represented as a segment of positive slope on the low density portion of the curve representing suitability (Fig. 3). With humans it is easy to imagine circumstances that might generate this pattern. Especially low density may make it difficult to locate a mate of an appropriate sex, age and kinship category. It may induce other problems related to demographic stochasticity. It may impede benefits associated with mutualistic or cooperative activities. For instance, newcomers to a habitat may more quickly and reliably gain subsistence and survival skills if they come into contact with experienced residents. Actually, for socially obligate species like humans and most primates, Allee effects may operate over much of the normal density range (Courchamp et al., 1999). Opportunities for Allee effects expand significantly in humans because of our ability to implement socially organized and linguistically shared technologies that produce economies of scale in the capture, defense and use of resources. Range expansion, colonization episodes, and recovery from stochastic population declines all provide a context in which Allee effects may be important.

The general interpretation of Fig. 3 is similar to that described in the caption for Fig. 2. The difference is the Allee effect. Habitats still are ranked by their suitability for the first occupant, but peak suitability for habitats *b* and *c* occurs after a period of influx and local population growth. As a result (lower panel), Allee effects typically
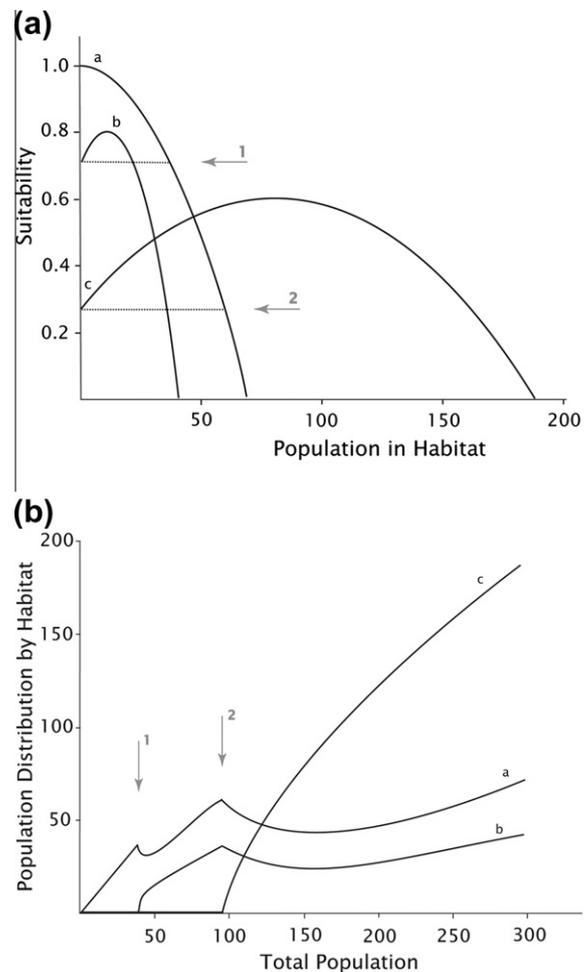
Fig. 3. Ideal free distribution, with Allee effects. The upper graph depicts habitat suitability in three ranked habitats as a function of habitat-specific density. Habitats b and c are characterized by an Allee effect: at low densities, habitat suitability increases with increasing density. After this initial phase, interference and depletion competition again come to dominate, causing suitability to decline. The lower graph shows the resulting population distribution over habitats, as a function of total population size. Suitabilities are given by Eq. (1) with: $Q_a = 1$, $B_a = 0.0002$, $M_a = 0$; $Q_b = 0.8$, $B_b = 0.0008$, $M_b = 10$; $Q_c = 0.6$, $B_c = 0.00005$, and $M_c = 80$.

cause abrupt population relocations. Individuals do not begin relocating to habitat *b* until the marginal suitability in habitat *a* matches the initial suitability in *b* (shaded arrow #1). But, by improving suitability in habitat *b*, the initial occupants quickly draw a small pool of follow-up migrants, from *a* or external sources. Although it is not shown here, if Allee effects caused habitat *b* suitability to increase significantly above that of any segment of the curve for habitat *a*, this relocation might temporarily and entirely empty out habitat *a*. Habitat *c* is characterized by a more prolonged Allee effect of greater magnitude, one causing population to decline in habitats *a* and *b* over a lengthy range of total population growth. Allee effects are dramatic illustrations of the observation that marginal quantitative changes in one parameter (here population size) may result in large qualitative changes in another (e.g., rapid emptying of one habitat and redistribution of its inhabitants into another). In Fretwell's terms, with an Allee effect, "a remarkable event may occur" (1972: 90–91).

The Allee effect gives us yet another IFD prediction:

(vi) If second or lower ranked habitats are characterized by an Allee effect, the first individual to settle there will attract a temporary exodus of occupants from higher-ranked habitats. Complete abandonment of the higher-ranked location is possible.

Creative use of the IFD turns on imagining how a factor of interest, the independent variable, will affect the number, shape or relative positioning of suitability curves. Climate change might elevate or depress suitability of all or some habitats. A technological development might change the shape of the curve as well as its relative position. Suitability curves of habitats highly sensitive to degradation under exploitation will slope steeply downward as a function of human density. Those of more resilient habitats will have a shallower form. Economies of scale and technological ability to implement efficient, group-dependent technologies (net hunting, weirs, terrace systems, irrigation networks) will produce ascending suitability curves over some range of densities. Once habitats are characterized by their unique suitability functions, it is fairly easy to derive predictions linking population growth, intensification and habitat enhancement or degradation to predictions about the population ecology of migration, settlement, and distribution.

In the analysis to follow, we will present empirical evidence for the first two of these IFD predictions, hypotheses (i) and (ii): The order and timing of settlement for 29 locations on the Northern Channel Islands are well-predicted by a model of basic suitabilites; and high-ranking habitats typically are occupied more-or-less continuously as new settlements are added in less suitable locations.

Environment and comparative archaeology

Interpretation of prehistory using the IFD requires that we assess the temporal sequence and other features of settlement and social development in light of the suitabilities of the localities being occupied. Although archaeological datasets can be rich in time depth, they rarely provide the fine-grained demographic information (e.g., a time-series of population densities in each habitat) needed to precisely fit a model such as the IFD (e.g., Eq. (1)). However, given archaeological and geomorphological data of sufficient detail, it is possible to fit a model which relates basic suitability to environmental variables, and timing of settlement to basic suitability, and therefore to test the IFD by this means.

Environmental analysis and data

General archaeological and ethnohistoric information on the subsistence practices of populations living on the Northern Channel Islands (Kennett, 2005) and adjacent mainland (Erlandson, 1994; Gamble, 2008) directs our attention to four environmental features: (i) watershed or drainage area, for variety and yield of terrestrial resources and security of a perennial fresh water supply; (ii) extent of shoreline with resource-rich, rocky intertidal zone, (iii) sandy beach, for canoe haul-out; and, (iv) off-shore kelp forest beds, with their concentration and productivity of marine resources (mammals, fish and shellfish). Shoreline may also take the form of rocky-sea cliffs with no access to beach or intertidal resources, therefore providing minimal economic benefits. Rocky-sea cliffs are economically important only in that their presence diminishes the extent of rocky intertidal and sandy beach. We do not include them in our analysis.

(i) Watershed or drainage area (km^2). Because stream flow data are unavailable, we use watershed area as a proxy measure for water availability at the mouth of each drainage analyzed. Most of the large historic Island Chumash villages were positioned on larger drainages. This is not surprising, because access to an adequate, year-around water source is essential on these relatively dry islands. In general the largest watersheds occur on the larger islands of Santa Rosa and Santa Cruz. Smaller watersheds are present on the west-ernmost island of San Miguel, but major drainages do not occur on the small rocky islets composing Anacapa. Most of these large drainages contain perennial streams, but other geological and hydrological factors also contribute to stream flow intensity. Watershed area also measures the diversity and abundance of terrestrial resources. Drainages provide shelter from the prevailing northwesterly wind and micro-habitats for economically valuable trees and other plant species, such as island oaks that favor sheltered valley locations or sage scrub that favors south and east-facing slopes of drainages (Philbrick, 1980).

Watersheds were demarcated using ArcMap and a digital elevation model for the Islands, then analyzed with ESRI's grid function for hydrological features. High (1.5 m) resolution color, digital aerial photographs were used to confirm drainage evaluations. Very small drainages and springs and specific localized plant communities (e.g., Torrey Pines, Eastern Santa Rosa, Biondi et al., 1997) were not included in the analysis except in a few instances, when very small drainages were lumped with closely adjacent large drainages (e.g., Garanon with Tecolote and Cow with Lobo canyons).

(ii) Rocky intertidal (km). The rocky intertidal zone and associated tide pools are important for their abundant and easily gathered marine organisms. California mussels (*Mytilus californianus*) are the most abundant and easily accessible of these species and are ubiquitous in prehistoric midden deposits extending back into the terminal Pleistocene and early Holocene (Erlandson et al., 1996; Kennett et al., 2008). Large mussels can easily be plucked out of the intertidal zone or small groups can be stripped out *en masse* to produce higher return rates (Jones and Richman, 1995). Two large species of abalone (*Haliotis*) are also found on rocky substrates in the lower intertidal to subtidal zones (Braje et al., 2007).

Coastal survey and color digital aerial photographic images were used to measure the linear extent of this habitat within a 2-km radius of each drainage outlet analyzed in this study.

(iii) Sandy beach (km). Inhabitants first explored and colonized the islands by boat from the mainland. They later engaged in a significant amount of inter-island and island-mainland trade using large plank canoes. Sandy beach was essential for safe canoe landing and haul-out, particularly for the use of the plank canoe after 1500 years ago (Arnold, 1995, 2007; Arnold and Bernard, 2005; Gamble, 2002). The small gastropod *Olivella biplicata* is also found along sandy beach habitats and this species was harvested increasingly *en masse* for its shell to produce beads after 1500 years ago (Arnold and Graesch, 2001; Arnold and Munns, 1994; Kennett, 2005; Munns and Arnold, 2002). The linear extent of this environmental feature was measured as for rocky intertidal.

(iv) Kelp forest (km^2). The relatively shallow water and rocky reef substrates that fringe the Islands support scattered patches of dense kelp forest (*Macrocystis pyrifera*, *Nereocystis spp.*). This marine habitat provides concentrated food and shelter for a rich community of invertebrates, fish and sea-mammals. Over 125 different fish species are found in this sheltered environment (Love, 1996) and several major mollusk species feed in this high nutrient zone, including the largest available abalone species (*Haliotis rufescens*) that grazes on the kelp itself. The species composition associated with these habitats varies and is heavily influenced by a major gradient in surface water temperatures and nutrients from east (warm, lower productivity) to west (cooler, high productivity). Kelp forests are generally denser and more extensive in the west. The extent of kelp forests in the

1980s was estimated through a combination of visual survey and color digital aerial photographs, which show the surface canopy of the kelp, and the 25 m isobath around each island, known to be the maximum water depth where kelp is viable (Kinlan et al., 2005).

Fig. 4 shows how these environmental features are assessed for a high and a low-ranking watershed.

Comparative archaeological data

The archaeological dataset is based on the collective archaeological and ethnohistoric work accomplished on these islands during the last century or so (Arnold, 2004; Erlandson, 1994; Glassow, 1980; Kennett, 2005; Rick, 2004b). These islands are particularly well-suited as a testing ground for the IFD model because they contain the longest, best-preserved archaeological sequence available for study along the west coast of North America. Archaeological deposits are relatively undisturbed compared with the adjacent mainland, because the pocket gopher (*Thomomys spp.*) never colonized these islands (Erlandson, 1984) and only modest development occurred historically. Archaeological survey and excavation on these islands extends back to the late 1800s. Many of the larger excavations of "village" sites and cemeteries occurred in the early 1900s and continued through the 1960s (Mills, 1956 [1901]; Orr, 1968; Rogers, 1929). Subsequent reanalysis of museum collections coupled with direct radiocarbon dating of artifacts from these assemblages are important sources of data (Erlandson, 1994; Kennett, 1998, 2005; King, 1990; Rick, 2001; Rick et al., 2002). Surveys, site assessments, smaller-scale sampling and radiocarbon dating provide additional data regarding the character and age of archaeological sites on these islands (Braje, 2007; Erlandson and Moss, 1999; Glassow, 1980; Kennett and Kennett, 2000). A major-

ity of these data are summarized in Kennett (2005) and Arnold (2001; see also Braje, 2007; Kennett et al., 2007, 2008; Perry, 2003; Rick, 2004a).

Table 1 provides a summary of the archaeological and chronological data associated with the known settlements at the mouth of each ranked drainage. Dates for earliest settlement components are based on radiocarbon ages or diagnostic artifacts associated with archaeological materials inferred to represent the onset of more permanent settlement at these locations. Direct radiocarbon dates on house floors or cemeteries were preferred, but often not available. Diverse faunal and artifact assemblages were also used in conjunction with estimates of site size and thickness/density of deposits. Justifications for these assessments are provided in Kennett (1998, 2005). Data quality and chronology are considered to be relatively high for sites dating to between 8000 and 3000 cal. years BP, and for those dating to between 1500 and 250 cal. years BP. Sites dating to the 3000–1500 cal. years BP range are based on moderately diverse faunal and artifact assemblages and the size and density of midden deposits. All assessments are considered to be provisional until large-scale excavations are carried out at these sites, perhaps as a test of the IFD model. Candidates for permanent village settlements dating prior to 8000 cal. years BP have not been identified and are likely under water. Our IFD model could be used to help constrain a search for underwater archaeological sites.

Assumptions engaged in using this data to model the IFD

Use of the mouth of each drainage as the central node of settlement is based on the assumptions that: (1) these would generally be the most desirable village locations compared with other locations along the coast or in the interior and (2) people living in these villages had access to and controlled interior areas defined roughly
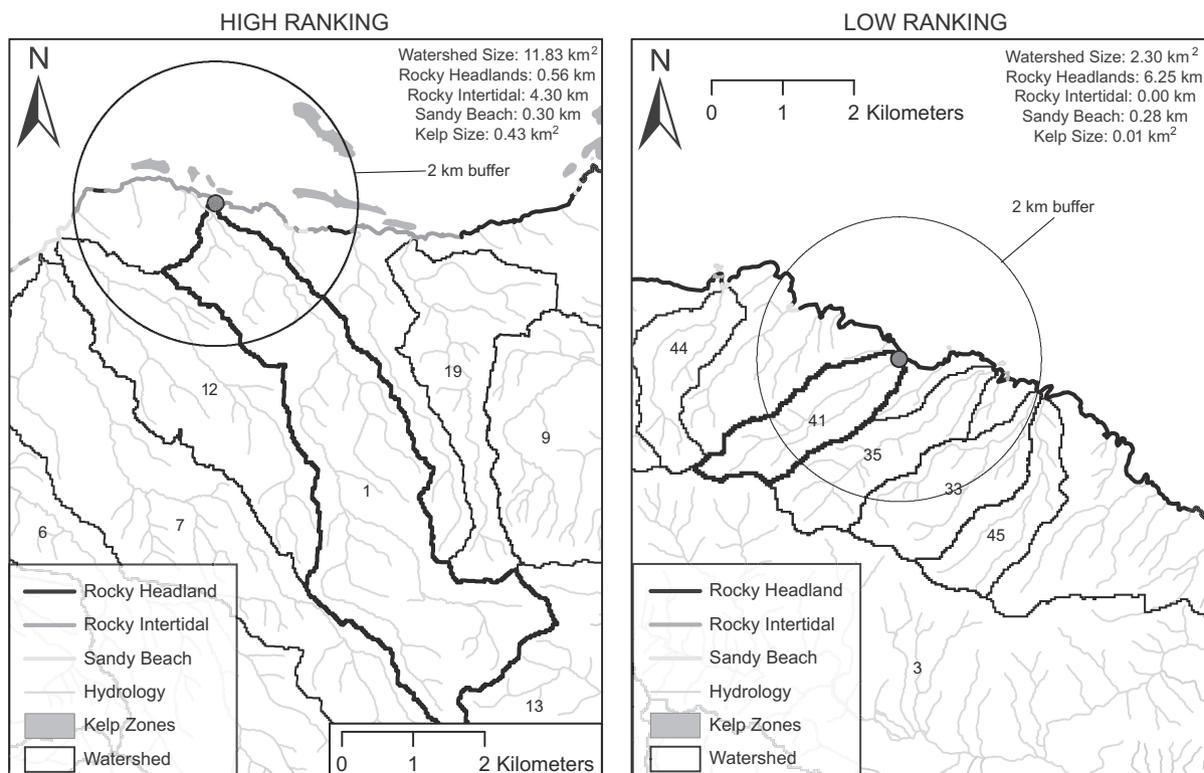
Fig. 4. Environmental features of a high – (Canada Verde, Santa Rosa Island) and low – (Unnamed San Miguel South 1, San Miguel Island) ranking watershed. Watershed numbering corresponds to the first column of Table 1.

Table 1
Environmental and archaeological dataset.

Rank	Island	Location	Drainage area	Rocky Intertidal Length	Sandy Beach Length	Kelp Forest Area	Critical Site	Material	Lab Number	14C Date ESC (Error)	Calibrated Date ESC (Lower -Upper Bound)	Predicted Suitability (Lower–Upper Bound)	Predicted ESC (Lower–Upper Bound)	Latest Settlement
1	SR	Canada Verde	11.83	4.30	0.30	0.43	SRI-41	C	UCLA-0140	4260 (90)	4803 (4548–5172)	8.5 (8.4–8.6)	4801 (4543–5173)	250
2	SR	Canada Tecolote	12.14	3.82	0.71	1.70	SRI-3	M	Beta-31788	7480 (90)	7688 (7488–7898)	8.9 (8.9–9.0)	7684 (7488–7898)	250
3	SC	Canada de la Calera 1	34.35	0.00	1.70	0.03	SCrI-240	C	UCR-0165	2825 (150)	2986 (2572–3338)	8.0 (7.9–8.1)	2985 (2568–3333)	200
4	SC	Canada Christi	18.10	1.57	2.46	0.11	SCrI-333	M	CAMS-9660	5610 (90)	5716 (5482–5932)	8.7 (8.6–8.7)	5710 (5478–5928)	250
5	SR	Old Ranch Canyon	18.59	1.46	2.98	0.12	SRI-187	M	OS-34475	3670 (40)	3261 (3062–3428)	8.1 (8.0–8.1)	3258 (3063–3428)	250
6	SR	Arlington Canyon	11.93	2.87	1.54	1.46	SRI-4	M	UCLA-0659C	6980 (120)	7215 (6918–7468)	8.9 (8.8–8.9)	7207 (6903–7463)	1260
7	SR	Canada Soledad	12.28	2.57	1.95	0.67	SRI-19	M	Beta-107049	3340 (60)	2865 (2702–3088)	8.0 (7.9–8.0)	2862 (2698–3083)	–
8	SC	Laguna Canyon	12.55	2.37	1.58	0.04	SCrI-109	C	Beta-119186	5520 (70)	6321 (6188–6448)	8.8 (8.7–8.8)	6319 (6183–6443)	1040
9	SR	Ranch Canyon	8.84	2.58	1.90	1.38	SRI-60	A	-	–	1300 (1104–1496)	7.2 (7.0–7.3)	1305 (1108–1498)	250
10	SC	Willows Canyon	7.97	2.83	1.77	0.06	–	–	–	–	–	7.8 (6.4–9.2)	3179 (596–10,121)	–
11	SR	Unnamed China Camp 1	7.36	2.73	2.10	1.13	–	–	–	–	–	7.6 (6.2–9.0)	2696 (511–8430)	–
12	SR	Dry Canyon	6.84	2.66	1.95	0.55	–	–	–	–	U	6.0 (5.3–6.4)	T	U
13	SR	Water Canyon	12.28	0.57	2.55	0.95	SRI-77	M	OS-32376	1800(30)	1084 (938–1232)	7.0 (6.8–7.1)	1084 (938–1233)	–
14	SC	Canada de los Sauces	6.20	2.74	2.44	0.25	SCrI-145	M	UCR-0200	2140(150)	1441 (1098–1798)	7.3 (7.0–7.5)	1431 (1093–1783)	–
15	SC	Coches Prietos Canyon	5.39	3.11	0.92	0.00	SCrI-1	M	UCR-394	2900(130)	2330 (1968–2682)	7.7 (7.6–7.9)	2313 (1958–2673)	200
16	SC	Alamos Canyon	5.08	3.21	0.90	0.00	–	–	–	–	–	7.7 (6.2–9.1)	2849 (499–9375)	–
17	SR	Jolla Vieja Canyon	9.31	1.18	1.43	0.58	SRI-62	M	Beta-107046	3000(60)	2466(2232–2682)	7.8 (7.7–7.9)	2458 (2223–2678)	250
18	SM	Willow Canyon	4.63	2.82	1.68	0.00	–	–	–	–	U	6.0 (5.2–6.4)	T	U
19	SR	Canada Lobos	4.74	2.66	0.30	0.31	SRI-116	M	Beta-92291	6060(70)	6192(5978–6388)	8.7 (8.7–8.8)	6187 (5973–6383)	1300
20	SR	Unnamed China Camp 2	4.83	2.56	2.47	1.44	SRI-28	M	Beta-107988	2090(60)	1378(1212–1558)	7.2 (7.1–7.3)	1371 (1203–1548)	250
21	SR	Wreck Canyon	7.44	1.14	1.36	0.61	–	–	–	–	–	7.4 (6.0–8.8)	2170 (399–6847)	–
22	SC	Smugglers' Canyon	5.13	1.89	1.76	0.03	–	A	–	–	1300 (1104–1496)	7.2 (7.0–7.3)	1293 (1098–1493)	200
23	SC	Pozo Canyon	6.45	1.10	3.27	0.42	SCrI-474	C	Beta-032108	1530(100)	1443 (1288–1672)	7.3 (7.2–7.4)	1432 (1278–1648)	200
24	SM	Otter Creek	2.61	3.88	1.70	1.47	SMI-468	M	OS-33421	1900(30)	1179 (1028–1302)	7.1 (6.9–7.2)	1176 (1023–1298)	200
25	SR	Unnamed Bee Rock	3.79	1.95	2.49	1.86	SRI-31	M	Beta-95455	2050(60)	1337 (1168–1512)	7.2 (7.0–7.3)	1327 (1153–1503)	1260
26	SC	Scorpion Canyon	6.17	0.00	0.16	0.01	SCrI-615	M	Beta-105491	2420 (60)	1735 (1538–1938)	7.5 (7.3–7.6)	1725 (1528–1923)	200
27	SR	San Augustine Canyon	3.62	1.68	1.72	0.43	SRI-432	M	Beta-107050	2280 (80)	1577 (1352–1812)	7.3 (7.2–7.5)	1559 (1343–1793)	200
28	SR	Unnamed Cluster Point	2.81	1.34	3.17	1.77	–	–	–	–	U	5.8 (4.6–6.4)	T	U
29	SC	Montanon Canyon	2.78	1.17	2.35	0.98	–	–	–	–	U	5.8 (4.7–6.4)	T	U
30	SC	Johnson's Canyon	3.32	0.59	3.74	0.14	SCrI-192	C	UCR-0396	740 (150)	711 (502–958)	6.6 (6.3–6.8)	708 (543–923)	200

Rank	Island	Site					Critical Site	Material			Calibrated Date	Predicted Suitability	Predicted ESC	
31	SM	Nidever Canyon	1.97	1.54	2.41	0.06	SMI-163	M	OS-33420	1930 (30)	1208 (1062–1338)	7.1 (7.0–7.2)	1196 (1053–1323)	200
32	SC	Valdez Canyon	2.65	0.22	0.39	0.03	-	A	-	-	650 (454–846)	6.5 (6.3–6.7)	675 (533–843)	200
33	SC	Unnamed Twin Harbors 1	2.81	0.00	0.00	0.01	SCrI-369	M	UCR-0392	3080 (140)	2535 (2162–2892)	7.8 (7.6–8.0)	2483 (2098–2838)	2360
34	SC	Hazard's Canyon	2.58	0.22	0.20	0.00	SCrI-436	A	–	–	650 (454–846)	6.5 (6.3–6.7)	675 (528–848)	200
35	SC	Orizaba Canyon	2.73	0.00	0.00	0.01	SCrI-434	A	–	–	650 (454–846)	6.5 (6.3–6.7)	676 (533–848)	200
36	SC	Unnamed China Harbor	2.63	0.00	1.76	0.17	SCrI-306	C	UCR-1647	630 (100)	610 (498–752)	6.4 (6.3–6.6)	633 (533–763)	200
37	SC	Unnamed Profile Point	2.55	0.00	0.00	0.00	–	–	–	–	–	6.5 (5.0–8.0)	903 (150–2986)	–
38	SM	Unnamed San Miguel South 2	1.53	1.63	3.03	1.57	SMI-232	M	Beta-180770	1810 (60)	1093 (922–1258)	7.0 (6.8–7.1)	1067 (903–1243)	1000
39	SC	Unnamed Trident Cove	2.21	0.22	0.70	0.03	–	–	–	–	–	6.3 (4.9–7.8)	728 (129–2327)	–
40	SC	Unnamed Lady's Harbor	2.36	0.00	0.87	0.03	–	–	–	–	U	5.7 (4.6–6.4)	T	U
41	SC	Unnamed Dick's Cove	2.30	0.00	0.28	0.01	–	–	–	–	U	5.8 (4.7–6.4)	T	U
42	SM	Unnamed San Miguel South 1	1.28	1.65	2.50	0.65	–	–	–	–	U	5.5 (4.2–6.3)	T	U
43	SC	Diablo Canyon	2.09	0.00	0.94	0.01	–	–	–	–	–	6.2 (4.7–7.6)	T	–
44	SC	Unnamed Ruby Rock	2.09	0.00	0.00	0.00	–	–	–	–	–	6.4 (4.8–7.8)	766 (126–2540)	–
45	SC	Unnamed Twin Harbors 2	2.04	0.00	0.00	0.01	–	–	–	–	U	5.8 (4.6–6.4)	T	U
46	SC	Canada de la Calera 2	1.99	0.00	1.57	0.02	–	–	–	–	U	5.6 (4.4–6.3)	T	U

Notes: **Rank**: Order determined by preliminary analysis; ranks correspond to labeling of drainages in Fig. 1. **Island**: SR = Santa Rosa; SC = Santa Cruz; SM = San Miguel; **Critical Site** is the site that provided the key ^{14}C date; **Material** indicates what was ^{14}C dated; A = Artifact, C = Charcoal and M = Marine. If an A occurs in this column the age is estimated based on a diagnostic artifact date and associated calibrated age ranges (see Kennett, 1998); **Calibrated Date,** along with 95% lower and upper bounds, were obtained by the method of Buck et al. (1996, Section 9). For charcoal samples, we used the IntCal04 calibration curve (Reimer et al., 2004); for marine samples we used the Marine04 calibration curve (Hughen et al., 2004), assuming a reservoir age of 270 ± 60 based on adjustments to the calibration curve and data published by Ingram and Southon (1996). For sites dated by an "Artifact" (see Material column), the date and standard deviation were obtained directly from excavated materials; for these sites, Calibrated Date is the directly-obtained date. The letter "U" indicates unsettled locations, and "–" indicates locations having unknown settlement status because archaeological work has not been done in that region; **Predicted Suitability** is the average suitability over 20,000 posterior samples. The lower and upper bounds are the 2.5 and 97.5 percentiles of the posterior distribution (the 95% credibility interval); **Predicted ESC** is the average of the variable earliest settlement component over 20,000 posterior samples. The lower and upper bounds are the 2.5 and 97.5 percentiles of the posterior distribution. The letter "T" indicates locations having a predicted suitability below the estimated suitability threshold (6.3; see Table 2). Thus the model predicts that these locations would not be settled.

by each watershed. Archaeological surveys indicate that sites of different types (shell middens, lithic scatters, etc.) occur in a wide range of contexts, but that residential sites tend to be positioned at the mouths of the largest drainages (Kennett, 2005). These archaeological sites consist of laterally extensive and/or deep deposits. The remnants of houses (e.g., house depressions) occur at some of these sites and past excavations have revealed cemeteries suggesting generational continuity in settlement. Greater faunal and tool diversity indicate a wider range of activities compared to other locations. Given the maritime focus of island residents (substantiated by shell midden deposits), it makes sense from a central-place foraging perspective that people would be more tethered to coastal locations. Settlement locations near the mouths of drainages would provide immediate access and control over water, intertidal areas in close proximity to the village, and kelp beds immediately off-shore. Beaches in the vicinity could also be used as launch sites and storage locations for boats to access kelp beds, off-shore fisheries, and more distant sea-mammal or bird rookeries and to maintain contact with friends, family, and trade partners in other villages on other islands and the adjacent mainland.

The assumption that the communities at the mouths of drainages controlled access to resources in the entire watershed is more tenuous and conjectural. Although major village settlements were generally positioned on the coast, there are some exceptions (e.g., CA-SRI-147, Braje, 2007), and the intensity and character of interior resource use changed during the last 8000 years. A large number of substantial Middle Holocene (7500–3000 cal. years) midden deposits have been identified in the interiors of the larger islands of Santa Rosa and Santa Cruz (Kennett, 2005; Kennett and Clifford, 2004; Perry, 2003). These sites tend to be positioned on ridges or hilltops surrounding major drainages. Midden soil formation, artifact assemblages and faunal assemblages indicate the transport of marine foods to these interior locations (e.g., shellfish). Isotope seasonality data suggest that they were occupied periodically by smaller groups of people, perhaps task groups or individual families from larger coastal villages harvesting plant foods episodically. Kennett and Clifford (2004) have suggested that the strategic position of these interior sites may signal a flexible system of land tenure associated with periodic economic defensibility of interior plant foods. More rigid territories on the islands after 3000 years ago are suggested by the lack of inter-visibility between coastal settlements and the strategic placement of burials in older interior settlements and in caves. This parallels an increasing focus on maritime resources (particularly fish) and increased trade connections with the mainland coast, possibly to acquire carbohydrate-rich foods (e.g., acorns, Arnold, 1992).

All regional datasets are imperfect, and it is possible that further shortcomings are introduced by our assessment of the published record (Kennett, 2005). We address this in two ways: (a) by being as specific as possible about our sources, assumptions, choices of interpretation, and known qualifications; and (b) by adopting statistical methodologies that explicitly recognize the uncertainties in key types of data. Landscape transformations obscure the record. Earlier sites tend to be buried by natural or anthropogenic processes or, in the case of the Channel Islands, they may be under water. Arrival dates of the first permanent settlers at these locations are almost certainly earlier than the dates of the earliest settlement components – the archaeological observations used here for model fitting. Consistent standards of evidence for characterizing permanent settlement (e.g., house floors, diverse faunal and artifact assemblages, seasonality data, cemeteries) are also difficult to come by without large-scale and better dated excavations at all sites. The settlement data from 3000 to 1500 cal. years BP are particularly tenuous because this is a poorly studied period and artifacts tend to be rare in midden deposits. Finally, the history of

archaeological research on these islands also introduces biases into the record. For instance, we note that if archaeological deposits are viewed as "resources", then archaeological activities themselves conform to the expectations of the IFD, with early researchers choosing to focus on richer locations (e.g., Orr, 1968), persistent work in those rich areas (e.g., Erlandson, 1994; Kennett, 2005), and more recent work focused on areas with fewer and smaller assemblages (e.g., Braje, 2007).

In the "Discussion" section (below) we describe additional data shortcomings likely to confound the type of analysis we seek.

Data analysis and results

A preliminary analysis

In a preliminary semi-quantitative analysis of the Northern Channel Island dataset in the context of the IFD and the emergence of institutionalized social hierarchies, we focused on the late Holocene (3000 – 200 cal. years BP) archaeological and ethnohistoric record (Kennett et al., 2009). That paper examined an acceleration of social and technological change on the Islands that began between 4000 and 3000 years ago, arguing that it occurred concurrent with habitat in-fill, settlement of more and more marginal drainages, and territorial circumscription. The analysis took an intuitive approach. Each of the 46 drainages surveyed was ranked for each of the four environmental features. These rankings were then combined into a weighted score [50% watershed area; 30% rocky intertidal; 15% kelp forest and 5% for Sandy Beach] to generate a single, linear ranking of presumed basic suitability for each watershed (Kennett et al., 2009 see Table 20.1, "Rank"). The weightings are estimates based on qualitative impressions of the Chumash literature and knowledge about key environmental characteristics likely shaping adaptive decision-making (e.g., water availability). Weighted scores were then grouped into quartiles. Similarly, late Holocene settlement was examined over two periods: sites first settled 3000–1500 cal. years BP, and those settled 1500 – 200 cal. years BP. The analysis consisted of showing that village settlements were confined predominantly to the first- and second-ranked locations in the earlier period; they expanded into drainages in the third, much less suitable quartile after 1500 cal. years BP. Few fourth-ranked locations were settled. The observed pattern supported the prediction that drainages were occupied in descending order of basic suitability and, with other information on social hierarchy, it confirmed that institutionalized social stratification emerged late in the sequence as viable settlement locations became saturated, social circumscription increased (Carneiro, 1970) and environmental suitability declined throughout the Islands.

In Fig. 5 we replicate this analysis, extending it to the history of known village settlement back to ~8000 cal. years BP, at the time when sea level was stabilizing and we see the first settled villages appearing on these islands. The results are the same, a semi-quantitative pattern largely confirming hypotheses (i) and (ii). Settlement begins in watersheds ranked in the highest quartile of habitat suitabilities. With several exceptions, settled locations expand as predicted by the IFD throughout the Holocene to drainages of lesser and lesser suitability. There is considerable continuity over time in the occupation of the higher ranked watersheds. Once settled, locations tend to remain settled. The pattern observed is consistent with IFD predictions. The seven sites listed as an "Unranked Locale," are not associated with one of the 46 watersheds for which environmental parameters were assessed. They likewise tend to be late in settlement history, suggesting that they may be associated with increasing economic exchange and conflict.

Fig. 5. Northern Channel Island, Village Settlement History. Presence or absence of evidence for a village settlement at the mouth of watersheds by archaeological period, arrayed by decreasing quartiles of environmental suitability, as estimated in our preliminary analysis. The general pattern in these data substantiates hypotheses (i) and (ii) of the Ideal free distribution: high-ranking watersheds are settled earlier and low-ranking later, the order of settlement following habitat suitability; and, once settled, a habitat tends to remain settled. Unsettled locations, and those for which settlement is unknown are indicated along with the watershed names at the base of the illustration. Note that sites not at the mouth of major watersheds ("Unranked Locale") tend to be quite recent (e.g., since 1400 cal. years BP). They are: SCrI-495, SRI-15, 427, SMI-503/504, 525, 528, 602.

A Bayesian model for the settlement sequence

Encouraged by the general IFD pattern in the data, we undertake a more detailed analysis. We focus on the response variable, the earliest settlement component (ESC) cal. years BP for each location, in order to examine hypothesis (i). Characteristics of this variable guided our analysis strategy. ESC is determined by radiocarbon dates either directly or indirectly with artifact styles (Late Middle Period and Late Period sites) and therefore subject to the uncertainties of laboratory analysis and calibration to calendar years. And, ESC in the Northern Channel Islands dataset includes missing or censored dates for some records or potential settlement locations. Ideally we seek a method for model-fitting and inference that can handle each of these characteristics, without discarding useful information or analytical potential. That is, we wish to acknowledge uncertainty in ESC (the dependent variable), and also allow for the opportunities or partial information represented in missing and censored records, respectively. One usual strategy for dealing with censored observations – simply removing them from the dataset – is one we wish to avoid, because it discards potentially useful information and can lead to biased inferences and other problems of interpretation (Little and Rubin, 2002).

To proceed, we undertake a computationally intensive Bayesian approach, imbedding measurement error and data augmentation methods in a Gibbs sampler. Broadly speaking, the Gibbs sampler generates random datasets that "could have been" observed, given the partial information in the NCI sample. For each dataset, the Gibbs sampler updates a model of locational suitabilities; the updated model is then used to generate the next dataset. Aggregating information over thousands of iterations of this basic cycle leads to robust inferences about suitability. The Gibbs sampler is useful when a joint distribution (e.g., the probability of an ensemble, consisting of sample data, unknown parameters and unobserved variables) cannot be computed directly, but can be decomposed into

tractable conditional distributions (Gelfand and Smith, 1990; Geman and Geman, 1984). We obtain these distributions (shown explicitly in the Appendix) by Bayesian reasoning, combining *naïve prior* information with the observations. Computational approaches more general than the Gibbs sampler are available when conditional distributions are difficult to specify (see Gilks et al., 1996). Computational Bayesian methods for measurement error are described and demonstrated in Mallick and Gelfand (1996) and Gelfand et al. (1997); and Bayesian approaches specific to radiocarbon dating can be found in Buck et al. (1992) and Buck et al. (1996). General descriptions of Gibbs sampling can be found in Geman and Geman (1984), Gelfand and Smith (1990), Gelfand (2000) and Casella and George (1992); Gibbs sampling combined with data-augmentation for censored observations is described in Chib (1992), Holloway et al. (2004), Gelman and Hill (2007, section 18.5).

Drawing on the flexibility of the Gibbs sampler, we incorporate into the analysis two classes of observations. The first class consists of locations (drainage mouths) with a village site having an oldest radiocarbon date, which we treat as an imprecise proxy for ESC. Ignoring measurement error, these 29 cases taken alone would be amenable to conventional statistical analysis. However, we wish also to include a second class of observations: locations at which there has been sufficient archaeological investigation to eliminate with some confidence the possibility that they were ever settled ($n = 9$). We call these "unsettled" (U) locations. These locations are censored for ESC. However, they are clearly informative about the relationship between environmental suitability and the process of settlement. It does not make sense to assign unsettled locations a numerical value (such as zero) for ESC; we adopt instead a strategy described below. A third class of observations consists of locations surveyed for environmental variables, but not for archaeological sites ($n = 8$). We say these locations have an "unknown" ESC. Because no information about settlement is available at the third class of locations, they are not informative about the

relationship between suitability and timing of settlement, and are not used to fit models. However we can use fitted models to make *predictions* about settlement at these locations.

Our sample of 46 drainages has 29 locations that are uncensored but imprecisely observed for ESC; nine locations that are unsettled; and, eight additional locations we have classified as unknown. The models presented below were fitted using the 29 uncensored and nine unsettled locations, for a total of $N = 38$ observations.

In order to accommodate different scales of the environmental variables, we applied the natural log transform to Drainage Area and Kelp Forest Area. Prior to log-transformation, we added 0.01 to all observations of Kelp Forest Area, as 6 locations have the value zero for this variable (these locations are not censored for Kelp Forest Area – the value zero is observed). Scatter plots suggest that Drainage Area and Rocky Intertidal Length are likely to be informative about the settlement sequence (Fig. 6). A linear regression model for the basic suitability of the ith location, making use of all four variables, is

$$S_i^* = \beta_0 + \beta_1 \log(\text{Drainage Area}_i)$$
$$+ \beta_2 \text{ Rocky Intertidal Length}_i$$
$$+ \beta_3 \text{ Sandy Beach Length}_i$$
$$+ \beta_4 \log(\text{Kelp Forest Area}_i + 0.01) + \varepsilon_i, \quad (2)$$

where $\varepsilon_1, \ldots \varepsilon_N$ are independent Gaussian variables with mean zero and variance σ^2. The earliest settlement component of location i is connected to its basic suitability by the following threshold relationship:

$$\text{If } S_i^* > S_{min}, \ \text{ESC}_i = \exp(S_i^*);$$
$$\text{If } S_i^* \leqslant S_{min}, \ \text{location } i \text{ remains unsettled} \quad (3)$$

The parameters to be estimated are then $\boldsymbol{\beta} = (\beta_0, \beta_1, \beta_2, \beta_3, \beta_4)'$, σ^2 and S_{min}. Our initial uncertainty about the parameters suggests the use of naïve prior distributions (see e.g., Gelman and Hill, 2007 Section 18.3; Gill, 2008 Section 4.1): thus the prior for S_{min} is uniform over the real numbers, and the prior for $(\boldsymbol{\beta}, \sigma^2)$ is uniform over all non-negative values of σ^2. Expressions given in the Appendix show that these priors yield well-defined conditional distributions. We understand the naive priors to be justified by a relative paucity of information about the relationships between environmental variables and human settlement patterns. Additional studies exploring the forms of these relationships, and/or identifying particularly useful variables, may facilitate the use of more informative priors.

In Eqs. (2) and (3), the basic suitability S_i^* mediates the relationship between environmental variables and ESC_i, and these relationships across the sample determine the scale of $S_1^*, \ldots S_N^*$ and S_{min}. Conventional IFD models view suitability as a function of con-specific density, and are not explicit about the relationship between
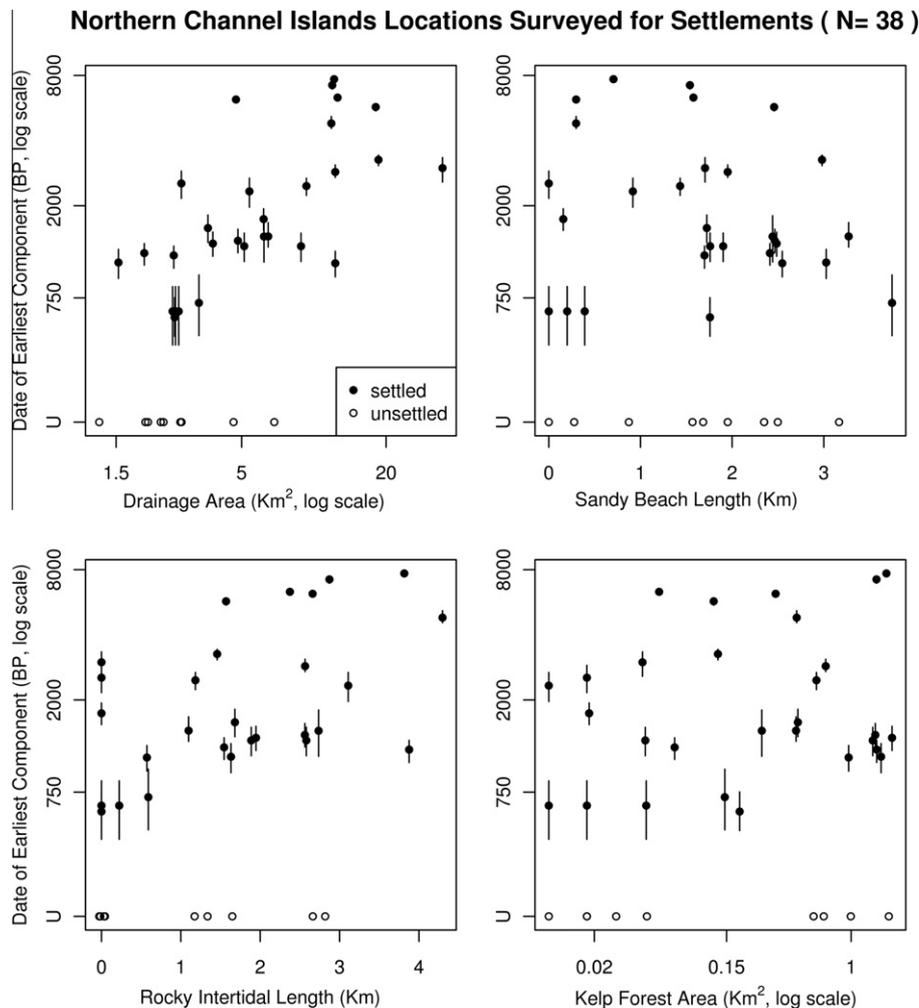
Fig. 6. Scatter plots of earliest settlement component (cal. years BP) versus four environmental variables. For settled locations ($n = 29$), the conditional mean deposition date (cal. years BP), given the radiocarbon date of the earliest component, is calculated by the method of Buck et al. (1996, section 9.2) and shown with a filled circle. Error bars show 95% credibility intervals for deposition date. Open circles show environmental variables for the unsettled locations ($n = 9$). The letter "U" positions the unsettled locations within the plot, but does not refer to a numerical value for earliest settlement component.

basic suitability and timing of settlement. The exponential relationship between S_i^* and ESC_i specified in Eq. (3) is reasonable in our view, as it ensures that model predictions of ESC_i are consistent with the ordering of basic suitabilities (the transformation is monotonic). Although S_i^* could hypothetically take any real value, ESC_i measured in cal. years BP must be non-negative; the exponential transformation ensures this as well. Future work may productively involve other non-negative, monotonic transformations. The two-equation form of the model aids in conceptualizing the role of unsettled cases. Although these nine cases do not have numerical values for ESC, under Eq. (2) they do have basic suitabilities. We treat the basic suitabilities of the unsettled cases as unobserved variables, imputing their values probabilistically at each iteration of the Gibbs sampler with the help of Eq. (2). The conditional distributions given in the Appendix provide the basic tools for these imputations.

Table 2 gives parameter estimates for the suitability model of Eqs. (2) and (3), in the form of summary statistics of the Gibbs sampler output, and also includes estimates for a 3-variable model, described below. The regression coefficients in Table 2 refer to *marginal* effects of variables (see e.g., O'Hagan, 1994 Section 9). For example, β_2 estimates the change in basic suitability associated with a 1-km increase in Rocky Intertidal Length, averaged over the effects of other variables. In the 4-variable model, the coefficient of log Drainage Area (km^2) is positive ($\beta_1 = 0.84$), with a 95% credibility interval (0.5–1.2) distant from zero. The modeling relationships in Eqs. (2) and (3) suggest that ESC is, on average, proportional to (Drainage Area)$^{0.84}$, for settled locations on the Northern Channel Islands. However, direct proportionality cannot be ruled out, as the value 1.0 is contained in the credibility interval. Credibility intervals for Rocky Intertidal Length, Sandy Beach Length and log(Kelp Forest Area) in the 4-variable model all contain zero, the value indicating no marginal effect. The estimated threshold $S_{min} = 6.31$ suggests that NCI locations without evidence for settlement by about $e^{6.31} \approx 550$ cal. years BP were essentially unsuitable for permanent human habitation.

Preliminary work (not shown here) using model selection methods described in Gelfand and Ghosh (1998) suggested that a 3-variable model containing log(Drainage Area), Rocky Intertidal Length and Sandy Beach Length would have slightly better predictive accuracy than the 4-variable model. Parameter estimates for the 3-variable model are included in Table 2: the basic conclusions are essentially unchanged. In both the 4-variable and 3-variable models, the coefficients for Rocky Intertidal Length and Sandy Beach Length are of the same order of magnitude but have opposite signs, suggesting a trade-off favoring the availability of Rocky Intertidal zones over Sandy Beach. Compared to log(Drainage Area), there is less certainty about the utility of these variables as predictors of basic suitability, as their 95% credibility intervals contain zero in both the 4-variable and 3-variable models.

Figs. 7 and 8 illustrate the fit of the 3-variable model to the sample (analogous graphs for the 4-variable model, not shown here, lead to the same conclusions). Fig. 7 shows that ESC predicted by the model agrees closely with ESC based on radiocarbon dating alone, for the $n = 29$ settled locations. The level of agreement seems exceptional, compared to conventional regression modeling; how-

ever, our approach prioritizes this agreement, perhaps at the expense of sensitivity to the predictors. The "full conditional" which predicts suitability (and hence ESC) for settled locations under the model is the product of two probability densities (see Appendix item 5): the first of two factors connects ESC to the regression model; the second connects ESC to the observed radiocarbon date, prohibiting prediction of ESC outside the range of radiocarbon date support. The agreement shown in Fig. 7 is therefore not unexpected. More revealing is that relationships between ESC and the predictors can be discerned under these stringent goodness-of-fit conditions.

Fig. 8 shows that the unsettled locations are well distinguished by the model parameter S_{min}, all having posterior mean suitabilities below the estimated threshold. The five settled locations depicted in Fig. 8 are thought to be among the last to be occupied (with approximate settlement dates of 650–670 cal. years BP, based on artifact assemblages; see Table 1). The model suggests that these settled locations have relatively low suitabilities.

Fig. 9 shows the full sample of $N = 38$ locations used to fit the model, along with 8 additional locations having unknown settlement times. We display the environmental covariates, along with suitabilities for the 3-variable model (with locations arrayed left to right in descending order of mean suitability). A decreasing trend in Drainage Area is apparent from left to right, though it is interrupted by a few large unsettled locations. The threshold S_{min} enforces a separation between the predicted suitabilities of settled and unsettled locations, even though the two kinds of locations may have similar environmental covariates in some cases. Thus we do not expect ranges of Drainage Area (for example) to discriminate perfectly between settled and unsettled locations. Locations having the value zero for Rocky Intertidal Length are noticeably common on the right, where predicted suitabilities are lower. The relationship between suitability and Sandy Beach Length is less clear: locations with the highest predicted suitabilities tend to have little Sandy Beach, while those with lower suitabilities tend to have more Sandy Beach. Negative estimates for β_3 (Table 2) support this trend, as does archaeological knowledge: beaches likely became more important later in the settlement sequence, with increased use of the plank canoe (for landing) and demand for *Olivella* shells. There are notable anomalies disrupting the trend in Sandy Beach Length: among these are Canada Christi, Old Ranch Canyon and Canada de la Calera 1, all settled early and appearing highly suitable, but having much Sandy Beach compared to Rocky Intertidal.

Fig. 9 also places the locations having unknown settlement in context, with the bottom panel highlighting the predictive capabilities of the model for these cases. The 95% credibility intervals for the unknown locations are notably wider than those for settled locations, and modestly wider than those for unsettled locations; this reflects added uncertainty in prediction. Nonetheless we can say with some confidence that the unknown locations Willows Canyon, Alamos Canyon, Unnamed China Camp 1 and Wreck Canyon have relatively high suitabilities under the model, and may well have undiscovered settlement. By contrast, the four "unknown" locations having low predicted suitabilities (Unnamed Profile Point, Unnamed Ruby Rock, Unnamed Trident Cove and

Table 2
Parameter estimates (posterior means and 95% credibility intervals) for regression models of earliest settlement component (cal. years BP), fitted with a Gibbs sampler to $N = 38$ surveyed locations. The parameter estimates are summary statistics based on 20,000 posterior samples. We ran the Gibbs sampler for a total of 300,000 iterations, discarding the initial 100,000 iterations for a burn-in, and thinning at an interval of 10 iterations, in order to obtain the posterior samples.

	Intercept β_0	log(Drainage Area km^2) β_1	Rocky Intertidal Length (km) β_2	Sandy Beach Length (km) β_3	log(Kelp Forest Area km^2) β_4	SD(ε) σ	Suitability threshold S_{min}
Four variable model	5.95 (4.9, 6.9)	0.84 (0.5, 1.2)	0.20 (0.0, 0.4)	−0.24 (−0.5, 0.0)	0.06 (−0.1, 0.2)	0.7 (0.5, 1.0)	6.31 (6.0, 6.5)
Three variable model	5.74 (5.0, 6.4)	0.83 (0.5, 1.2)	0.24 (0.0, 0.4)	−0.19 (−0.4, 0.0)	–	0.7 (0.5, 1.0)	6.31 (6.0, 6.5)
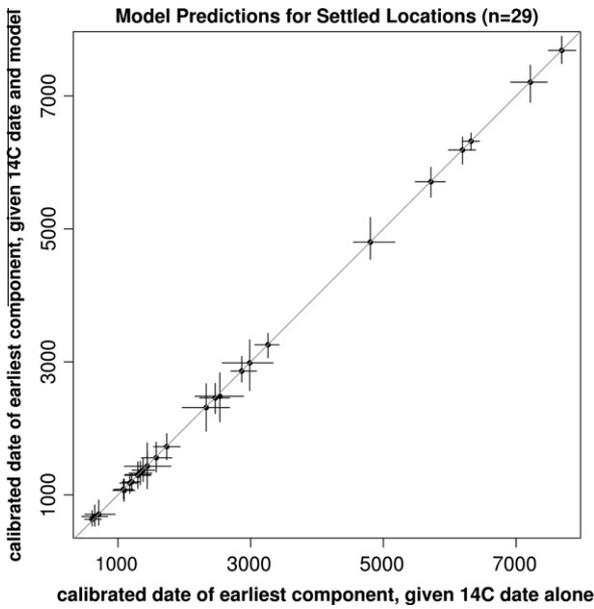
Fig. 7. Scatter plot of posterior mean earliest settlement component (ESC, cal. years BP) predicted by the 3-variable model, versus posterior mean ESC predicted by radiocarbon date alone, for the $n = 29$ settled locations. Model means and 95% credibility intervals are summary statistics based on 20,000 posterior samples. Means and 95% credibility intervals based on radiocarbon dates alone were calculated using the method of Buck et al. (1996, section 9.2).

Diablo Canyon), are unlikely to have supported permanent human settlement.

The predicted suitabilities displayed in the bottom panel of Fig. 9 are posterior means, obtained for each location by averaging the random suitabilities produced over iterations of the Gibbs sampler. These numerical predictions are distinct from those that would be obtained by simple use of the regression formula (Eq. (2)), substituting estimates from Table 2 in place of parameters. The two different approaches to prediction highlight a key difference between conventional and Bayesian statistical modeling. Posterior means give the preferred predictions here, as they incorporate aspects of the model – such as measurement error in dates – not captured by the regression formula alone. Posterior means and regression formula predictions will be relatively similar for unknown locations, where no additional information about dating or settlement constrains the suitabilities produced by the Gibbs sampler. Yet even for unknown locations, posterior means more faithfully incorporate all of the sources of uncertainty in the Northern Channel Islands dataset.

Discussion

Behavioral ecology and the ideal free distribution

Behavioral ecology models have established themselves in a wide variety of archaeological and ethnographic subject areas, from foraging to life history decisions (reviews in Winterhalder and Kennett, 2006; Winterhalder and Smith, 2000). However, applications drawing on the IFD have lagged behind other models of comparable generality and importance (e.g., diet breadth, polygyny threshold). Recent heuristic applications of the IFD focus on regional patterns of colonization and settlement in Oceania (Kennett et al., 2006b) and Malay–Australia (Allen and O'Connell, 2008),
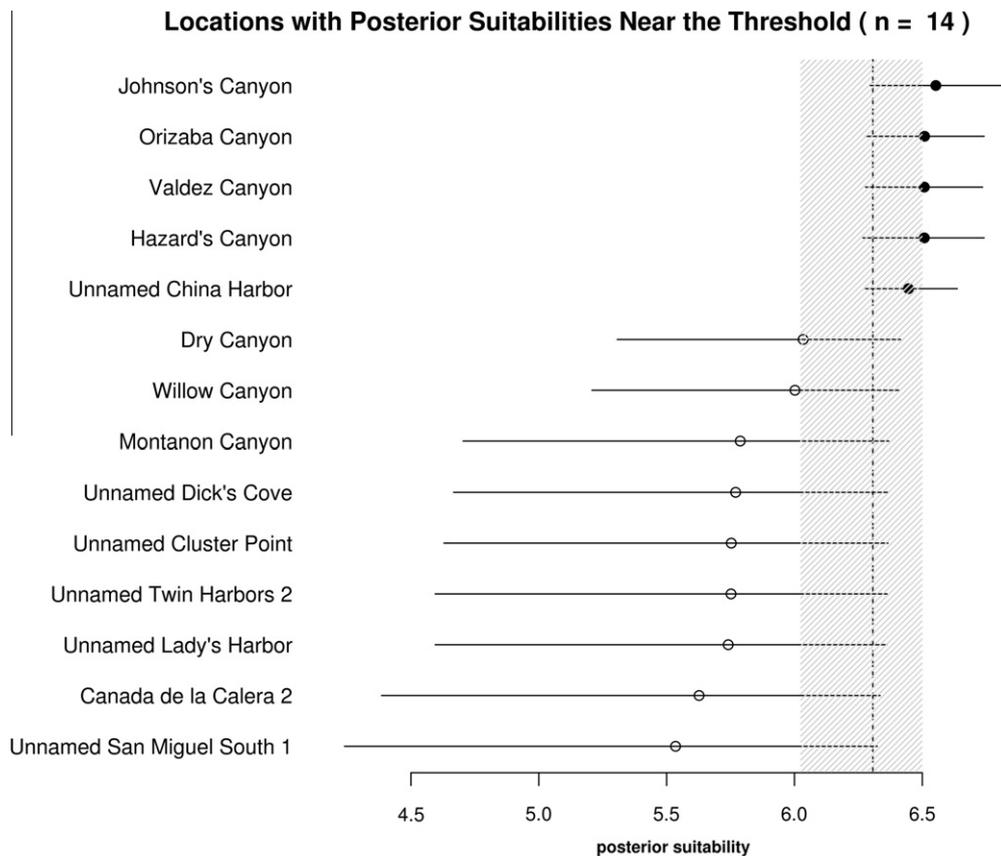
Fig. 8. Posterior suitabilities for locations with suitabilities closest to the threshold S_{min}. Posterior mean suitabilities and 95% credibility intervals are summary statistics based on 20,000 posterior samples. The vertical dashed line and shaded area show the posterior mean and 95% credibility interval for S_{min} (see parameter estimate in Table 2). Filled circles indicate settled locations, and open circles indicate unsettled locations.
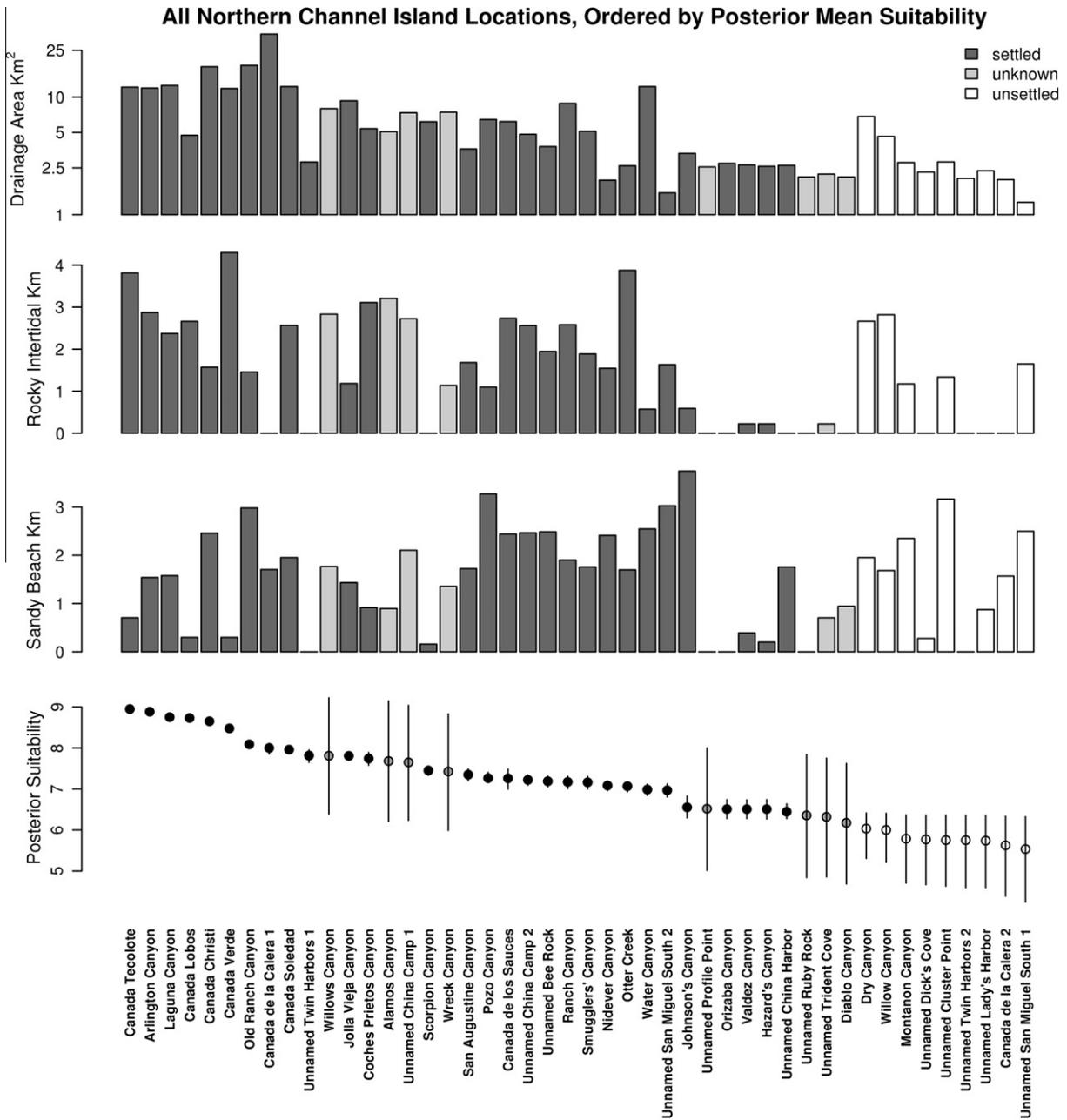
Fig. 9. (Top to bottom) Drainage Area, length of Rocky Intertidal zone, length of Sandy Beach and estimated suitability for each location, in descending order of suitability. Posterior mean suitabilities and 95% credibility intervals in the bottom panel are summary statistics based on 20,000 posterior samples. The x-axis labels are location names. *Settled* locations (n = 29) are shown with darkly shaded bars and circles, locations with *unknown* settlement (n = 8) have lightly shaded bars and circles, and *unsettled* locations (n = 9) have un-shaded bars and circles.

adoption of agriculture in Spain (McClure et al., 2009), and spread of agriculture across Europe (Shennan, 2007). In this paper we explore similar settlement processes but on a smaller and more detailed scale, and with a dataset amenable to quantified investigation of key IFD predictions.

A second aim of this paper is methodological. We seek to illustrate a significant shift in statistical analysis, from conventional inference and null hypothesis testing to computationally-intensive methods, uniquely tailored to the observations and the questions asked about them. We do not argue the case here for a shift from hypothesis testing to model fitting; that has been done well elsewhere (e.g., Anderson et al., 2000; Towner and Luttbeg, 2007). We do intend, along with Litton and Buck (1995), to demonstrate and encourage the use of Bayesian and other computationally-intensive methods for archaeological problems.

Assumptions and confounding factors

Our statistical analysis confirms that prehistoric settlement location by early residents of the Northern Channel Islands is consistent with the general pattern predicted by the IFD. Watershed area emerges as a significant positive predictor of earliest settlement component; lengths of rocky intertidal zone and sandy beach have weakly supported effects—a positive effect for the former, negative for the latter. A strong IFD signal emerges from this dataset despite multiple factors that, because they were ignored in our analysis, should act to obscure any underlying pattern. We describe potential confounding factors in this section.

To start with, the metrics we adopt for our four environmental measures – area for drainage and kelp beds; length for rocky intertidal; and sandy beach – are at best very rough substitutes for the

experienced and highly localized assessments of resource productivity that we presume were exercised by prehistoric peoples. One kilometer of rocky intertidal is not the same as the next; observations made on airphotos are not nearly as informative as those on the ground. One 10 km² drainage may yield abundant terrestrial resources and the next of similar size may be meager by comparison. Analysis by area ignores exposure, windward-leeward climatic factors, geological substrate, localized springs and variations in plant cover. Water availability in drainages across the islands is improving as vegetation communities recover from historical overgrazing. The northern, coastal-facing side of Santa Rosa features a concentration of highly ranked drainages, whereas the northern coast of Santa Cruz is dominated by quite small, low-ranking drainages (Kennett et al., 2009).

By examining only four environmental features we surely have neglected other localized factors important in the decisions of early residents. Early sites on these islands are sometimes found in caves or rockshelters (Erlandson et al., 1996; Kennett et al., 1997) and the distribution of these may be an important parameter for settlement as in other island contexts (Kennett et al., 2006a). In addition, permanent springs are not always tied to the largest drainages and could be mapped independently and included as an additional environmental parameter. For instance, the geology and hydrology of San Miguel Island favors springs on the north coast and partially explains the biased distribution of sites on that side of the island (Braje, 2007; Kennett, 2005). Sources of economically valuable stone (e.g., obsidian, chert) also are known to influence human behavior and settlement. Exposed chert sources are well-known on eastern Santa Cruz Island (Arnold, 1990b; Perry, 2003) and other smaller sources of chert are also known elsewhere (Erlandson et al., 1997). Also, concentrations of other types of subsistence resources are well-known on the islands and include a sea-mammal rookery on the western tip of San Miguel Island at Point Bennett (Rick et al., 2009; Walker et al., 2000) and an associated decreasing gradient from west to east in certain species during certain seasons (e.g., California sea lions, Northern Fur Seals and Elephant seals, Le Boeuf and Bonnel, 1980). This is also the case with bird rookeries on San Miguel and the rocky islets of Anacapa (Rick, 2004a).

We likewise assume that the present-day configuration of these environmental qualities persisted backwards in time for some 8000 years. This may be roughly accurate for relative watershed size, it surely is problematic for features like rocky intertidal and kelp beds, dependent as they are on precise relationships between surface morphology and sea level. Productivity in these marine systems is also known to be spatially variable and fluctuate through time (Dayton et al., 1992; Kennett and Kennett, 2000; Kennett et al., 2007, 2008; Ono et al., 1993; Tegner and Dayton, 1987, 1991). Sea-level had a major transformative effect on the coastline of these islands (Fairbanks, 1989; Kennett et al., 2008; Porcasi et al., 1999). Changes in sea level continued after 8000 years ago and would have influenced the distribution of kelp forests that only grow in a certain depth range (Kinlan et al., 2005). One estuary existed at the mouth of Old Ranch Canyon on Santa Rosa Island during the early Holocene, but had largely filled in by 5000 based on the presence/absence of estuarine shellfish in middens on this part of the island (Rick, 2009; Rick et al., 2005, 2006). El Niño frequency is also known to have changed during the last 8000 years (Kennett et al., 2007; Ramage, 1986). Finally, we do not consider the potential for differential human impacts on resources (e.g., resource depression) or the associated trophic interactions and landscape modification by prehistoric inhabitants of the islands (Braje, 2007; Erlandson et al., 2004; Rick and Erlandson, 2009; Timbrook et al., 1982).

Our analysis also assumes that these resource features mattered in the same way and to the same degree through time, from rela-

tively small groups of egalitarian hunter–gatherers focused heavily on shellfish coupled with terrestrial foods (e.g., grass and sage seeds), to centrally organized chiefdoms making greater and greater use of near and off-shore marine resources and trade with mainland communities. This may help explain why kelp bed distribution does not appear to be a significant predictor of the early settlement sequence on these islands. In fact, kelp beds apparently had a significant impact on the economy only toward the later part of the sequence, because of changing or intensifying marine subsistence practices (Kennett, 2005; Kennett and Kennett, 2000; Rick, 2004b). Similarly, beaches became much more important later in time (after 1500 years ago) for hauling out and storing plank canoes (Arnold, 1995, 2007; Gamble, 2002). They also became an important source of *Olivella biplicata* used to produce immense amounts of shell bead money, particularly after 800 cal. years BP (Arnold and Graesch, 2001; Arnold and Munns, 1994; King, 1990). These patterns may help to explain the inverse relationship we detect between length of sandy beach and ESC.

We also have assumed each new settlement to be independent in the sense that it has an autonomous economy drawn only from the local resources of its watershed, adjacent coastline and off-shore zone. This neglects the possibility that some locations were settled as economically dependent outposts or satellites of a nearby settlement. Such a pattern is evident even in the Middle Holocene, when the north coast of Santa Rosa Island served as a social gravitational center, with spinoff communities developing nearby rather than at more distant, higher-ranked locations (e.g. SRI-116 at the mouth of Lobo Canyon). Economic independence was almost surely compromised in the Late Holocene, when shell-beads-for-food & materials exchange systems were active, and chiefs were coordinating multi-site political units.

We likewise acknowledge that we have ignored regular NCI interaction with Chumash settlements on the Santa Barbara coast, through dynamic systems of intermarriage and trade. In fact, trends in population expansion and the emergence of social complexity on the mainland paralleled that on the Islands (Gamble, 2008), with earlier evidence for stable settlements on the mainland coast at the junctures between large drainages and highly productive estuaries (Erlandson, 1994). Early exploration of these islands was staged from the adjacent mainland, and it is likely that high-ranked habitats filled there prior to the colonization of these islands (Fitzhugh and Kennett, 2010). A regional application of the IFD in this area of high mobility and trade would include the mainland coastal areas of the Santa Barbara Channel, allowing for the possibility that the strains of population growth and declining habitat suitability were felt equally there. In particular, spillover of Island populations to the mainland was not possible because the mainland was undergoing a similar process of in-fill and ecological saturation. We examine only ecological factors, yet we know that this was a socially complex system, increasingly so in the later part of the historical sequence. This complicates tactics of economic cooperation and competition. Our database and consequently our analysis do not sufficiently reflect social variables likely to influence settlement, from kinship to witchcraft.

Finally, the outcome we have modeled—earliest settlement component—is distinct from and surely more recent than the arrival time of permanent settlers at each of these locations. Buck et al. (1992) showed that arrival times (start dates of deposition phases) can be inferred separately from artifact deposition times, given archaeological data of sufficient richness. They assumed uniform rates of deposition and discovery of datable materials, and obtained conditional distributions for arrival times that can be included in a Gibbs sampler. We experimented with the methods of Buck et al. (1992), but concluded that the availability of dated materials at several NCI locations was insufficient for valid inferences. We conjecture that additional radiocarbon dates, bringing

the total number of available dates to perhaps 10–20 at each location, will likely permit inference of arrival times.

Given this list, it is somewhat surprising – and for that reason a sound endorsement of the cogency of the IFD model – that we detect an 8000-year pattern consistent with our behavioral ecology predictions.

Pattern and process in settlement of the NCI

Scholars of Chumash prehistory debate not only the causes of socio-economic evolution on the Islands, but questions of their absolute timing and whether the changes were gradual or episodic (Arnold, 1992, 2001; Erlandson and Rick, 2002; Kennett and Kennett, 2000; Kennett et al., 2009; King, 1990; Raab and Larson, 1997), in the latter case consistent with an interpretation of punctuated equilibrium (Arnold, 1992). If human socio-economic adaptation simply tracks environment, then the pattern of cultural evolution largely is a simple matter; allowing for lag, it matches that of environmental change. However, the IFD gives us a somewhat more sophisticated understanding of this relationship, by demonstrating how slow, continuous change in environmental or demographic variables might cause abrupt, discontinuous change in population-level responses. A few additional individuals and a new habitat is colonized; with Allee effects this colonization might be an abrupt relocation of a significant portion of the population to a new habitat. Marginal change in one variable produces discontinuous change in a related variable. A highly suitable habitat sees its population slowly decline while that of a habitat with low basic suitability, but high resilience to exploitation, grows rapidly. Each of these patterns is evident in Figs. 2 and 3. These observations also suggest that terms like "gradual" or "punctuated" seldom will characterize a whole system; they more properly should be used to refer to specific variables and properties.

Population increase during the Late Holocene parallels the expansion of primary village locations around the coasts of the three largest islands. Sometimes the location of villages and associated cemeteries shifted to a slightly different location, but a majority of the high-ranked habitats that were settled in the Middle Holocene continued to be locations of permanent settlement later in time (Kennett, 2005). This is consistent with prediction (ii) that the highest ranked habitats should continue to be occupied as expansion to secondary and tertiary habitats occurs. The real world consequences of infilling, environmental saturation, and declines in suitability toward the late Holocene are also reflected in decreases in body size, indicators of poor health (cribra orbitalia and periosteal lesions) and increases in violence (Lambert, 1994, 1997). However, it is interesting that these trends in health and violence reverse after about 600 years ago, perhaps more consistent with the improvement of environmental conditions overall or a sociopolitical reorganization that increased the suitability of all island habitats.

Archaeologists debate the origins of institutionalized social hierarchy in the Santa Barbara region, with status differentiation assessed by such indicators as funerary objects marking high-status burials. Estimates range from 2400 cal. years BP (King, 1990) to 800 cal. years BP (Arnold, 1992). Our preliminary analysis (Kennett et al., 2009: 309) placed this development between 1500 and 650 cal. years BP, based on the observation that 1st through 3rd quartile locations were nearly completely occupied by this time. Dry unstable climatic conditions in the Late Holocene interval probably rendered all habitats we identified as 4th quartile, and some of those in the 3rd quartile, unsuitable due to lack of potable drinking water (Kennett and Kennett, 2000). The quantitative analysis presented in this paper gives us another way to triangulate an estimate of the timing of this phenomenon. Arranged in declining order, the posterior suitabilities (Fig. 9; lower panel)

indicate three sharp drops or discontinuities: Canada Verde to Old Ranch Cyn; unnamed China Camp 1 to Scorpion Cyn; and, unnamed San Miguel South 2 to Johnson's Cyn.

The latter discontinuity is the largest and in the period of interest. Unnamed San Miguel South 2 has a suitability estimate of 7.0, for a predicted ESC of 1067 cal. years BP (Table 1). The comparable values for Johnson's Cyn are 6.6 and 708 cal. years BP. Notably, Johnson's Cyn initiates a short run of locations that skirt the upper edge of the S_{min} credibility interval, before another discontinuity drops clear through it (Unnamed China Harbor to Dry Canyon). Our model suggests that expansion of growing population to any location after Unnamed San Miguel South 2 (1067 cal. years BP) would be quite stressful, hovering on the boundary of locations unsuitable for settlement. By Hazard's Canyon (675 cal. years BP) and Unnamed China Harbor (633 cal. years BP) viable options are exhausted; all remaining locations fall below the lower bound of minimum suitability. Island residents seeking to relocate faced settlement opportunities that were becoming both rare and relatively poor in their prospects; the remaining inventory of empty watersheds was apparently not viable for villages. This suggests a period of heightened social stress due to the environmental pressures of circumscription in the interval 1067 to 675 cal. years BP, overlapping our earlier estimate of 1500–650 cal. years BP, and toward the more recent end of the range debated by King and Arnold (2400–800 cal. years BP).

Computationally-intensive methods and the peculiarities of archaeological datasets

We embedded the Gibbs sampler in a Bayesian model in order to turn to our analytical advantage features of the NCI dataset that would be problematic for conventional modeling: error in radiocarbon estimates and informative censoring of unsettled watersheds. We argue that this approach is both powerful and particularly well-suited to research on prehistory. Litton and Buck (1995) make a similar argument for archaeological dating and spatial sampling. Archaeology is maturing as an empirical science. Archaeological data are becoming much more abundant, reliable, and diverse in the subjects they address. However censored and missing observations as well as other features that impede conventional statistical modeling are frequently encountered in archaeology. It is important to develop analytical and statistical methods suited to large-scale, comparative analysis of archaeological datasets that nonetheless accommodate the peculiar difficulties of this work. A better understanding of the most intriguing, important and enduring archaeological problems will require these new approaches.

The Gibbs sampler provides a practical means of retaining information from records that are afflicted with missing data, measurement error or censoring (Knight et al., 1998). Rather than ignore measurement error or discard partial records along with the information they do contain – standard tactics because conventional methods do not handle such irregularities gracefully – we impute unobserved variables probabilistically. Principled imputation replaces more *ad hoc* approaches, allowing us to use the valuable information in partial or error-prone records. This is especially important if the data are by their nature (a) unique and highly localized, (b) difficult and costly to gather, and (c) not replaceable or replicable following recovery, all attributes characterizing archaeological datasets. Sites cannot be re-excavated any more than we can replicate the socio-economic behaviors that produced them. Often we are working with small samples, and with records produced by older and less thorough methods, or with datasheets unevenly completed. The larger the comparative or multi-site dataset we assemble for analysis, the more likely it is to have various compromising faults. But even if it is messy, we seek

methods to make the most of the information contained in such datasets.

Measurement error in radiocarbon estimates and calibration

When an imprecise proxy (such as a radiocarbon date) is observed in place of a variable of interest (such as a calendar date), additional uncertainty can, and should, be incorporated into model fitting and inference (Buck et al., 1996; Mallick and Gelfand, 1996). If needed, the relationship between the unobserved variable and its proxy can be specified by a calibration curve.

Missing data

Conventional responses to missing data are to eliminate the record, estimate the missing value by interpolating, or conduct a new investigation to fill in what is missing (Knight et al., 1998: 471). The first tactic ignores what may be quite useful information in the remainder of the record; the second embroils us in arbitrary choices; the third is, as noted above, often impossible with archaeological samples. The Gibbs sampler takes a probabilistic approach to missing values, completing a record not with a single best guess but with a distribution of plausible values, which concretely characterizes uncertainty about the missing observation.

Censored data

Broadly speaking, censoring occurs when a variable is truncated or unobserved due to relatively specific, external mechanisms. Some examples are a time trial stopped before the outcome is observed for all participants; observations taken by an instrument limited to a minimal measurement value; or, in the NCI data, locations never settled, and therefore censored for earliest settlement component, perhaps as a consequence of human habitat selection. The Gibbs sampler permits censored values to be treated as probabilistic unknowns, incorporating information about the censoring mechanism when available. The distribution of these random draws informs about the censored observation as well as other model unknowns.

Conclusions

Ecologists are attracted to islands because insular environments appear to simplify processes that are thought to be pervasive, but are more difficult to isolate and observe in other settings. From the work of Darwin and Wallace forward, the history of biological science supports the merit of this inclination. It would be fair however to point out that it is easier to argue for the merits of problem simplification than for the point that ecological processes analyzed on islands are, in some straightforward manner, representative of other landscapes. The *hunch* that this is true is regularly reinforced, but has not been rigorously demonstrated, and there are major differences between island and continental contexts that cannot be ignored (Grayson and Meltzer, 2002).

Our analysis of NCI settlement follows in the island ecology tradition (see Kirch, 1997). We have pursued population ecology analysis of the NCI dataset because it is unusually thorough in its time depth and spatial coverage, data recovery and interpretive possibilities. Indeed, comparable datasets within archaeology, amenable to detailed, comparative behavioral ecology investigation, are still fairly rare. But, we also have pursued this case because we believe it to contain clues to similar processes in continental environments, which for a variety of reasons, are more difficult to investigate. All environments are spatially heterogeneous in factors affecting their suitability for human occupation; all are made up of spatially isolated habitat "islands," differing in their suitability to human use. This is likely to be true of landscapes structurally similar to those of the Northern Channel Islands (e.g.,

coastal Peru), and those quite divergent (e.g., Columbia River plateau).

Analysis of 38 watersheds, 29 with and nine without village sites, demonstrates that settlement of the Northern Channel Islands generally follows a pattern predicted by the ideal free distribution (Fretwell and Lucas, 1969). This is confirmed by model-building that isolates drainage size, length of rocky intertidal zone and, inversely, length of sandy beach, as environmental features potentially used for decisions about prehistoric site location. The IFD signal emerges strongly despite a long list of potential confounding effects. In addition, we can rank the eight drainages classified as "Unknown" according to predicted suitabilities, distinguish those that may contain as yet undiscovered villages, and suggest their approximate ages.

As population grows, organisms distribute themselves over habitats differing in their suitability in an orderly fashion that sometimes can be predicted by the IFD. The model links individual-level adaptive decisions to population-level consequences. It allows for dynamically changing suitability; it incorporates both negative density dependence, in the form of exploitation and interference competition, and positive density dependence, through Allee effects representing economies of scale. We envision the IFD being useful in analyses of migration, habitat choice, settlement pattern and intensification, in insular and pseudo-insular habitats (Allen and O'Connell, 2008; Kennett et al., 2006b; Kennett and Winterhalder, 2008; McClure et al., 2009; Shennan, 2007). We hope to see it tested in other settings, with methods like those demonstrated here.

Appendix The Gibbs sample

Full conditional distributions

Statistical inferences about the suitability model (Eqs. (2) and (3)) need to incorporate two key features of the sample: first, the eight locations classified as unsettled are censored for earliest settlement component (ESC); and second, even for settled locations, ESC is observed with error, via a radiocarbon date proxy. We take a Bayesian approach to model fitting, treating the basic suitabilities $S_1^*, \ldots S_N^*$ as unobserved random variables. We impute suitabilities for the unsettled locations stochastically by data-augmentation. For settled sites, we use a stochastic measurement-error model to impute suitabilities conditional on radiocarbon dates. Here we give details of a Gibbs sampler, implemented in the programming language *R* (R Development Core Team, 2010, version 2.11.1), which generates realizations from the posterior distributions of the model parameters $\boldsymbol{\beta}$, σ^2, $S_{\min}$ and basic suitabilities $S_1^*, \ldots S_N^*$.

The Gibbs sampler works in an iterative manner, producing at every iteration a new random draw from the conditional distribution of each stochastic quantity of the model, given the current values of all other quantities. These "full conditional" distributions are given below in items 1–5. We use the general form $p(Y|Z_1, \ldots Z_M)$ to indicate the conditional distribution of Y given $Z_1, \ldots Z_M$. Variables

on which Y does not depend are not included in the conditioning set. The symbol "α" indicates equality up to an unspecified constant of integration. The covariates for location $l = 1, \ldots N$ (including the intercept) are indicated by the k-dimensional row-vector $\mathbf{x}_l$, $\mathbf{X}$ is the N by k matrix having rows $\mathbf{x}_1, \ldots \mathbf{x}_N$, and $\mathbf{S} = (S_1^*, \ldots S_N^*)'$ is the column-vector of basic suitabilities.

(1) $p(\sigma^2 | \boldsymbol{\beta}, \mathbf{S}, \mathbf{X})$ is Inverse-Gamma with parameters $a = (n - k - 2)/2$ and $b = \Sigma_l\, e_l^2/2$, where $e_l = S_l^* - \mathbf{x}_l \boldsymbol{\beta}$ is the residual for location $l = 1, \ldots N$.

(2) $p(\boldsymbol{\beta} | \sigma^2, \mathbf{S}, \mathbf{X})$ is multivariate Gaussian with mean vector $(\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}'\mathbf{S}$ and covariance matrix $\sigma^2 (\mathbf{X}'\mathbf{X})^{-1}$. The full conditionals 1 and 2 are consequences of the naive prior on $(\boldsymbol{\beta}, \sigma^2)$ in a Bayesian linear model for $S_1^*, \ldots S_N^*$ (see e.g., O'Hagan, 1994 Section 9). The *sim* function of the *R* library *arm* (Gelman et al., 2010 version 1.3-02) conveniently produces realizations of $\boldsymbol{\beta}$ and σ^2 from the full conditionals.

(3) The full conditional for $S_{\min}$ is

$$p(S_{\min} | \boldsymbol{\beta}, \sigma^2, \mathbf{S}, \mathbf{X}) \alpha (\Pi_i (\Phi((S_{\min} - \mathbf{x}_i \boldsymbol{\beta})/\sigma))^{-1})$$
$$(\Pi_j (1 - \Phi((S_{\min} - \mathbf{x}_j \boldsymbol{\beta})/\sigma))^{-1}) \chi_{(u,v)}(S_{\min})$$

where the product Π_i is over unsettled sites, the product Π_j is over settled sites, Φ is the standard Gaussian cumulative distribution function, u is the maximum basic suitability among unsettled sites, v is the minimum basic suitability among settled sites, and $\chi_{(u,v)}(S_{\min}) = 1$ if $S_{\min}$ is in the interval (u, v) and is otherwise zero. In an analogous setting, Holloway et al. (2004, section 2.3) suggest sampling from $p(S_{\min} | \mathbf{S}) \propto \chi_{[u,v]}(S_{\min})$, but this does not make use of the entire conditioning set.

(4) For an unsettled location i, $p(S_i^* | \boldsymbol{\beta}, \sigma^2, S_{\min})$ is truncated Gaussian with mean $\mathbf{x}_i \boldsymbol{\beta}$, variance σ^2 and upper truncation threshold $S_{\min}$. This is a data-augmentation step, as in Chib (1992 Section 5).

(5) For a settled location j,

$$p(S_j^* | \boldsymbol{\beta}, \sigma^2, S_{\min}, R_j) \; \alpha \; f_j(S_j^* | \boldsymbol{\beta}, \sigma^2, S_{\min}) g_j(R_j | S_j^*) \chi_{\{S_j^* < \log E\}}$$

where R_j is the radiocarbon date of the earliest component at location j, f_j and g_j are densities given immediately below, E is a fixed earliest boundary for the onset of human occupation (common to all locations), and $\chi_{\{S_j^* < \log E\}} = 1$ if $S_j^* < \log E$ and is otherwise zero. The full conditional for S_j^* is derived from a measurement-error model of Mallick and Gelfand (1966; see also Gelfand et al., 1997) in combination with the radiocarbon calibration model of Buck et al. (1996, chapter 9). The factor χ is included in order to prevent imputation of basic suitabilities that would imply unreasonably early occupation of these locations, with E chosen to be 25000 cal. years BP for the Northern Channel Islands. $f_j (S_j^* | \boldsymbol{\beta}, \sigma^2, S_{\min})$ is a truncated Gaussian density with mean $\mathbf{x}_j \boldsymbol{\beta}$, variance σ^2 and lower truncation threshold $S_{\min}$. $g_j(R_j | S_j^*)$ is a conditional density for radiocarbon date R_j, given the basic suitability S_j^* and a calibration model connecting R_j to S_j^*. Buck et al. (1996, chapter 9) model the radiocarbon date R as a Gaussian variable with mean $\mu(\theta)$ and variance τ^2, where θ is the true calendar date for the radiocarbon sample in years BP, μ is a calibration curve and τ^2 is a total variance, incorporating radiocarbon dating error and error in the calibration curve. Typically, μ is a piecewise linear curve fitted by dendrochronological (tree-ring) methods (Buck et al., 1996). For radiocarbon dates of terrestrial components, we obtained μ from the IntCal04 Northern Hemisphere calibration curve (Reimer et al., 2004), while for marine components, we obtained μ from the Marine04 global marine radiocarbon

calibration curve (Hughen et al., 2004). The dating-error contribution to τ^2 for each component is provided by the dating laboratory, and the calibration-error contribution to τ^2 is recorded in the appropriate calibration curve data set. We estimate τ_j^2 for a settled location j directly, using the given errors; τ_j^2 is not treated as a parameter of the suitability model. For a settled location j, the basic suitability S_j^* and calendar date θ_j are related by the equation $\theta_j = \exp(S_j^*)$. By a straightforward extension of the model in Buck et al. (1996, chapter 9), $g_j(R_j | S_j^*)$ is then Gaussian with mean $\mu(\exp(S_j^*))$ and variance τ_j^2.

Samples $S_1^*, \ldots S_N^*$ generated probabilistically by steps 4 and 5 are saved over iterations for posterior analysis. Along with these, we save predicted values of ESC (measured in calendar years BP), generated as $\exp(S_1^*), \ldots \exp(S_N^*)$. In analogy with the plant reproductive biomass modeled in Gelfand et al. (1997), predicted ESC is a conceptual quantity, subject to truncation by a suitability threshold (which in the present case is a parameter to be inferred).

Running the Gibbs sampler and assessing output quality

We initialize the Gibbs sampler as follows. For a settled location j, the initial value of S_j^* is $\log(m_j)$, where m_j is the conditional mean calendar date given R_j, under the calibration model of Buck et al. (1996, chapter 9). For an unsettled location i, the initial value of S_i^* is a random variable $\log(U_i)$, where U_i is uniform on the interval $(0.01, \underline{m})$, and $\underline{m}$ is the smallest conditional mean calendar date among settled locations. $\boldsymbol{\beta}$ and σ^2 are initialized by a regression of the initial values of $S_1^*, \ldots S_N^*$ on the covariates $\mathbf{x}_1, \ldots \mathbf{x}_N$. Iterations of steps 1–5 then follow.

We find the arguments in favor of inference based on a single very long run of the Gibbs sampler persuasive (Gill, 2008 chapter 12 presents differing views in detail). Prior to starting a long run, we conducted several short preliminary runs (on the order of 10,000 iterations) in order to determine Gibbs sampler settings, paying attention to autocorrelation functions and time-series plots of the stochastic variables over iterations. We used these graphs to check that ranges of the variables were adequately explored over iterations (i.e., that the Gibbs sampler "mixes"), and to rule out problems of non-stationarity. The sampler performs well for the suitability model, though moderate autocorrelation between successive draws of the threshold parameter $S_{\min}$ can be detected (extending over lags of about 10–20 iterations). Final runs for the 3- and 4-variable models consisted of 300,000 iterations, from which we discarded the initial 100,000 iterations (for a burn-in). We thinned the output at an interval of 10 iterations (discarding the intervening samples) in order to avoid data-storage problems. Our posterior summaries are then based on a total of 20,000 retained samples. We ran the Gibbs sampler separately to fit the 3- and 4-variable models, with respective run times of 27 and 28 h on a Dell Precision Workstation 650.

The threshold parameter $S_{\min}$ presents issues of statistical *identifiability* – our ability to infer a unique value of $S_{\min}$, while at the same time uniquely inferring other parameters. Examination of the full conditional for $S_{\min}$ (item 3 above) hints at potential problems: the expression $(S_{\min} - \mathbf{x}_i \boldsymbol{\beta})/\sigma$ is unchanged in value if the same constant is added to both $S_{\min}$ and β_0. Multiplication of $S_{\min}$, $\boldsymbol{\beta}$ and σ by a constant also leaves the expression unchanged. It then falls to the term $\chi_{(u,v)}(S_{\min})$, as well as distributions of other variables, to be sensitive to these parameter combinations. We view the basic suitabilities among settled sites as sensitive to differences in $S_{\min}$. The product form of $p(S_j^* | \boldsymbol{\beta}, \sigma^2, S_{\min}, R_j)$ (item 5 above) ensures that basic suitabilities S_j^* for settled sites remain close to the values that would be inferred from radiocarbon dates alone (see also Fig. 7). These radiocarbon dates are fixed; thus the random draws S_j^* for settled sites, as well as the minimum v, vary in a narrow range over Gibbs
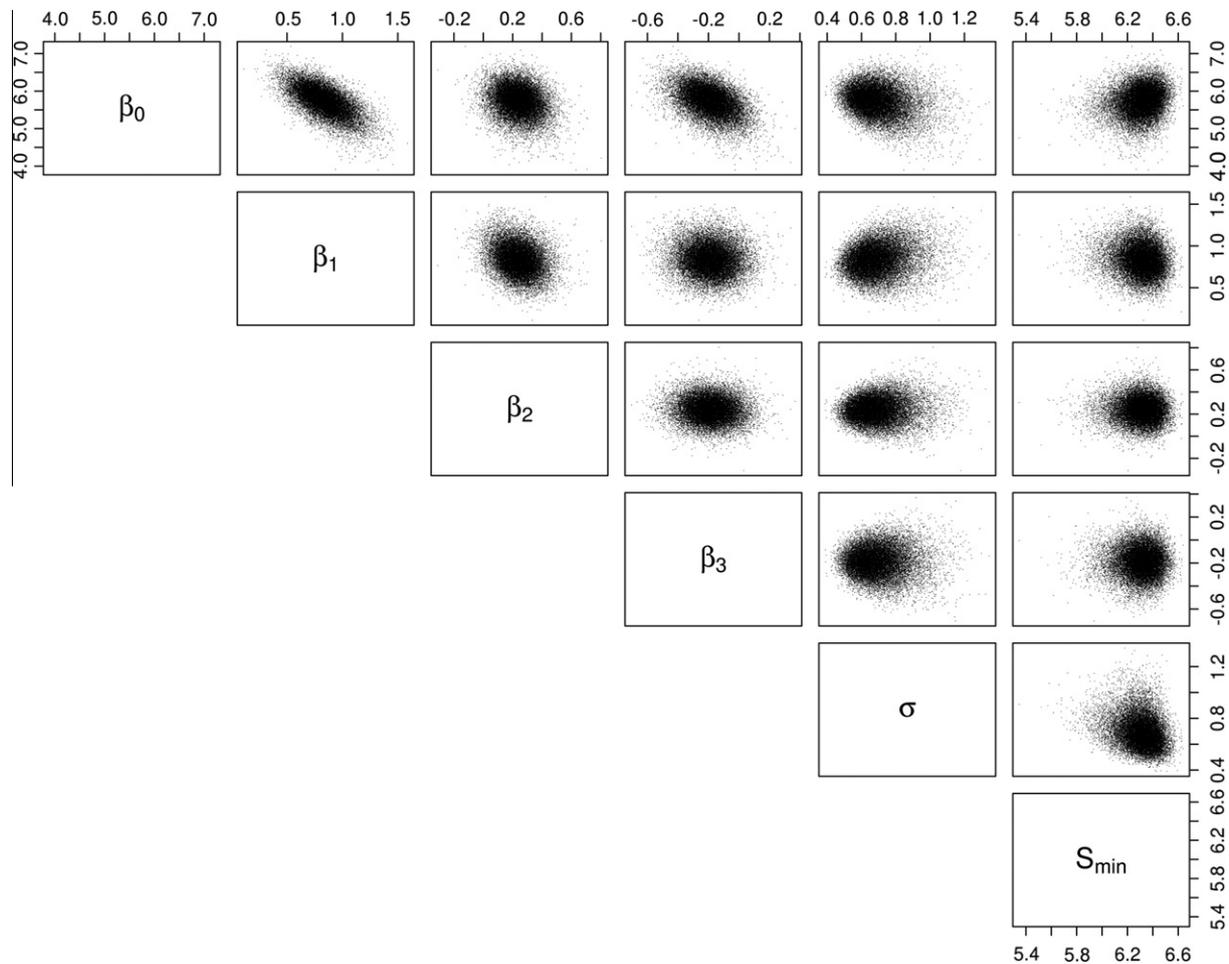
Fig. 10. Pairwise scatter plot matrix showing posterior samples of model parameters. Each row–column combination contains a scatter plot for a unique pair of model parameters. Each point within a scatter plot consists of a pair of parameters from one posterior sample. 20,000 posterior samples are displayed in the plots.

sampler iterations. Broadly speaking, the relative invariance of S_j^* permits inference of S_{min}, because S_j^* distinguishes values of S_{min} having different levels of probabilistic support.

We examine pairwise scatter plots of model parameters across posterior samples as a numerical check for identifiability. If the model is indeed indifferent to addition of a constant to S_{min} and β_0, we would expect a scatter plot of posterior samples of these parameters to show a strong linear relationship. Problems of identifiability elsewhere in the model would similarly be detectable as underlying deterministic relationships between parameters. The pairwise scatter plots shown in Fig. 10 give no cause for concern – in fact the only notable relationship is between β_0 and β_1, which are nonetheless both identified.

References

Agenbroad, L.D., Johnson, J.R., Morris, D., Stafford Jr., T.W., 2005. Mammoths and humans as late Pleistocene contemporaries on Santa Rosa Island. In: Barcelon, D.K., Schwemm, C.A. (Eds.), Proceedings of the Sixth California Islands Symposium. Institute for Wildlife Studies, Arcata, CA, pp. 3–7.

Allen, J., O'Connell, J.F., 2008. Getting from Sunda to Sahul. In: Clark, G.A., Leach, F., O'Connor, S. (Eds.), Islands of Inquiry: Colonisation, Seafaring and the Archaeology of Maritime Landscapes. Australian National University, Canberra, pp. 31–46.

Anderson, D.R., Burnham, K.P., Thompson, W.L., 2000. Null hypothesis testing: problems, prevalence, and an alternative. Journal of Wildlife Management 64 (4), 912–923.

Arnold, J.E., 1990a. An archaeological perspective on the historic settlement pattern on Santa Cruz Island. Journal of California and Great Basin Anthropology 12 (1), 112–127.

Arnold, J.E., 1990b. Lithic resource control and economic change in the Santa Barbara Channel region. Journal of California and Great Basin Anthropology 12 (2), 158–172.

Arnold, J.E., 1992. Complex hunter–gatherer–fishers of prehistoric California: chiefs, specialists, and maritime adaptations of the Channel Islands. American Antiquity 57, 60–84.

Arnold, J.E., 1995. Transportation innovation and social complexity among maritime hunter–gatherer societies. American Anthropologist 97 (4), 733–747.

Arnold, J.E. (Ed.), 2001. The Origins of a Pacific Coast Chiefdom: The Chumash of the Channel Islands. University of Utah Press, Salt Lake City, UT.

Arnold, J.E. (Ed.), 2004. Foundations of Chumash Complexity. Cotsen Institute of Archaeology, Los Angeles, CA.

Arnold, J.E., 2007. Credit where credit is due: the history of the Chumash oceangoing plank canoe. American Antiquity 72, 196–209.

Arnold, J.E., Bernard, J., 2005. Negotiating the coasts: status and the evolution of boat technology in California. World Archaeology 37, 109–131.

Arnold, J.E., Graesch, A.P., 2001. The evolution of specialized shell working among the Island Chumash. In: Arnold, J.E. (Ed.), The Origins of a Pacific Coast Chiefdom: The Chumash of the Channel Islands. University of Utah Press, Salt Lake City, UT, pp. 71–112.

Arnold, J.E., Munns, A., 1994. Independent or attached specialization: the organization of shell bead production in California. Journal of Field Archaeology 21, 473–489.

Biondi, F., Cayan, D.R., Berger, W.H., 1997. Dendroclimatology of Torrey Pine (*Pinus torreyana Parry* ex Carr.). American Midland Naturalist 138 (2), 237–251.

Braje, T.J., 2007. Archaeology, Human Impacts and Historical Ecology on San Miguel Island, California. University of Oregon, Eugene, OR.

Braje, T.J., Kennett, D.J., Erlandson, J.M., Culleton, B.J., 2007. Trans-Holocene subsistence changes and human impacts on a marine ecosystem on Santa Rosa Island, California. American Antiquity 72 (4), 735–756.

Buck, C.E., Cavanagh, W.G., Litton, C.D., 1996. Bayesian Approach to Interpreting Archaeological Data. John Wiley & Sons, New York.

Buck, C.E., Litton, C.D., Smith, A.M.F., 1992. Calibration of radiocarbon results pertaining to related archaeological events. Journal of Archaeological Science 19, 497–512.

Carneiro, R.L., 1970. A theory of the origin of the state. Science 169 (3947), 733–738.

Casella, G., George, E.I., 1992. Explaining the Gibbs sampler. The American Statistician 46 (3), 167–174.

Chib, S., 1992. Bayes inference in the Tobit censored regression model. Journal of Econometrics 51, 79–99.

Courchamp, F., Clutton-Brock, T., Grenfell, B., 1999. Inverse density dependence and the Allee effect. TREE 14 (10), 405–410.

Dayton, P.K., Tegner, M.J., Parnell, P.E., Edwards, P.B., 1992. Temporal and spatial patterns of distribution and recovery in a kelp forest community. Ecological Monographs 62, 421–445.

Erlandson, J.M., 1984. A case study in faunalturbation: delineating the effects of the burrowing pocket gopher on the distribution of archaeological materials. American Antiquity 49, 785–790.

Erlandson, J.M., 1994. Early Hunter–Gatherers of the California Coast. Plenum Press, New York.

Erlandson, J.M., Kennett, D.J., Behl, R.J., Hough, I., 1997. The Cico chert source on San Miguel Island, California. Journal of California and Great Basin Anthropology 19, 124–130.

Erlandson, J.M., Kennett, D.J., Ingram, B.L., Guthrie, D., Morris, D., West, G.J., 1996. A radiocarbon chronology for the archaeology and paleontology of Daisy Cave, San Miguel Island, California. Radiocarbon 38 (2), 355–373.

Erlandson, J.M., Moss, M.L., 1999. The systematic use of radiocarbon dating in archaeological surveys in coastal and other erosional environments. American Antiquity 64 (3), 431–443.

Erlandson, J.M., Moss, M.L., des Lauriers, M., 2008. Life on the edge: early maritime cultures of the Pacific Coast of North America. Quaternary Science Reviews 27, 2232–2245.

Erlandson, J.M., Rick, T.C., 2002. Late Holocene cultural developments along the Santa Barbara coast. In: Erlandson, J.M., Jones, T.L. (Eds.), Catalysts to Complexity: Late Holocene Societies of the California Coast. Cotsen Institute of Archaeology, University of California, Los Angeles, Los Angeles, pp. 166–182.

Erlandson, J.M., Rick, T.C., Jones, T.L., Porcasis, J.F., 2007. One if by land, two if by sea: who were the first Californians? In: Jones, T.L., Klar, K.A. (Eds.), California Prehistory: Colonization, Culture and Complexity. Alta Mira Press, Landam, MD, pp. 53–62.

Erlandson, J.M., Rick, T.C., Vellanoweth, R.L., 2004. Human impacts on ancient environments: a case study from California's Northern Channel Islands. In: Fitzpatrick, S. (Ed.), Voyages of Discovery: The Archaeology of Islands. Praeger Publishers/Greenwood Press, Westport, CT, pp. 51–83.

Fairbanks, R.G., 1989. A 17,000 year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature 342, 637–641.

Fitzhugh, B., Kennett, D.J., 2010. Modeling seafaring intensity and island-mainland exchange along the Pacific coast of North America. In: Anderson, A., Barrett, J., Boyle, K. (Eds.), The Global Origins (and Development) of Seafaring. McDonald Institute of Archaeological Research, Cambridge, pp. 69–80.

Fretwell, S.D., 1972. Populations in a Seasonal Environment. Princeton University Press, Princeton, NJ.

Fretwell, S.D., Lucas Jr., H.L., 1969. On territorial behavior and other factors influencing habitat distribution in birds. I. Theoretical development. Acta Biotheoretica 19, 16–36.

Gamble, L.H., 2002. Archaeological evidence for the origin of the plank canoe in North America. American Antiquity 67, 301–315.

Gamble, L.H., 2008. The Chumash World at European Contact: Power, Trade, and Feasting among Complex Hunter–Gatherers. University of California Press, Berkeley, CA.

Gelfand, A.E., 2000. Gibbs sampling. Journal of the American Statistical Association 95 (452), 1300–1304.

Gelfand, A.E., Ghosh, S.K., 1998. Model choice: a minimum posterior predictive loss approach. Biometrika 85 (1), 1–11.

Gelfand, A.E., Mallick, B.K., Polasek, W., 1997. Broken biological size relationships: a truncated semiparametric regression approach with measurement error. Journal of the American Statistical Association 92 (439), 836–845.

Gelfand, A.E., Smith, A.F.M., 1990. Sampling-based approaches to calculating marginal densities. Journal of the American Statistical Association 85 (410), 398–409.

Gelman, A., Hill, J., 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press, Cambridge.

Gelman, A., Su, Y., Yajima, M., Hill, J., Pittau, M.G., Kerman, J., Zheng, T., 2010. arm: Data analysis using regression and multilevel/hierarchical models. <http://www.r-project.org>.

Geman, S., Geman, D., 1984. Stochastic relaxations, Gibbs distributions and the Bayesian restoration of images. IEEE Transactions on Pattern Analysis and Machine Intelligence 6 (6), 721–741.

Gilks, W.R., Richardson, S., Spiegelhalter, D.J. (Eds.), 1996. Markov Chain Monte Carlo in Practice. Chapman and Hall, London.

Gill, J., 2008. Bayesian Methods: A Social and Behavioral Sciences Approach. Chapman and Hall/CRC, New York.

Glassow, M.A., 1980. Recent developments in the archaeology of the Channel Islands. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Glassow, M.A., Perry, J.E., Paige, P.F., 2008. The Punta Arena Site: Early and Middle Holocene Cultural Development on Santa Cruz Island. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Goldberg, C.F., 1993. The Application of Stable Carbon and Nitrogen Isotope Analysis to Human Dietary Reconstruction in Prehistoric Southern California. University of California, Los Angeles.

Grayson, D.K., Meltzer, D.J., 2002. The human colonization of North American, Clovis hunting and large mammal extinction. Journal of World Prehistory 16, 313–359.

Greene, C.M., Stamps, J.A., 2001. Habitat selection at low population densities. Ecology 82 (8), 2091–2100.

Holloway, G., Nicholson, C., Delgado, C., Staal, S., Ehui, S.K., 2004. A revised Tobit procedure for mitigating bias in the presence of non-zero censoring with an application to milk-market participation in the Ethiopian highlands. Agricultural Economics 31, 97–106.

Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., et al., 2004. Marine04 marine radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1059–1086.

Ingram, B.L., Southon, J.R., 1996. Reservoir ages in eastern Pacific coastal and estuarine waters. Radiocarbon 38 (3), 573–582.

Johnson, J.R., 1982. An Ethnohistoric Study of the Island Chumash. University of California, Santa Barbara.

Johnson, J.R., 1988. Chumash Social Organization: An Ethnohistoric Perspective. University of California, Santa Barbara, CA.

Johnson, J.R., 1993. Cruzeño Chumash social geography. In: Glassow, M.A. (Ed.), Archaeology on the Northern Channel Islands of California. Coyote Press, Salinas, CA, pp. 19–46.

Johnson, J.R., Stafford Jr., T.W., Ajie, H.O., Morris, D.P., 2000. Arlington Springs revisited. In: Brown, D.R., Mitchell, K.C., Chaney, H.W. (Eds.), The Fifth California Islands Symposium. Department of the Interior Minerals Management Service, Pacific OCS Region, Camarillo, CA, pp. 541–545.

Jones, T.L., Richman, J.R., 1995. On mussels: *Mytilus californianus* as a prehistoric resource. North American Archaeologist 16 (1), 33–58.

Kelly, R.L., 1995. The Foraging Spectrum: Diversity in Hunter–Gatherer Lifeways. Smithsonian Institution Press, Washington.

Kennett, D.J., 1998. Behavioral Ecology and the Evolution of Hunter–Gatherer Societies on the Northern Channel Islands. University of California, Santa Barbara, CA.

Kennett, D.J., 2005. The Island Chumash: Behavioral Ecology of a Maritime Society. University of California Press, Berkeley.

Kennett, D.J., Anderson, A., Prebble, M., Conte, E., Southon, J.R., 2006a. Human impacts on Rapa, French Polynesia. Antiquity 80, 340–354.

Kennett, D.J., Anderson, A., Winterhalder, B., 2006b. The ideal free distribution, food production, and the colonization of Oceania. In: Kennett, D.J., Winterhalder, B. (Eds.), Behavioral Ecology and the Transition to Agriculture. University of California Press, Berkeley, CA, pp. 265–288.

Kennett, D.J., Clifford, R.A., 2004. Flexible strategies for resource defense on the Northern Channel Islands of California: an agent-based model. In: Fitzpatrick, S.M. (Ed.), Voyages of Discovery: The Archaeology of Islands. Praeger, Westport, CT, pp. 21–50.

Kennett, D.J., Ingram, B.L., Erlandson, J.M., Walker, P.L., 1997. Evidence for temporal fluctuations of marine radiocarbon reservoir ages in the Santa Barbara Channel Region, California. Journal of Archaeological Science 24, 1051–1059.

Kennett, D.J., Kennett, J.P., 2000. Competitive and cooperative responses to climatic instability in coastal southern California. American Antiquity 65 (2), 379–395.

Kennett, D.J., Kennett, J.P., Erlandson, J.M., Cannariato, K.G., 2007. Human responses to Middle Holocene climate change on California's Channel Islands. Quaternary Science Reviews 26, 351–367.

Kennett, D.J., Kennett, J.P., West, G.J., Erlandson, J.M., Johnson, J.R., Hendy, I.L., West, A., Culleton, B.J., Jones, T.L., Stafford Jr., T.W., 2008. Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at the Ållerød-Younger Dryas Boundary (13.0–12.9 ka). Quaternary Science Reviews 27, 2528–2543.

Kennett, D.J., Winterhalder, B., 2008. Demographic expansion, despotism, and the colonisation of East and South Polynesia. In: Clark, G., Leach, F., O'Connor, S. (Eds.), Islands of Inquiry: Colonisation, Seafaring and the Archaeology of Maritime Landscapes (Terra Australis 29). Australia National University Press, Canberra, pp. 87–96.

Kennett, D.J., Winterhalder, B., Bartruff, J., Erlandson, J.M., 2009. An ecological model for the emergence of institutionalized social hierarchies on California's Northern Channel islands. In: Shennan, S. (Ed.), Pattern and Process in Cultural Evolution. University of California Press, Berkeley, pp. 297–314.

King, C.D., 1976. Chumash inter-village economic exchange. In: Bean, L.J., Blackburn, T.C. (Eds.), Native Californians: A Theoretical Perspective. Ballena Press, Ramona, CA, pp. 289–318.

King, C.D., 1990. Evolution of Chumash Society: A Comparative Study of Artifacts used for Social System Maintenance in the Santa Barbara Channel Region before A.D. 1804. Garland Publishing, Inc., New York.

Kinlan, B.P., Graham, M.H., Erlandson, J.M., 2005. Late quaternary changes in the size, shape, and isolation of the California Islands: ecological and anthropological implications. In: Garcelon, D.K., Schwemm, C.A. (Eds.), Proceedings of the Sixth California Islands Symposium. Institute of Wildlife Studies, Arcata, CA, pp. 131–142.

Kirch, P.V., 1997. Microcosmic histories: island perspectives on "Global" change. American Anthropologist 99 (1), 30–42.

Klar, K., Whistler, K., McLendon, S., 1999. The Chumash languages: an overview. In: McLendon, S., Johnson, J.R. (Eds.), Cultural Affiliation and Lineal Descent of Chumash Peoples in the Channel Islands and the Santa Monica Mountains. Santa Barbara Museum of Natural History, Santa Barbara, CA, pp. 21–28.

Knight, J.R., Sirmans, C.F., Gelfand, A.E., Ghosh, S.K., 1998. Analyzing real estate data problems using the Gibbs sampler. Real Estate Economics 26 (3), 469–492.

Lambert, P.M., 1994. War and Peace on the Western Front: A Study of Violent Conflict and Its Correlates in Prehistoric Hunter–Gatherer Societies of Coastal Southern California. University of California, Santa Barbara, CA.

Lambert, P.M., 1997. Patterns of violence in prehistoric hunter–gatherer societies of coastal southern California. In: Martek, D.L., Frayer, D.W. (Eds.), Troubled Times. Gordon and Breach Publishers, Amsterdam, pp. 77–109.

Le Boeuf, B.J., Bonnel, M.L., 1980. Pinnipeds of the California Islands: abundance and distribution. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, CA, pp. 475–496.

Little, R.J.A., Rubin, D.B., 2002. Statistical Analysis with Missing Data, 2nd edition. John Wiley & Sons, Inc., Hoboken, NJ.

Litton, C.D., Buck, C.E., 1995. The Bayesian approach to the interpretation of archaeological data. Archaeometry 37 (1), 1–24.

Love, M., 1996. Probably More Than You Want to Know about the Fishes of the Pacific Coast. Really Big Press, Santa Barbara, CA.

Mallick, B.K., Gelfand, A.E., 1996. Semiparametric errors-in-variables models: a Bayesian approach. Journal of Statistical Planning and Inference 52, 307–321.

McClure, S.B., Barton, C.M., Jochim, M.A., 2009. Human behavioral ecology and climate change during the transition to agriculture in Valencia, Eastern Spain. Journal of Anthropological Research 65 (2), 253–269.

Mills, P., 1956. Archaeological Investigation on Santa Rosa Island in 1901. University of California, Berkeley, CA (1901).

Moratto, M.J., 1984. California Archaeology. Academic Press, New York.

Munns, A.M., Arnold, J.E., 2002. Late Holocene Santa Cruz Island: Patterns of continuity and change. In: Erlandson, J.M., Jones, T.L. (Eds.), Catalysts to Complexity: Late Holocene Societies of the California Coast. Cotsen Institute of Archaeology, Los Angeles, CA, pp. 127–146.

O'Hagan, A., 1994. Kendall's Advanced Theory of Statistics: Bayesian Inference, vol. 2B. Edward Arnold, London.

Ono, K.A., Boness, D.J., Oftedal, O.T., Iverson, S.J., 1993. The effects of El Niño on mother–pup biology in the California Sea Lion. In: Hochberg, F.G. (Ed.), Third California Islands Symposium: Recent Advances in Research on the California Islands. Santa Barbara Museum of Natural History, Santa Barbara, CA, pp. 495–500.

Orr, P.C., 1968. Prehistory of Santa Rosa Island. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Perry, J.E., 2003. Changes in Prehistoric Land and Resource use among Complex Hunter–Gatherer–Fishers on Eastern Santa Cruz Island, California. University of California, Santa Barbara, CA.

Philbrick, R., 1980. Distribution and evolution of endemic plants of the California Islands. In: Power, D.M. (Ed.), The California Islands: Proceedings of a Multidisciplinary Symposium. Santa Barbara Museum of Natural History, Santa Barbara, CA, pp. 173–188.

Porcasi, P., Porcasi, J.F., O'Neill, C., 1999. Early Holocene coastlines of the California Bight: the Channel Islands as first visited by humans. Pacific Coast Archaeological Society Quarterly 35, 1–24.

R Development Core Team, 2010. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.r-project.org>.

Raab, L.M., Larson, D.O., 1997. Medieval climatic anomaly and punctuated cultural evolution in coastal Southern California. American Antiquity 62 (2), 319–336.

Ramage, C.S., 1986. El Niño. American Scientist 254 (6), 77–83.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., et al., 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1026–1058.

Rick, T.C., 2001. AMS radiocarbon dating of a shell fishhook from Santa Rosa Island, California. Radiocarbon 43 (1), 83–86.

Rick, T.C., 2004a. Daily Activities, Community Dynamics, and Historical Ecology on California's Northern Channel Islands. University of Oregon, Eugene, Oregon.

Rick, T.C., 2004b. Social and economic dynamics on late Holocene San Miguel island, California. In: Arnold, J.E. (Ed.), Foundations of Chumash Complexity. Cotsen Institute of Archaeology, Los Angeles, CA, pp. 97–112.

Rick, T.C., 2006. A 5000-year record of coastal settlement on Ancapa Island, California. Journal of California and Great Basin Anthropology 26 (1), 65–72.

Rick, T.C., 2009. 8000 years of human settlement and land use in Old Ranch Canyon, Santa Rosa Island, California. In: Damiani, C., Garcelon, D. (Eds.), Proceedings of the Seventh California Islands Symposium. Institute for Wildlife Studies, Arcata, CA, pp. 21–31.

Rick, T.C., DeLong, R.L., Erlandson, J.M., Braje, T.J., Jones, T.L., Kennett, D.J., Wake, T.A., Walker, P.L., 2009. A trans-Holocene archaeological record of Guadalupe Fur Seals (*Arctocephalus townsendi*) on the California coast. Marine Mammal Science 25, 487–502.

Rick, T.C., Erlandson, J.M., 2009. Coastal exploitation. Science 325, 952–953.

Rick, T.C., Kennett, D.J., Erlandson, J.M., 2005. Preliminary report on the archaeology and paleoecology of the Abalone Rocks Estuary, Santa Rosa Island, California. In: Garcelon, D.K., Schwemm, C.A. (Eds.), Proceedings of the Sixth California Islands Symposium. Santa Barbara Museum of Natural History, Santa Barbara, CA, pp. 237–245.

Rick, T.C., Kennett, D.J., Erlandson, J.M., 2006. Early Holocene land use and subsistence on eastern Santa Rosa Island, California. Current Research in the Pleistocene 22, 60–62.

Rick, T.C., Vellanoweth, R.L., Erlandson, J.M., Kennett, D.J., 2002. On the antiquity of the single-piece shell fishook: AMS radiocarbon evidence from the Southern California coast. Journal of Archaeological Science 29, 933–942.

Rogers, D.B., 1929. Prehistoric Man of the Santa Barbara Coast. Santa Barbara Museum of Natural History, Santa Barbara, CA.

Shennan, S., 2007. The spread of farming into central Europe and its consequences. In: Kohler, T.A., van der Leeuw, S.E. (Eds.), The Model-Based Archaeology of Socionatural Systems. School for Advanced Research Press, Santa Fe, pp. 141–155.

Sutherland, W.J., 1983. Aggregation and the 'ideal free' distribution. Journal of Animal Ecology 52, 821–828.

Sutherland, W.J., 1996. From Individual Behaviour to Population Ecology. Oxford University Press, Oxford.

Tegner, M.J., Dayton, P.K., 1987. El Niño effects on southern California kelp forest communities. Advances in Ecological Research 17, 243–279.

Tegner, M.J., Dayton, P.K., 1991. Sea urchins, El Niños and the long term stability of southern California kelp forest communities. Marine Ecology Progress Series 77, 49–63.

Timbrook, J., Johnson, J.R., Earle, D.D., 1982. Vegetation burning by the Chumash. Journal of California and Great Basin Anthropology 4 (2), 163–186.

Towner, M.C., Luttbeg, B., 2007. Alternative statistical approaches to the use of data as evidence for hypotheses in human behavioral ecology. Evolutionary Anthropology 16 (3), 107–118.

Tregenza, T., 1995. Building on the ideal free distribution. Advances in Ecological Research 26, 253–307.

Walker, P.L., DeNiro, M.J., 1986. Stable nitrogen and carbon isotope ratios in bone collagen as indices of prehistoric dietary dependence on marine and terrestrial resources in southern California. American Journal of Physical Anthropology 71, 51–61.

Walker, P.L., Kennett, D.J., Jones, T.L., DeLong, R.L., 2000. Archaeological investigations of the Point Bennett pinniped rookery on San Miguel Island. In: Brown, D.R., Mitchell, K.C., Chaney, H.W. (Eds.), The Fifth California Islands Symposium. Department of Interior Minerals Management Service, Pacific OCS Region, Camarillo, CA, pp. 628–632.

Wilcoxon, L.R., 1993. Subsistence and site structure: an approach for deriving cultural information from coastal shell middens. In: Glassow, M.A. (Ed.), Archaeology on the Northern Channel Islands of California. Coyote Press, Salinas, CA, pp. 137–150.

Winterhalder, B., 2002. Models. In: Hart, J.P., Terrell, J.E. (Eds.), Darwin and Archaeology: A Handbook of Key Concepts. Bergin & Garvey, Westport, Connecticut, pp. 201–223.

Winterhalder, B., Kennett, D.J., 2006. Behavioral ecology and the transition from hunting and gathering to agriculture. In: Kennett, D.J., Winterhalder, B. (Eds.), Behavioral Ecology and the Transition to Agriculture. University of California Press, Berkeley, CA, pp. 1–21.

Winterhalder, B., Smith, E.A., 2000. Analyzing adaptive strategies: human behavioral ecology at twenty-five. Evolutionary Anthropology 9, 51–72.