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Acorns in Pre-Contact California: A Reevaluation of Their Energetic Value, Antiquity of Use, and Linkage to Mortar-Pestle Technology

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Mortar and pestle technology has long been considered prima facie evidence for the intensive use and storage of acorns in pre-contact California. The relatively late adoption of this technology has commonly been interpreted as a direct measure of population pressure and—due to the presumed low caloric return rate of acorns—declining foraging efficiency. Conversely, hand-stone and milling-slab technology was used throughout the Holocene, and was equated with the non-intensive processing of small seeds. Here we decouple these erroneous assumptions by demonstrating that acorns are among the most productive native plant foods widely available in California, and small seeds are among the least productive. Archaeobotanical data also show that the regular use of acorns in central California began early in the Holocene when hand-stones and milling-slabs were the only milling technology used. Bowl mortars and pestles first appear in some parts of central California by 7,000 years ago. Because they are highly efficient but costly to produce and transport, they are typically found in residentially stable contexts, characteristic of a transition to delayed-return, energy-maximizing economies. Hand-stone and milling-slab technology persists in residentially mobile situations well into the late Holocene and was used to process a variety of resources including acorns, reflecting time-minimizing, immediate-return economies. We conclude that milling tool form has as much to do with labor investment, processing efficiency, and settlement strategy as the types of resources processed.

The emergence of acorn-dependent economies in California has been an issue of long-standing interest to archaeologists concerned with the nature and origin of intensive food production and complex social organization within hunter-gatherer societies (e.g., Basgall 1987; Baumhoff 1963; Cohen 1977; Heizer 1974; Schulz 1981). In the absence of formal agriculture, the intensive collection, storage, and processing of acorns among California aboriginal groups is thought to have, in part, fostered the high native population densities and structurally complex societies recorded ethnographically (Basgall 1987; Baumhoff 1963; Gifford 1936; Kroeber 1925). The preeminence of this resource in post-contact native economies is well-documented (e.g., Gifford 1936; Kroeber 1925), but the origins of balanophagy in central California remain poorly defined (cf. Basgall 1987). In this respect, the antiquity of acorn use has traditionally been inferred from the earliest occurrence of bowl mortars and pestles (Basgall 1987; Glassow 1996) and not from more direct measures, such as the systematic recovery and identification of archaeobotanical remains (Wohlgemuth 1996). As this deficit is remedied, we are beginning to develop a new perspective on the nature and antiquity of acorn use, and on the functional relationship between milling tools and important native plant foods (Meyer and Rosenthal 1997; Rosenthal and McGuire 2004; White 2003; White et al. 2002; Wohlgemuth 1996, 2004).

Early treatments of acorn use among aboriginal groups in central California assumed a high priority for this resource, largely due to its ubiquity in traditional native California diets (Basgall 1987; Gifford 1936; Glassow 1996; Kroeber 1925; Schulz 1981). The assumed value of acorns led many archaeologists to believe that the only significant impediment to intensive acorn use was "unavailability, induced by either environmental factors (an absence of suitable oak tracts) or technological limitations (ignorance of the leaching process)," but not the productivity of the resource itself (Basgall 1987:23). Basgall (1987) argued that neither of these alternatives seemed to be a substantial impediment to intensive acorn use, prompting him to reconsider evidence for the timing and role of acorns in prehistoric subsistence economies. Using the relative frequency of bowl mortars and pestles in regional archaeological sites, he observed that this technology was adopted at different times in different places, and that uniformly, these tools were not used until relatively late in prehistory. He noted, "this pattern suggests an obvious paradox: if the resource is inherently so superior, why was it deemphasized by early populations?" (Basgall 1987:23). Contrary to the prevailing view that acorns were a preferred food, Basgall (1987) argued that the energetic costs of processing (i.e., pulverizing and leaching of tannic acids) made this resource relatively unproductive:

> Available ethnographic data portray a resource procurement system that encumbered a society with cumbersome and laborious processing commitments. This revised characterization has obvious ramifications for how the problem is phrased: if the resource is seen as a high-cost item that should *ceteris paribus*, be only minimally used, the emergence of balanophagy becomes a question of why it happened at all rather than why it took so long to happen [Basgall 1987:41].

Basgall (1987) concluded that the adoption of balanophagy in California reflects a process of demographic-driven resource intensification, whereby subsistence yields were increased at the expense of energetic efficiency: "When viewed from this perspective, the initial de-emphasis on acorns is consonant with expectations, and the cost-based model offers a parsimonious explanation for the relatively late and non-synchronous emergence of balanophagy" (Basgall 1987:41).

Subsequent to Basgall's work, Wohlgemuth (1996, 2004) amassed a substantial record of plant food use in precontact central California, particularly for the late Holocene. Based on nearly 1,000 archaeobotanical samples collected from throughout central California, Wohlgemuth (2004) demonstrated that the relative abundance of acorn residues in regional archaeological sites significantly increased during the Middle Period (i.e., 2,500 to ~1,000 cal B.P.), consistent with Basgall's (1987) predictions. However, at sites from interior central California, this increase was followed by an almost ten-fold rise in the abundance of small seeds during the Late Period (<1,000 cal B.P.). Wohlgemuth (2004) attributed this development to more labor-intensive subsistence practices, spurred by increasing human population densities—i.e., resource intensification.

The concept of resource intensification and related cost-benefit models has framed most discussions of economic and social change in central California for more than 20 years (e.g., Broughton 1994a, 1994b; Rosenthal et al. 2007; White 2003; White et al. 2002; Wohlgemuth 1996, 2004). And while resource intensification is now seen as an almost universal trend in pre-contact Native California economies, several assumptions drawn from this model require further consideration. For example, while Basgall (1987) asserted that the acquisition and processing of acorns was a relatively costly enterprise, balanophagy was not evaluated against the profitability of other plant foods. A second source of confusion comes from simply equating milling tool form with a specific resource. Although the bowl mortar and pestle are often taken as evidence for intensive acorn use, the relationship between different types of milling tools and associated archaeobotanical assemblages from central California has rarely been assessed (but see Rosenthal and McGuire 2004). Nevertheless, many researchers have assumed that the transition in milling technologies—from the hand-stone and milling-slab to mortar and pestle—also represented a shift in the types of resources that were processed (e.g., McGuire and Hildebrandt 1994; Stevens and McElreath 2015; Wohlgemuth 1996). This is largely due to ethnographic analogies which link use of the hand-stone and milling-slab with small seed processing and the mortar and pestle with the preparation of acorns. Likewise, if assumptions about the hand-stone and milling-slab and small seed processing are correct, how do we account for the upswing in small seed consumption late in the precontact sequence in the same regions where bowl mortars and pestles were the predominant or exclusive type of milling gear?

As described below, many of these suppositions prove false. In fact, acorns were a trans-Holocene resource, common even in the earliest archaeobotanical assemblages from central California. Energetic measures of profitability demonstrate that rather than representing a food with comparatively low return-rates, acorns were among the most profitable plant foods available in prehistoric central California. Furthermore, acorns never directly competed with small seeds in the subsistence economy, simply because these resources ripen at different times of the year, and thus the use of one resource did not preclude the use of the other. Comparisons of archaeobotanical assemblages and associated milling tools from central California sites clearly show that acorns were used long before the mortar and pestle was widely employed.

Contrary to prevailing views, we propose that milling tool use in native central California related more to the exigencies of land use and the extent to which different foraging groups were primarily time-minimizers or energy maximizers (Bettinger 2001; Bettinger and Baumhoff 1983; Tushingham and Bettinger 2013). The latter characteristic also influenced the degree to which foraging groups were residentially mobile or lived in fixed settlements where storage and reliance on off-season resources mandated the use of more efficient, yet labor-intensive, technologies. Thus, we suggest that the decision to invest in different sorts of milling tools was a compromise between processing efficiency and manufacturing/transport costs, but was not necessarily based on the types of plant foods that were processed.

PLANT FOODS IN CENTRAL CALIFORNIA AND THE RELATIONSHIP BETWEEN ACORNS AND SMALL SEEDS

The Mediterranean climate of California has a strong influence on plant-food productivity, as periods of peak rainfall are out of phase with the growing season. As a result, cold winter temperatures and summer drought both constrain the period of plant-food ripening. When warm temperatures converge with adequate water supplies in spring, a variety of seed-bearing plants, geophytes, and leafy greens are widely available. In summer, native plant foods consist mainly of small seeds and various fruits (e.g., manzanita berries, elderberry, blackberry, grape), whereas in the fall, a variety of nut crops ripen, including acorn, pine nuts, bay nuts, and buckeye. Except for a few types of roots (e.g., cattail and tule) and greens, virtually no plant foods are available during the winter months in central California. This latter characteristic is important for understanding prehistoric economies, as use of plant foods in winter either relied on stored resources or focused on patchy and geographically restricted species of wetland plants (e.g., cattail and tule). The fact that acorn and other nut crops (e.g., pine nuts, bay, buckeye) came at an entirely different time of year than small seeds means that collection of these different types of plant foods did not interfere with one another—they were sequential, and thus were complimentary resources.

Although Basgall (1987) and others (e.g., Bettinger et al. 1997) have gone to great lengths to describe the labor-intensive process of pounding and leaching acorns, the true profitability of this resource can only be evaluated in relationship to other potential food sources. The most common way of measuring resource profitability is through post-encounter return rates (i.e., the net gain in food energy divided by the time required to procure and process the item; see e.g., Simms 1987). Although return rates have not been calculated for many plant foods in central California, this information now exists for some of the most important individual species, including acorns (i.e., *Quercus kelloggii*, *Q. douglasii*, *Q. lobata, Q. chrysolepis*, *Lipocarpus desilora*). Using the common index of kilocalories per hour, several estimates have been generated for various types of acorns, small seeds, geophytes, and roots (see Table 1 and Fig. 1). Contrary to prevailing assumptions, however, acorns rank among the most profitable plant foods available in central California. Return rate estimates for five different acorn species far exceed those calculated for small seeds, including chenopods, maygrass, and Indian rice grass, while pine nuts—in this case pinyon pine—provide return rates similar to or higher than acorns. Although we lack return-rate estimates for pine species common to western California (e.g., gray or foothill pine), the value of these foods is presumably comparable to, or perhaps slightly less than, pinyon pine found in eastern California and throughout the Great Basin.

Table 1

RETURN RATES FOR VARIOUS PLANT FOODS

		kcal/hour		
Common Name	**Scientific Name**	**Low**	**High**	**Source**
Black Oak	*Quercus kelloggii*	793	793	Bettinger et al. 1997
Black Oak	*Quercus kelloggii*	1,070	1,070	Basgall 1987
Black Oak	*Quercus kelloggii*	848	848	Talaley et al. 1984
Tanbark Oak	*Lipocarpus desiflora*	866	866	Barlow and Heck 2002
Blue Oak	*Quercus douglasii*	915	919	Barlow and Heck 2002
Golden Cup Oak	*Quercus chrysolepis*	979	979	Barlow and Heck 2002
Valley Oak	*Quercus lobata*	1,135	1,138	Barlow and Heck 2002
Black Oak	*Quercus kelloggii*	1,091	1,194	Barlow and Heck 2002
Black Oak	*Quercus kelloggii*	1,166	1,276	Barlow and Heck 2002
Pinyon Pine	*Pinus monophylla*	841	1,408	Simms 1987
Bulrush roots	*Scirpus* spp.	146	160	Simms 1987
Cattail Roots	*Typha latifolia*	128	267	Simms 1987
Indian Rice Grass	*Oryzopsis hymenoides*	301	392	Simms 1987
Chenopod	–	433	433	Gremillion 2004
Maygrass	–	457	457	Gremillion 2004
Great Basin Wild Rye	*Elymus cinereus*	266	473	Simms 1987
Bluegrass	*Poa* spp.	418	491	Simms 1987
Sunflower	*Helianthus annus*	467	504	Simms 1987
Bulrush Seeds	*Scirpus* spp.	900	900	Simms 1987
Salina Wild Rye	*Elymus salinas*	921	1,238	Simms 1987
Blue Dicks	*Brodiaea* spp.	50	239	Ugan and Rosenthal 2016

Because the availability of different plant foods is also bounded by the period of ripening, prehistoric foragers could not continue to pursue a specific resource beyond its period of availability, regardless of its energetic profitability. Thus, return-rate estimates also indicate that plant food productivity fluctuated substantially throughout the year. It is probably significant that fall-ripening nut crops were among the most profitable plant foods available throughout the annual cycle, and these came just prior to the most deficient period—winter. As pine nuts and some species of acorn can last for a year or more in the shell without spoilage, it follows that these should have been among the first types of plant foods to be stored in prehistoric central California (McCarthy 1993).

It is also true, as Bettinger et al. (1997) point out, that delaying the actual processing of acorns until winter incurs very little opportunity costs, simply because few other plant foods are available at that time; and those that are (e.g., cattail and bulrush roots) do not occur widely across the landscape or have lower energetic returns, even factoring in processing costs (but see McGuire and Stevens 2017). And while pine nuts may have been more productive than acorns, given existing return-rate estimates, pine trees are not as broadly distributed in central California as oak trees, and rarely occur in lowland valleys where precontact human population densities were highest. Furthermore, acorns have very low upfront costs, as they can simply be collected and stored as is, with most processing delayed until the time of consumption (Tushingham and Bettinger 2013). Pine nuts, in contrast, require either removal from the bulky cone, or caching in proximity to their point of collection to minimize transport and storage costs. This latter strategy was employed in the Great Basin, but except for the Western Mono, caching plant foods away from primary settlements seems to have been rarely practiced in western California (Morgan

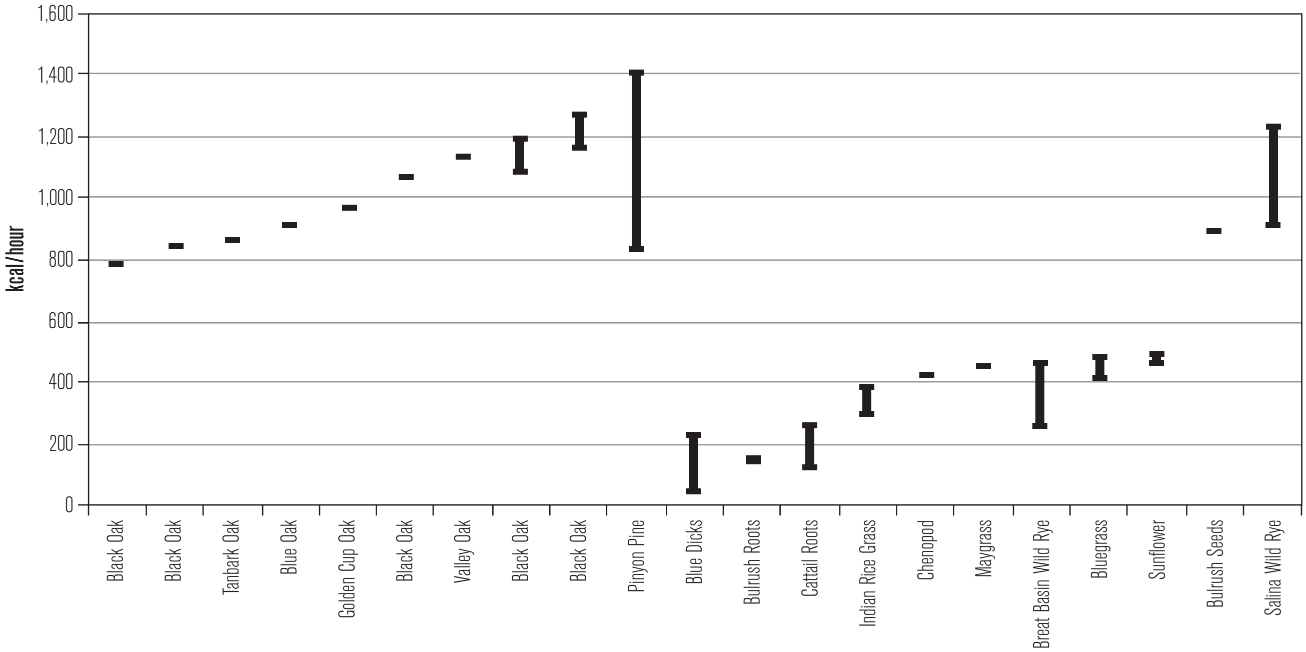


Figure 1. Comparative return rates for acorns and other plant foods.

2006:157). Given the comparatively high energetic return-rate estimates for acorns, and the understanding that these foods never directly competed with small seeds, or even root crops, due to differences in their season of ripening, acorns no longer appear to be the "costly" resource so often asserted in the archaeological literature. Rather, we would expect acorns to have been used at least seasonally throughout the prehistoric sequence, particularly in regions like the Central Valley, where pine trees cannot grow. Once they were widely stored, we would also expect acorns to have been consumed even in the spring and summer, since they have a substantially higher return rate than other plant foods available during those seasons. As a result, seasonally-specific archaeobotanical assemblages should be common in situations of high residential mobility where acorns were not stored, but less apparent in more sedentary contexts where storage was an important strategy and plants from multiple seasons were used throughout the annual cycle.

THE ARCHAEOLOGICAL RECORD OF ACORN USE IN CENTRAL CALIFORNIA

Acorn use during the Late Holocene (i.e., after 3,000 cal B.P.) in central California is well documented (e.g., Wohlgemuth 1996, 2004), but there are now enough archaeobotanical assemblages from the Early and Middle Holocene to demonstrate the use of acorns for nearly 10,000 years. A summary of 249 archaeobotanical samples from 29 stratified or single component central California sites greater than 4,000 years old (cal B.P.; Table 2, Fig. 2), clearly demonstrates that acorn use was ubiquitous, as charred acorn hulls occur in five of eight Early Holocene sites and more than 40% of all samples (33 of 71) from that time period (Table 2; Fig. 3). All 21 sites from the Middle Holocene and 85% of all samples (151 of 178) from that time period include acorn hulls (Fig. 3). Furthermore, pine nuts were widely used in habitats, such as the foothills of the Sierra Nevada and Coast Ranges, where pine species are common, but are virtually non-existent in the earliest samples from lowland valleys (e.g., the Central Valley) and coastal regions (Table 2).

Table 2 compares the ubiquity of acorn to gray pine and bay (*Umbellularia californica*), the most common fall-ripening nut crops found in Early and Middle Holocene central California sites. Seventy-one archaeobotanical samples are available from eight buried Early Holocene deposits radiocarbon dated between 10,300 and 7,890 cal B.P. (excluding one date of 4,780 cal B.P. from TUO-2797/H). These sites occur in a diverse range of habitats from the Pacific coast to the interior

Table 2

UBIQUITY OF ACORN AND OTHER COMMON NUTS IN STRATIFIED AND SINGLE COMPONENT, EARLY AND MIDDLE HOLOCENE SITES

Site	Reference	# of Samples	Acorn (%)	Gray Pine (%)	Bay (%)	^{14}C Range (cal B.P.)	# of Dates
EARLY HOLOCENE							
Pacific Coast							
SON-348	Schwaderer (1992)	2	–	–	100	8,000–7,210	2
SLO-832	Jones et al. (2002)	7	83	–	–	9,313–6,066	11
SLO-1797	Fitzgerald (2000)	8	–	–	–	10,295–4,780	16
Southern North Coast Ranges							
ALA-684	Meyer (2015)	23	–	–	–	8,200–9,560	6
CCO-696D	Meyer and Rosenthal (1997)	10	90	–	10	9,870–7,400	3
P-48-000897	Hildebrandt et al. (2012)	1	100	–	–	8,865	1
Sierra Nevada Foothills							
CAL-629/630	Rosenthal and McGuire (2004)	10	70	60	10	10,200–7,765	7
TUO-2797/H	Whitaker and Rosenthal (2010a)	10	100	100	–	8,850–4,850	3
MIDDLE HOLOCENE							
Southern North Coast Ranges							
LAK-72E-A	White et al. (2002)	1	100	100	–	4,494	1
LAK-510W-C	White et al. (2002)	6	100	100	50	7,820–3,000	2
LAK-509/881	Compas et al. (1994)	1	100	100	100	6,880	1
SON-2098	Origer (1993)	5	100	20	80	5,590–5,130	2
NAP-916	Martin and Meyer (2005)	3	100	–	33	5,730-5,520	3
SOL-468	Rosenthal and Whitaker (2016)	7	100	–	29	8,100–6,700	4
MRN-67, Strat. 1	Schwitalla and Powell (2014)	9	100	–	100	4,860–3,895	16
Northern Diablo Range/Central Coast Range							
CCO-637	Meyer and Rosenthal (1998)	10	100	80	100	5,797–2,585	7
CCO-309	Price et al. (2006)	4	100	–	100	5,050–4,420	3
CCO-18/548, Lower	Rosenthal (2010)	5	100	100	80	7,060–5,025	9
Laguna Socayre	Kaijankoski et al. (2018)	3	67	–	67	5,940–5,320	2
SCR-313	Jones et al. (2000)	14	29	–	43	5,935–4,985	2
Pacific Coast							
SBA-54	Levulett et al. (2002)	3	33	–	–	6,155–4,810	1
Sacramento Valley							
COL-247	White (2003)	9	100	–	22	4,385–3,575	3
GLE-701	Hildebrandt and McGuire (2019)	16	100	–	–	7,300–6,100	7
SAC-38	Tremaine (2008)	22	100	–	–	7,580–6,670	3
SAC-1142	Wohlgemuth (personal communication 2009)	9	78	–	–	7,470–5,215	2
Sierra Nevada Foothills							
CAL-789	Rosenthal and McGuire (2004)	12	92	100	–	5,390–2,720	8
FRE-61	McGuire (1995)	3	67	–	–	6,760–3,010	2
TUO-4559	Meyer (2008)	34	71	82	–	6,510–4,415	23
AMA-34	Whitaker and Rosenthal (2010b)	2	100	100	–	4,850	1

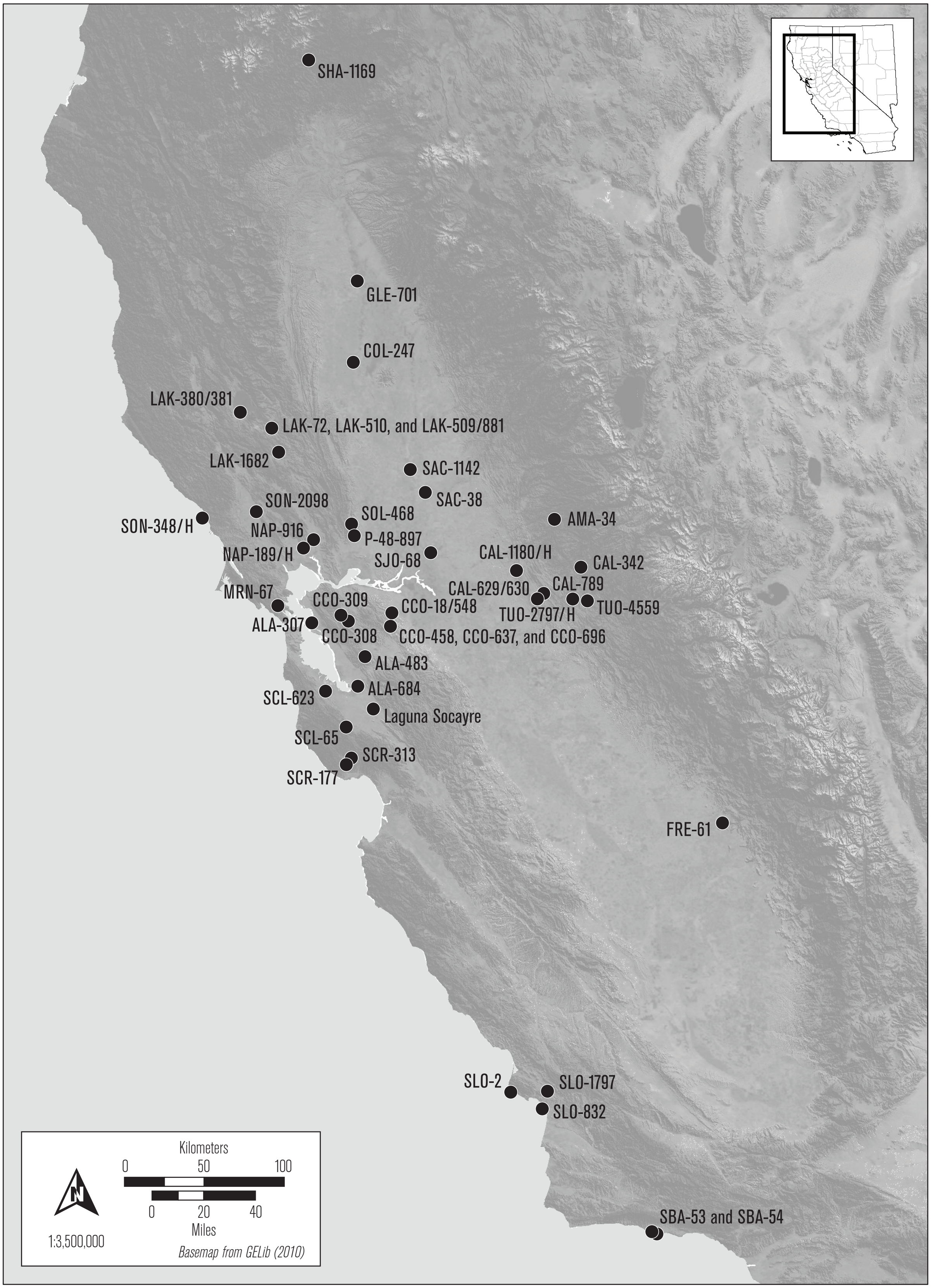


Figure 2. Location of central California sites mentioned in text.

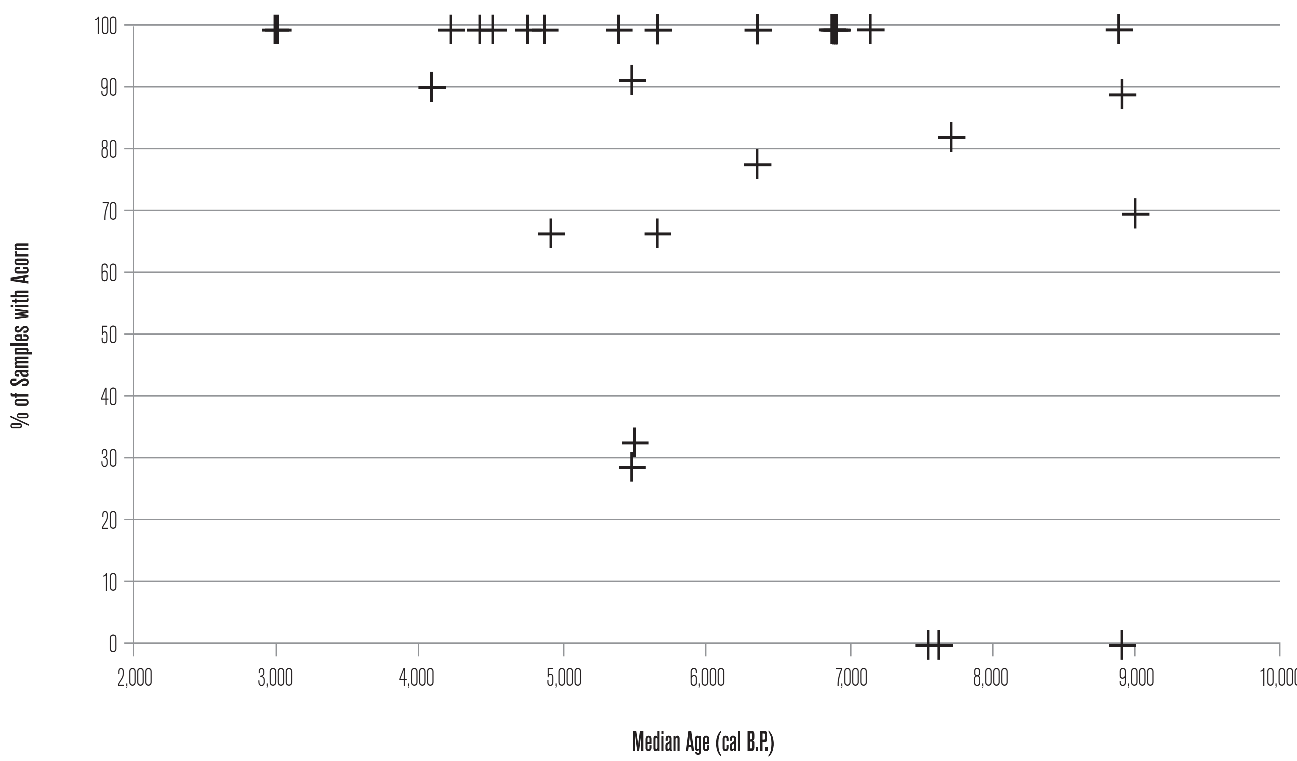


Figure 3. Ubiquity of acorn remains in Early and Middle Holocene archaeobotanical samples.

Diablo Range and lower foothills of the Sierra Nevada. Acorn nutshell is the most common, identified in 70% to 100% of flotation samples collected from five of eight sites (Table 2). These five deposits include SLO-832 at Pismo Beach, CCO-696D in the northern Diablo Range, P-48-897 in the southern North Coast Ranges, and CAL-629/630 and TUO-2797/H in the lower Sierra Nevada foothills. Bay nutshell was found in samples at three sites, and gray pine was only recovered at the two Sierra Nevada sites (CAL-629/630 and TUO-2797/H). A lack of acorn and gray pine nutshell in the Duncan's Landing rock shelter (SON-348) may be related to the small number of flotation samples collected from a single feature, but more likely results from the absence of significant oak and gray pine tracts in proximity to the coastal terrace. This, however, is unlikely at the Cross Creek (SLO-1797) and Fremont sites (ALA-684) where no acorn or other nuts were found, but charred oak wood and small seeds were identified (Fitzgerald 2000; Meyer 2015). The recovery of oak wood confirms that these trees occurred near the two sites, but the absence of acorn is likely due to occupation during spring or summer months, prior to fall ripening.

Plant macrofossil assemblages from Middle Holocene deposits in central California are more than twice as common as those from the preceding period (Table 2). One hundred and seventy-eight samples have been recovered from 21 sites radiocarbon dated between 7,820 and 2,585 cal B.P., with 100 of 108 radiocarbon dates falling between 7,820 and 4,320 cal B.P. Excluding near-surface samples from SBA-54, all archaeobotanical samples derive from buried stratigraphic contexts. Every sample from 14 sites and 29–92% of samples from seven other sites contain acorn hulls (Table 2). Gray pine nutshell was identified in almost half (9 of 21) of the Middle Holocene sites, occurring in 20% to 100% of the samples. Because gray pine is endemic to the foothills of the Coast Ranges and Sierra Nevada, the lack of this species in sites from the Santa Clara Valley (Laguna Socayre site), Central Valley (COL-247, SAC-1142, SAC-38, GLE-701) and those near the coast (SBA-54 and SCR-313) may be related to its absence in local habitats. Bay nutshell reveals perhaps the most substantial difference in ubiquity through time, occurring in 39% of Middle Holocene samples, compared to just 8% from the Early Holocene. However, this might simply be related to the comparatively high number of Middle Holocene sites from the interior Coast Ranges, where bay trees are abundant. All but one (92%) site from that region contain bay nutshell, whereas just one of nine (11%) sites from elsewhere in central California includes that species.

The relative importance of acorn is also indicated by its ratio to small seeds in Early and Middle Holocene contexts (Table 3; Fig. 4). At the five Early Holocene sites where acorn is present, four have more acorn than small seeds, with ratios ranging between 2.50:1 and 10.75:1, with the fifth producing nearly equal counts of both plant foods (0.74:1). Similar ratios are found among 16 of the 21 Middle Holocene assemblages, where acorn-to-small seed ratios range from 0.28:1 to 11.20:1. Two other assemblages have slightly higher ratios (13.55:1 and 17.77:1), while the remaining three show a much more dominant presence of acorn (30.85:1, 40.33:1, and 133.99:1).

THE ARCHAEOLOGICAL RECORD OF MILLING TOOL USE IN CENTRAL CALIFORNIA

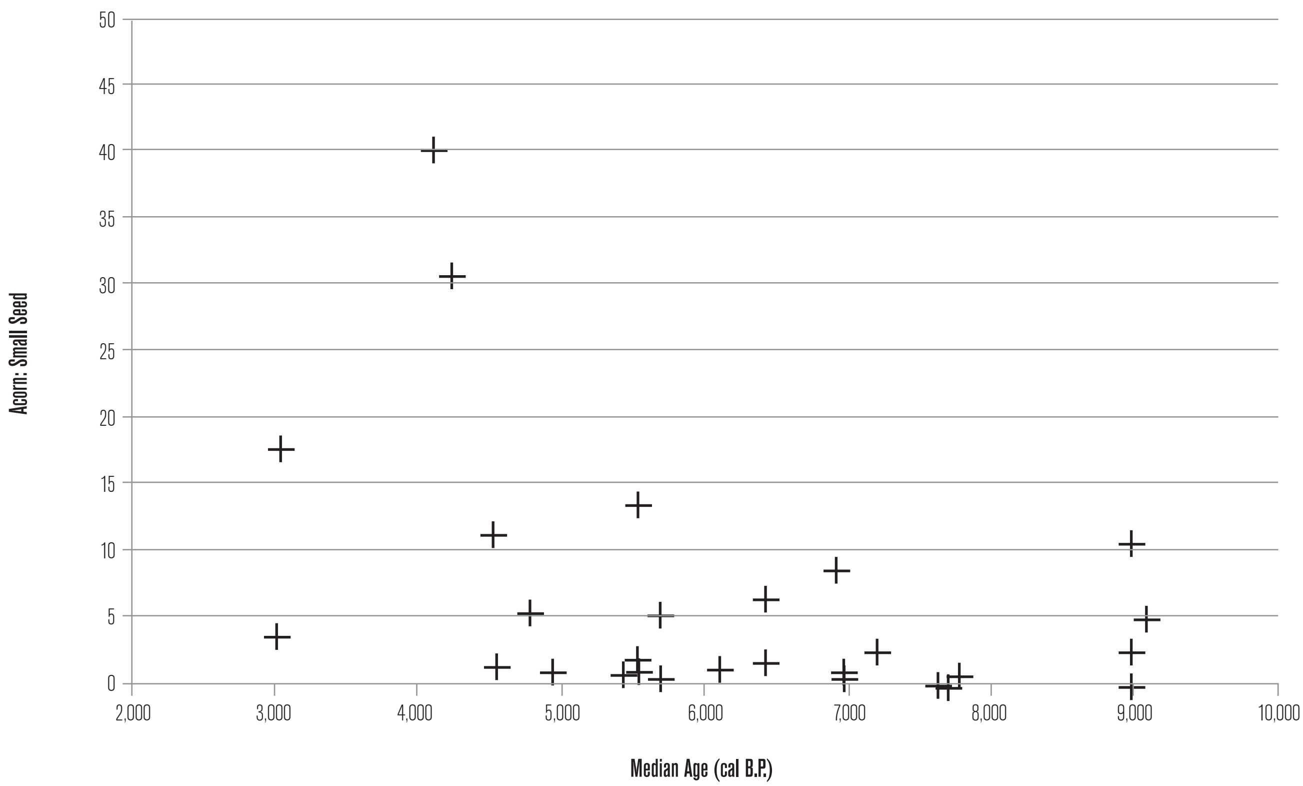
To better define the relationship between plant foods and milling tools in central California, Table 4 identifies ground-stone tools from 42 stratified and single component sites dating to the Early and Middle Holocene, including 26 sites with archaeobotanical assemblages (discussed above). For comparative purposes, ground-stone tools reported from ten Late Holocene strata are also included (Table 4; Fig. 5). In total, the 42 site components produced 2,560 pieces of complete and fragmentary ground stone, including 354 bowl mortars, 465 pestles, 1,010 hand-stones, and 731 milling-slabs.

The stratigraphic distribution of bowl mortars and pestles clearly indicates that these milling tools were not widely used in most regions of central California until after about 6,900 cal B.P. (Fig. 5). Hand-stones and milling-slabs are the only plant processing tools from Early Holocene coastal deposits dated between 10,200 and 6,150 cal B.P., including Cross Creek (SLO-1797), Pismo Beach (SLO-832), and Duncan's Landing (SON-348/H). Middle Holocene coastal deposits dating after 6,150 cal B.P. all contain bowl mortars and pestles, including Aero Physics (SBA-53), Corona Del Mar (SBA-54), Diablo Canyon (SLO-2), Nursery (MRN-67),

Table 3

ACORN TO SMALL SEED RATIOS FROM STRATIFIED AND SINGLE COMPONENT EARLY AND MIDDLE HOLOCENE SITES

Sites	# Samples	Acorn: Small Seed Ratio	Median Age cal B.P.
EARLY HOLOCENE			
Pacific Coast and Vicinity			
SON-348	2	0.00:1	7,605
SLO-832	7	0.74:1	7,690
SLO-1797	8	0	7,539
Northern Coast Ranges			
ALA-684	23	0.00:1	8,880
CCO-696D	10	10.75:1	8,880
P-48-897	1	2.50:1	8,865
Sierra Nevada Foothills			
CAL-629/630	10	5.03:1	8,985
TUO-2797/H	10	8.80:1	6,850
MIDDLE HOLOCENE			
Southern North Coast Ranges			
LAK-72E-A	1	1.36:1	4,494
LAK-510W-C	6	17.77:1	3,005
LAK-509/881	1	0.88:1	6,880
SON-2098	5	0.60:1	5,360
NAP-916	3	5.07:1	5,625
SOL-468	7	0.44:1	6,900
MRN-67	9	11.20:1	4,475
Northern Diablo and Central Coast Ranges			
CCO-637	10	30.85:1	4,190
CCO-309	4	5.47:1	4,735
CCO-18/548, Lower	5	1.26:1	6,045
Laguna Socayre	3	0.28:1	5,630
SCR-313	14	1.79:1	5,460
Pacific Coast			
SBA-54	3	1.00:1	5,485
Sacramento Valley			
COL-247	9	3.54:1	2,980
GLE-701	16	1.74:1	6,340
SAC-1142	9	6.34:1	6,343
SAC-38	22	2.44:1	7,125
Sierra Nevada Foothills			
CAL-789	12	40.33:1	4,055
FRE-61	3	0.95:1	4,885
TUO-4559	34	13.55:1	5,465
AMA-34	2	133.99:1	4,850



Note: Does not include anomolously high ration of 134:1 from AMA-34.

Figure 4. Acorn to small seed ratios from stratified and single component Early and Middle Holocene sites.

and West Berkeley mound (ALA-307) on San Francisco Bay. All of these latter sites have diversified artifact and feature assemblages, as well as human graves, consistent with relatively high levels of residential stability.

Similar sequences have been identified elsewhere in central California, including strong correlations between the introduction of bowl mortar/pestle technology and subsistence resources representing multiple seasons of occupation, domestic features, evidence of long-distance shell bead and obsidian exchange, and multiple human burials. At the Los Vaqueros Reservoir locality in the northern Diablo Range (CCO-696 and CCO-458), hand-stones and milling-slabs were found exclusively in the Early Holocene Kellogg paleosol, dated between 7,400 and 11,000 cal B.P. However, overlying strata in the valley floodplain, younger than 6,400 cal B.P., included only bowl mortars and pestles (Meyer and Rosenthal 1997). That these latter tools were used exclusively at Los Vaqueros during the Middle Holocene is clearly indicated at nearby site CCO-637, where bowl mortars and pestles are the singular plant processing tools found in deposits dated between 5,700 and 2,600 cal B.P. This pattern appears to prevail throughout the valleys of the northern Diablo Range, as bowl mortars and pestles are by far the dominant milling tools reported in Middle and Late Holocene strata at Stone Valley (CCO-308), Laguna Oaks (ALA-483), Rossmoor (CCO-309), and the Marsh House (CCO-18/548), all dated between 6,200 and 2,830 cal B.P. In the Santa Clara Valley, several hand-stones and milling-slabs are reported from the Middle Holocene component at SCL-65, dated between 7,350 and 6,850 cal B.P., whereas one mortar and one pestle were the only milling tools found in the Middle Holocene stratum at the Classic Residence site (SCL-623/H), dated between 5,160 and 4,030 cal B.P.

In the Central Valley, Early and Middle Holocene sites are quite rare, although the available evidence indicates bowl mortars and pestles were in use by 7,000 to 5,000 cal B.P. The oldest ground-stone assemblages are from Middle Holocene sites GLE-701, on the Sacramento

Table 4

RADIOCARBON-DATED EARLY AND MIDDLE HOLOCENE GROUND STONE ASSEMBLAGES FROM STRATIFIED AND SINGLE COMPONENT SITES

Site	Reference	Stratum	BM	PES	HND	MLG	^{14}C Range (cal B.P.)	# of Dates
Sierra Nevada, Foothills								
Skyrocket (CAL-629/630)	LaJeunesse and Pryor (1996)	Green, Black, and Gray Clay	–	–	61	206	10,200–7,765	7
		Tan-gravelly Clay	6	20	43	5	7,500–5,980	5
		Olive Silt and Black Clay	4	2	13	16	4,470	1
		Brown Clayey Silt	12	8	38	10	4,415–2,720	3
		Surface Loam	11	48	179	26	1,965–465	5
Clarks Flat (CAL-342)	Peak and Crew (1990)	Spit B	–	–	134	104	7,470–1,940	6[a]
		Spit A	–	–	9	8	610–355	3
Black Creek (CAL-789)	Rosenthal and McGuire (2004)	Stratum II	5	7	18	26	5,390–2,720	8
		Stratum III	–	1	2	3	1,210	1
Taylors Bar (CAL-1180/H)	Milliken et al. (1997)	Stratum III	–	1	1	–	10,715–1,905	2
		Stratum II	11	5	31	11	970–390	3
Edgemont Knoll (TUO-4559)	Meyer (2008)	Stratum II	8	4	133	107	6,510–4,415	23
Poppy Hills (TUO-2797/H)	Whitaker and Rosenthal (2010a)	Stratum II	1	3	10	1	3,635–530	4
		Stratum I	–	–	5	6	8,850–4,850	3
Wahtoke Creek (FRE-61)	McGuire (1995)	Stratum II	–	–	17	8	6,760–3,010	2
		Stratum I	–	2	14	–	2,420	1
Defender Grade (AMA-34)	Whitaker and Rosenthal (2010b)	Locus F	–	–	1	5	4,850	1
North Coast Ranges								
SHA-1169	Basgall and Hildebrandt (1989)	Stratum 1b, Feature 6	–	–	29	20	5,830–3,570	2
Mostin (LAK-380/381)	White and King (1993)	Buried midden	1	1	5	2	13,260–7,770	3[b]
Crazy Creek (LAK-1682)	Rosenthal et al. (1995)	Feature 2	–	–	12	4	8,145	1
LAK-509/881	Compas et al. (1994)	above Buried soil	–	–	1	1	<6,880	1
Creager (LAK-510)	White et al. (2002)	WC-1	–	–	4	8	3,005	1
Anderson Ranch (LAK-72)	White et al. (2002)	EA-2	–	–	4	8	4,494	1
		EA-1	2	17	1	–	1,735–1,214	3
Huichica Creek (NAP-189/H)	Basgall et al. (2015)	Middle Archaic Component	4	2	1	3	4,705– 3,765	6
Memorial Hospital (SON-2098)	Origer (1993)	Layer 3	3	1	4	2	5,590–5,130	2
Laguna Creek (P-48-897)	Hildebrandt et al. (2012)	2Ab	–	–	1	–	8,865	1
Alamo Basin (SOL-468)	Rosenthal and Whitaker (2017)	Stratum II	1	–	1	–	8,100–6,700	4
Northern Diablo Range								
Los Vaqueros (CCO-696, -458)	Meyer and Rosenthal (1997)	Kellogg Paleosol	–	–	6	3	10,355–7,400	6
		Vaqueros Paleosol	25	37	–	–	7,210–690	14
		Brentwood Alluvium	1	15	–	–	665–250	5
Los Vaqueros (CCO-637)	Meyer and Rosenthal (1998)	Stratum I	5	18	–	–	5,795–2,585	7
Marsh House (CCO-18/548)	Wiberg (2010)	Upper Component	50	95	9	8	5,555–3,215	188
	Rosenthal (2010)	Lower Component	–	–	2	3	7,060–5,025	9
Stone Valley (CCO-308)	Fredrickson (1966)	Stratum C	5	1	–	–	5,030–2,990	2
		Stratum B	5	6	1	–	2,955–1,160	3
		Stratum A	3	1	–	–	950–470	4
Rossmoor (CCO-309)	Price et al. (2006)	Stratum I	6	7	2	1	5,050–4,420	3
Laguna Oaks (ALA-483)	Bard et al. (1992); Wiberg (1996)	–	4	8	–	–	6,180–2,830	4
Fremont Site (ALA-684)	Meyer (2015)	2Ab Horizon	–	–	1	–	9,560–8,200	6
Classic Residence (SCL-623/H)	Morley (2004)	2Ab horizon	1	1	–	–	4,030–5,160	5

Table 4 *(Continued)*

RADIOCARBON-DATED EARLY AND MIDDLE HOLOCENE GROUND STONE ASSEMBLAGES FROM STRATIFIED AND SINGLE COMPONENT SITES

Site	Reference	Stratum	BM	PES	HND	MLG	^{14}C Range (cal B.P.)	# of Dates
Central Coast Ranges								
Saratoga Site (SCL-65)	Fitzgerald (1993)	Component 3	–	–	6	3	7,350–6,850	2
Scotts Valley (SCR-313)	Jones et al. (2000)	Stratum III	–	–	3	5	5,935–4,985	2
Diablo Canyon (SLO-2)	Jones et al. 2008	Component II	3	4	8	–	6,260–5,270	7[c]
Cross Creek (SLO-1797)	Fitzgerald (2000)	Stratum 3Ab	–	–	21	21	10,295–4,780	16[d]
Scotts Valley (SCR-177)	Cartier (1993)	Area B and BB, > 50 cm.	–	–	15	3	10,970–8,500	5
Central Valley								
Reservation Road (COL-247)	White (2003)	Stratum 3	–	1	3	–	4,385–3,575	3
		Stratum 2	–	–	14	2	3,205–2,755	2
		Stratum 1	–	3	2	-	2,755–1,675	3
Hamilton City (GLE-701)	Hildebrandt and Kaijankoski (2010)	Stratum I	–	–	33	4	7,300–6,100	7
Blossom Mound (SJO-68)	Ragir (1972); Schulz (1981)	–	31	3	1	4	5,000–3,195	7
City Hall (SAC-38)	Tremaine (2008)	–	14	23	1	1	7,125–6,670	3
Coastal/Bay								
Duncans Landing (SON-348/H)	Schwaderer (1992)	Stratum VI	–	–	2	1	8,000–7,210	2
Nursery Site (MRN-67)	Schwitalla and Powell (2014)	Stratum 1	3	2	–	–	4,860–3,895	16
West Berkeley (ALA-307)	Wallace and Lathrop (1975)	>300 cm.	37	56	–	–	4,960–2,880	24
Pismo Beach (SLO-832)	Jones et al. (2002)	Stratum II	–	–	2	2	9,315–6,065	11
Corona Del Mar (SBA-54)	Levulett et al. (2002)	Stratum II/III	23	5	38	20	6,155–4,810	15[e]
Aero Physics (SBA-53)	Levulett et al. (2002)	–	69	57	68	60	6,105–5,580	6

[a]Excludes one intrusive date of 505 cal B.P.

[b]Charcoal dates only.

[c]Excludes one date of 3,490 cal B.P.

[d]Excludes one date of 1,910 cal B.P.

[e]Excludes one date of 8,905 cal B.P.; BM – Bowl mortar; PES – Pestle; HND – Hand-stone; MLG – Milling-slab.

River near Chico, and SAC-38 at the confluence of the Sacramento and American rivers, in downtown Sacramento. At GLE-701, only milling-slabs and hand-stones were recovered from a buried Middle Holocene deposit dated between 7,300 and 6,100 cal B.P. In contrast, 95% of the 39 milling tools and fragments from SAC-38 are mortars and pestles, found in buried dune deposits dated between 7,580 and 6,670 cal B.P. Middle Holocene deposits at Reservation Road (COL-247) and the Blossom Mound (SJO-68), dated between 5,000 and 3,195 cal B.P., include both bowl mortars and pestles, and hand-stones and milling-slabs. Likewise, in the southern North Coast Ranges, both types of milling technologies were documented in the Middle Holocene stratum (5,590–5,130 cal B.P.) at the Memorial Hospital site (SON-2098) and the Middle Archaic component (4,705–3,765 cal B.P.) at the Huichica site (NAP-189). A single hand-stone was identified in the buried, Early Holocene Laguna Creek site (P-48-897), dated to 8,865 cal B.P., while a mortar and pestle, along with several hand-stones and milling-slabs, was reported from the deeply buried Mostin site (LAK-380/381), just west of Clear Lake. Although radiocarbon dates between 13,300 and 7,700 cal B.P. indicate these are the oldest documented mortars and pestles in central California (Moratto 1984), problems with "old carbon" contamination in dated bone samples cloud the true antiquity of these tools (White and King 1993). Nevertheless, wood charcoal from hearth features at the Mostin site consistently date older than 7,000 cal B.P. Likewise, one of the oldest bowl mortars known

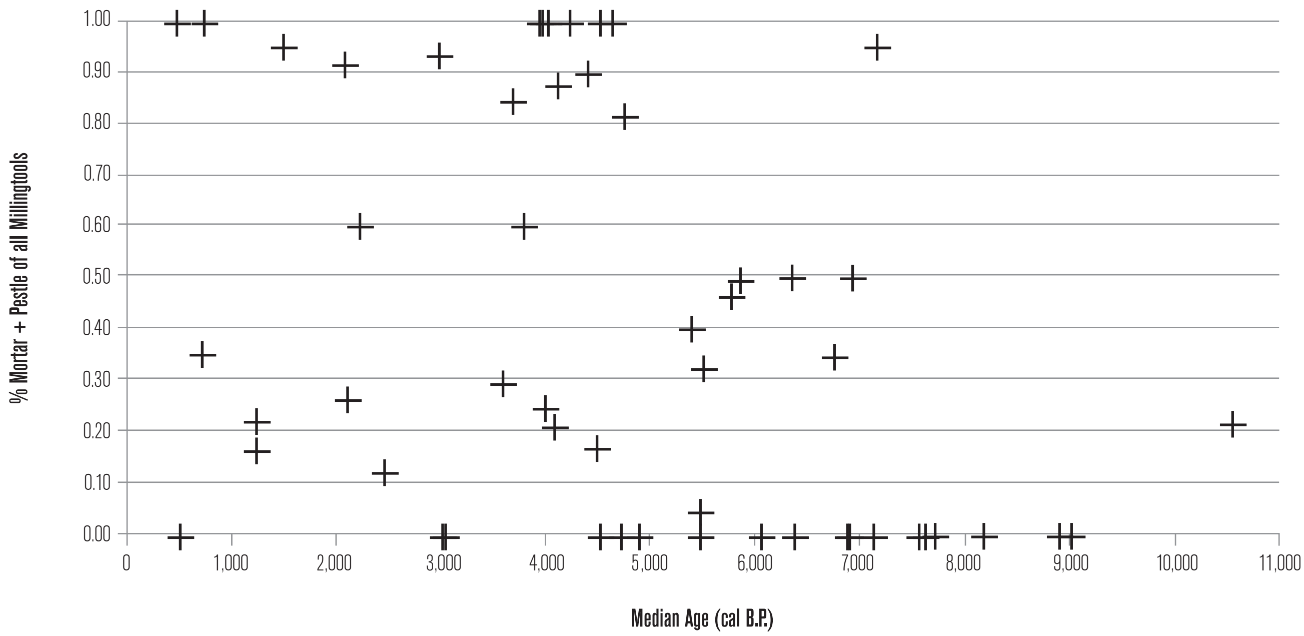


Figure 5. Proportion of bowl mortars and pestles of all milling tools by median calibrated age.

from central California comes from a buried stratum at the Alamo Basin site (SOL-468), dated no later than 6,700 cal B.P. (Rosenthal and Whitaker 2016).

In the Sierra Nevada foothills, only hand-stones and milling-slabs are reported from the Early Holocene Green, Black, and Gray clay strata at the Skyrocket site (CAL-629/630), dated between 10,200 and 7,500 cal B.P. The overlying tan-gravelly clay stratum (dated 7,500 to 4,500 cal B.P.) includes both hand-stones and milling-slabs and bowl mortars and pestles (see Table 4), while middle Holocene strata and pit features at the Edgemont Knoll site (TUO-4559), dated between 6,510 and 4,415 cal B.P., contained large numbers of hand-stones and milling-slabs, but just a few bowl mortars and pestles.

At several Middle Holocene sites in the Sierra Nevada foothills and Coast Range uplands (7,060–3,010 cal B.P.), hand-stones and milling-slabs are the only plant processing implements reported, including Clarks Flat (CAL-342), Poppy Hills (TUO-2797/H), Wahtoke Creek (FRE-61), Anderson Ranch (LAK-72), SHA-1169, and SCR-313. The absence of bowl mortars and pestles at these sites confirms geographic and temporal differences in the adoption of this technology during the Middle Holocene.

PLANT FOODS, MILLING TOOLS, AND ENERGY MAXIMIZING/TIME MINIMIZING ADAPTIVE STRATEGIES IN CENTRAL CALIFORNIA

Previous discussions of acorn use in central California have always directly or indirectly considered the energetic demands of acorn exploitation relative to the costs associated with the collection and processing of other plant resources—particularly small seeds—without actually demonstrating the relative energetic costs associated with these alternative food sources (Basgall 1987; Glassow 1996; Wohlgemuth 1996, 2004). As outlined above, however, new information on the productivity of a range of plant foods found in central California, coupled with the seasonal disparity in ripening of acorns and small seeds, leaves little doubt that acorns are not the “costly” resource often asserted.

We have also shown that acorns and pine nuts were commonly processed with the hand-stone and milling-slab during the Early and Middle Holocene across central California, and with the mortar and pestle in numerous locations, after about 6,900 cal B.P. Furthermore, there is considerable variability in the timing and geographic distribution of these different types of milling tools in central California (see also Basgall 1987; Stevens and McElreath 2015), with bowl mortars and pestles first widely used along the central California coast and interior valleys, and later, in the uplands of the North Coast and Sierra Nevada mountain ranges. Since there is not a strong correlation between milling technology and the foods being processed, what accounts for the persistence of hand-stones and milling-slabs in some areas and the early adoption of bowl mortars and pestles in others? Basgall (1987) has suggested that population-resource imbalances mandating more intensive regional subsistence strategies occurred differentially across central California, resulting in considerable temporal discontinuity in the persistence or adoption of these contrasting milling technologies. We agree and think that use of the mortar and pestle signals not simply a reliance on acorns, but a significant structural transformation in the organization of production related to a greater seasonal dependence on stored plant foods (Basgall 1987; Jackson 1991; McGuire and Hildebrandt 1994; Testart 1982).

We also think that the presence of different milling technologies in the archaeological record of central California can be viewed as an indicator of differing patterns of settlement mobility and land use, in much the same way that flaked-stone toolkits are thought to be related to these same aspects of prehistoric economies (e.g., Bamforth 1986; Kelly 1988; Nelson 1991). In other words, like flaked stone tools, the design of different types of plant processing implements results from attempts to maximize functionality, given the constraints imposed by the environment, mobility, and the broader economic system. As such, milling tool design stems from several variables specific to the context of use, and relates directly to the overall efficiency within the wider settlement system (Nelson 1991; Nelson and Lippmeier 1993). As measured by the currencies of time and energy, milling tool design should balance functional efficiency with the energetic costs of material acquisition, manufacture, transport, and the planned period of use (Buonasera 2015, 2018; Horsfall 1987; Nelson 1991; Nelson and Lippmeier 1993; Ugan et al. 2003).

From this perspective, hand-stones and milling-slabs represent a comparatively expedient technology that functioned well within a settlement-subsistence system organized around frequent residential moves (e.g., a forager system). This type of adaptive system has been characterized by Woodburn (1980, 1982) as immediate-return, in that labor expenditures result in direct, near-term economic benefits. Such systems are also typical of what Bettinger (2001) describes as time-minimizing adaptive strategies. Under such systems, storage is minimal, and technology is comparatively simple (Bettinger 1991:69; Woodburn 1982). With regard to the latter characteristic, hand-stones and milling-slabs require little initial manufacture, as appropriately shaped cobbles are naturally abundant in most settings of central California (except for the alluvial plains of the Central Valley), and subsequent maintenance can be accomplished with relatively little additional work (Buonasera 2015). Because of the low initial investment in these tools, more available labor can be directed toward the collection and requisite processing of targeted resources. Abandonment of these tools upon moving to new foraging locations sacrifices little in the way of overall time/labor expenditures. Thus, in the context of high residential mobility, the use of hand-stones and milling-slabs does not unduly encumber extraction and processing with additional labor costs, minimizing the effects that investment in technology may have on foraging efficiency. In addition, hand-stones and milling-slabs appear to comprise a very flexible technology, another hallmark of forager systems featuring time-minimizing strategies (Bettinger 1991:69). Presumably there is no morphological impediment to either pounding or grinding with these tools, and a single tool can therefore capably perform a variety of tasks (Hale 2001; Mikkelsen 1985).

In contrast, use of the bowl mortar and pestle likely signals a more residentially stable pattern of land use—referred to variously as a collector or processor strategy (Bettinger and Baumhoff 1982; Binford 1980)—in which energy-maximizing goals result in high degrees of storage, territorialism, and greater social complexity (Bettinger 2001). Such an adaptive strategy emphasizes delayed-return, in that the benefits of labor are not immediate, and storage and technological investment are high (Bettinger 1991; Woodburn 1980, 1982). In this respect, the mortar and pestle constitute a substantially greater technological investment than the hand-stone and milling-slab. To achieve a functional bowl mortar, a significant amount of time/energy must be invested. For example, experimental studies by Leventhal and Seitz (1989:156–165) and Schneider and Osborne (1996) have shown that it takes between about 8 and 17.2 hours of labor to create a single functional mortar cup, depending on the material type and manufacturing technique involved (see also Buonasera 2015). This is not an unreasonable manufacturing commitment if the expected period of use is long and the technology confers sufficient benefit in terms of increased processing efficiency (Bettinger et al. 2006; Stevens and McElreath 2015; Ugan et al. 2003). Additional experimental studies support this proposal, as bowl mortars and pestles have been shown to be more efficient than hand-stones and milling-slabs in processing a variety of resources, including acorns and small seeds (Buonasera 2018). By reducing processing time and unnecessary waste, significant increases in caloric return rates can be achieved (see also Bettinger 1991; Bettinger et al. 1997).

Mortar and pestle technology is probably less efficient in the context of high residential mobility for several reasons. Although these tools are sometimes described as "portable," they characteristically weigh in excess of nine kilograms (19.8 pounds), and it seems unlikely that carrying heavy implements from one locality to the next was a viable long-term strategy (this is especially true as high mobility mandates the transport of personal gear, young children, any excess provisions, etc.). Thus, manufacturing a mortar at each new foraging location would result in hundreds of hours of labor annually that could have been devoted directly to the collection and processing of plant and animal foods. More importantly, time-minimizing adaptations featuring high residential mobility invest little in technology designed to fully maximize productivity (Woodburn 1980, 1982). Instead, as foraging efficiency declines, labor is simply redirected to more productive resources or resource patches (Bettinger 1991; Binford 1979; Stevens and McElreath 2015).

While it is likely that bowl mortar and pestle use would be minimal in contexts of high residential mobility, there is no reason to believe hand-stones and milling-slabs would be totally excluded from situations of low residential mobility. For example, seasonal differences in residential mobility within the same settlement-subsistence system could result in the use of hand-stones and milling-slabs during one part of the year (e.g., spring and summer), and bowl mortars and pestles during another (e.g., fall and winter). However, as residential mobility decreases and logistical foraging and storage increases, reliance on the mortar and pestle or other more formal, efficient, milling tools is expected to increase, as well.

THE ARCHAEOLOGICAL RECORD OF MILLING TOOLS AND MOBILITY

Confirmation of the relationship between different milling technologies and variability in residential mobility can be found in a variety of places in central California, and is best illustrated through comparing chronological sequences from contrasting environmental settings. There is little doubt that most of California's earliest inhabitants were comparatively mobile, practicing a foraging strategy organized around the seasonal availability of different plant and animal foods (Hildebrandt 1983; Hull and Moratto 1999; Jones and Klar 2007; McGuire and Hildebrandt 1994; Moratto 1984, 1988). As noted above, acorn, nut, and small-seed crops were commonly used during the Early Holocene, and hand-stones and milling-slabs are found exclusively in these assemblages. Early Holocene sites also evince the most seasonally-specific plant food assemblages, suggesting that storage of off-season resources was minimal during this time period. Likewise, as we have argued elsewhere (Rosenthal 2008a, 2011; Rosenthal et al. 2007), foraging groups in the Sierra Nevada, for example, appear to have remained seasonally mobile throughout the Archaic Period (e.g., up to at least 1,100 cal B.P.). Hand-stones and milling-slabs comprise the great majority of milling tools used in the Sierra Nevada during this period to process acorns, pine nuts, and other plant foods, long after bowl mortars and pestles were introduced elsewhere.

Since it is predicted that hand-stones and milling-slabs should essentially be disposable tools in many contexts, given low initial time/labor investments relative to bowl mortars and pestles (Buonasera 2015, 2018), it is also not surprising that they are often found in overwhelming abundance at sites in the Sierra Nevada foothills (e.g., LaJeunesse and Pryor 1996; Peak and Crew 1990; Rosenthal 2008b, 2011), probably reflecting the residues of seasonal occupation over many millennia. For example, the Middle through Late Holocene-age Hess House site (TUO-4513) in Sonora and Early Holocene strata at the Skyrocket site (CAL-629/630) produced more than 200 milling-slabs each. Other enormous collections of hand-stones and milling-slabs are reported from the Sierra Nevada (TUO-4559; Meyer 2008), southern North Coast Ranges (LAK-1683; Rosenthal et al. 1995), and central California (e.g., SLO-1797; Fitzgerald and Jones 1999; see also Hale 2001), in situations thought to be associated with time-minimizing and comparatively mobile adaptations.

At the other extreme, bowl mortars and pestles are ubiquitous in virtually all Late Holocene central California sites that evince substantial residential continuity (Bickel 1981; Davis and Treganza 1959; Fredrickson 1974; Lillard et al. 1939; Moratto 1984; Wallace and Lathrap 1975). The Late Holocene mounded villages of San Francisco Bay contain these tools almost exclusively (e.g., Beardsley 1954; Bickel 1981; Davis and Treganza 1959; Kroeber 1925:926; Wallace and Lathrap 1975), as do the mounds of the Delta Region (Bouey 1995; Lillard et al. 1939). In fact, bowl mortars and pestles are nearly twice as common in Sacramento Valley sites as those in the adjacent Sierra Nevada and Coast Ranges (see Fig. 6), but milling tools overall appear less abundant in the lowlands, occurring at a frequency of about 20 tools per site (i.e., 632 tools/32 sites) compared to almost 40 tools per site (872 tools/22 sites) in the Sierra. Similar relationships have been revealed in Glenn and Colusa counties (White et al. 2009:213), where the ratio of milling implements to flaked stone tools in early components, pre-dating the bowl mortar/pestle (1:1.1), is many times higher than in later dating contexts after bowl mortars and pestles became an important part of the subsistence technology (1:17.5). These patterns confirm Horsfall's (1987) prediction that archaeological visibility of milling tools should be low in residential situations, but comparatively high in settlement systems featuring a "seasonal round." This is directly related to the amount of time and energy invested in milling tool production in each situation; they are highly curated in sedentary settings and largely disposable within more mobile settlement systems.

It also follows that in more sedentary situations, where bowl mortars and pestles were used, storage of acorns would have been a primary economic strategy. Their high caloric return relative to small seeds (see Fig. 1) and the comparatively low cost required to harvest an annual supply (Whalen et al. 2013) would have made acorns a preferred resource for storage and consumption during winter and early spring (even with storage losses due to mold, bug infestations, and theft by rodents) when alternative resources were scarce. In fact, the much higher energetic return compared to small seeds would have made the use of stored acorns attractive even during summer, when these alternative resources were locally available.

When we consider the sample of 26 Early and Middle Holocene sites that include both milling tools and archaeobotanical remains (Fig. 7), there is little correlation between acorn abundance and initial adoption of the mortar and pestle. As shown in Figure 7, prior to about 5,500 cal B.P., moderate frequencies of acorn often correspond to an exclusive use of hand-stones and milling-slabs. The few sites with mortars and pestles older than 5,500 cal B.P. include acorn in proportions similar to, or slightly lower than, all other sites from this time interval. After 5,500 cal B.P., high ratios of acorn to small seeds are documented at two sites that include mortars and pestles (i.e., CAL-789, 40.33:1; CCO-637, 30.85:1), but a third site, which has by far the highest proportion of acorn in the entire sample (AMA-34, 133:1), contains only hand-stones and milling-slabs. These relationships suggest to us that the use of one technology versus the other is largely

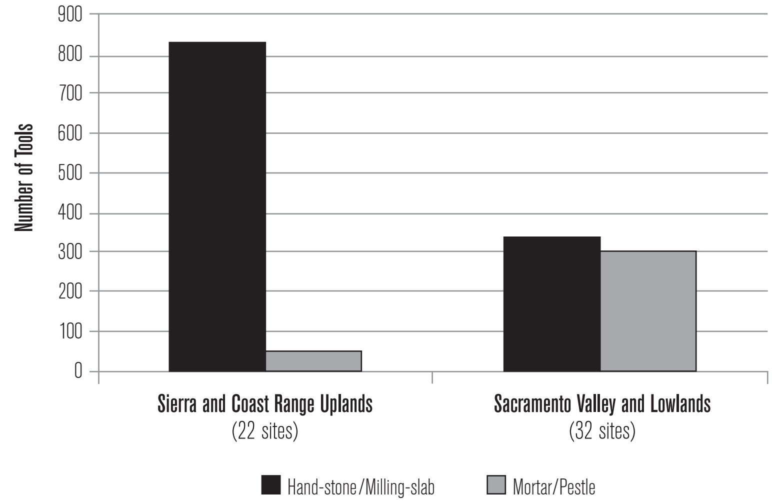


Figure 6. Late Holocene milling tools from the Central Valley and adjacent Sierra Nevada and Coast Range Uplands.

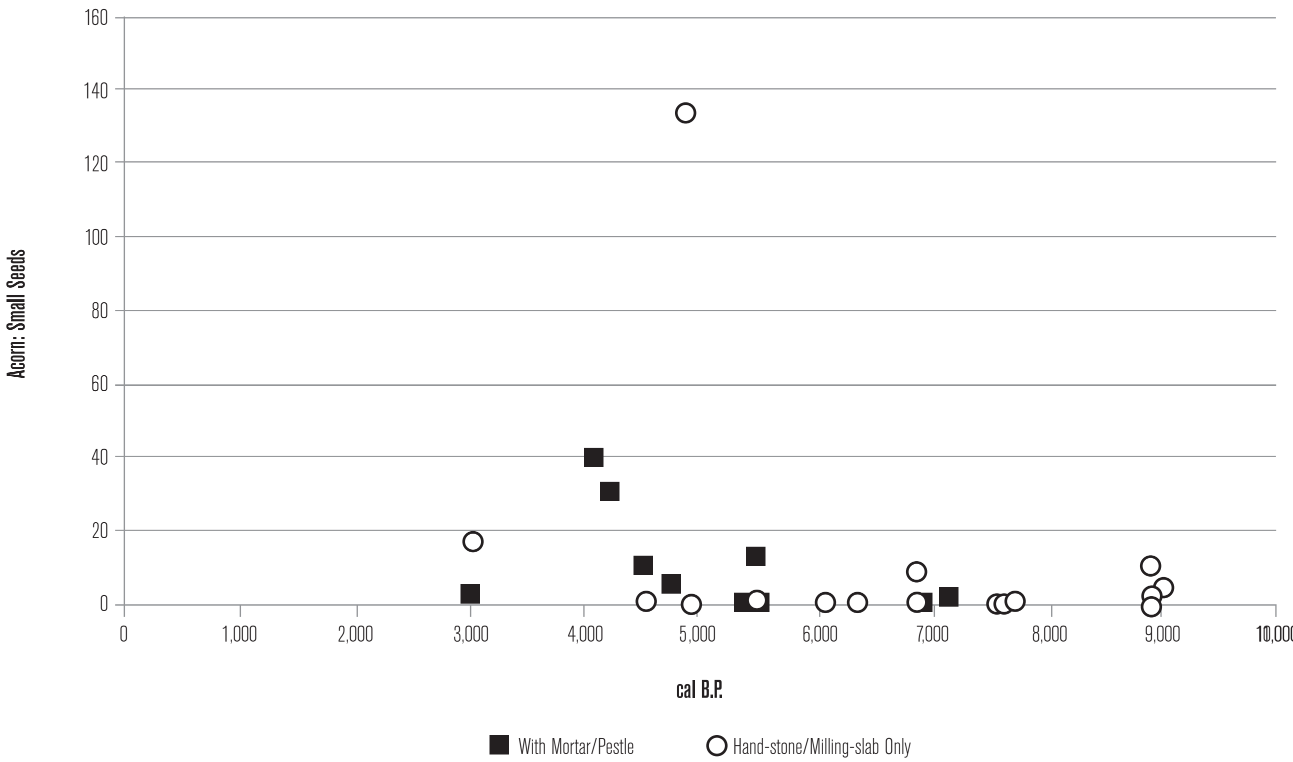


Figure 7. Acorn to small seed ratios and associated milling tools from stratified and single component Early and Middle Holocene sites.

independent of the types of resources processed. However, there is indeed a higher average proportion of acorn after 5,500 cal B.P. at those sites where bowl mortars and pestles were used (13.2:1) compared to all earlier sites (2.6:1), regardless of tool type (Fig. 7). This further suggests to us that storage and the off-season use of acorn first increased during the Middle Holocene in tandem with a greater investment in milling tools.

SUMMARY AND CONCLUSIONS

For many years, based largely on ethnographic analogy, California archaeologists have thought that bowl mortars and pestles were primarily used to process acorns, and hand-stones and milling-slabs were used to process small seeds. Because hand-stone and milling-slab technology was dominant in most parts of California during the Early and Middle Holocene, and mortar-pestle technology remained rare until the Late Holocene, it was concluded that acorns were not a primary resource until relatively late in time, perhaps due to the high costs associated with leaching tannic acid from the meal. But it is important to note that these conclusions were based on an archaeological record that lacked plant macrofossils.

Based on thousands of archaeobotanical assemblages generated over the last few decades, we now know that many of the above assumptions and conclusions about acorn use are incorrect. First, acorns were eaten throughout the Holocene, and in fact the consumption of small seeds actually increased in some regions late in time, contrary to expectations generated by the milling gear. Second, this finding makes perfect sense from the standpoint of Optimal Forging Theory, because caloric return rates for acorns, even accounting for tannic acid leaching, are significantly higher than for small seeds. Third, rather than being correlated with resource type, milling technologies appear to be more strongly linked to settlement organization. This latter point is supported by experimental studies showing that bowl mortars and pestles are more efficient for processing all plant-food types, including acorns and small seeds, but require a much greater investment in their manufacture than is the case with hand-stones and milling-slabs (Buonasera 2018). Because milling gear is too costly to carry great distances, an investment in bowl mortars and pestles should only occur among relatively sedentary people, and we have demonstrated that this was the case with multiple examples from throughout precontact central California.

The latter point brings us back to the ethnographic record and perceived correlations between milling technology and resource type. Hand-stones and milling-slabs were not widely used in central California during the early post-contact period, but they were the main technology used in the Great Basin, often to process small seeds. Great Basin family bands were also quite mobile, leading to the use of a more expedient, disposable milling technology. It is also true that most central California groups used bowl mortars and pestles to process acorns, but the majority lived in fixed villages within stable settlement systems, making it profitable to invest in tools that could last a lifetime or more. While acorns were clearly important for the latter groups, and contributed greatly to high levels of settlement stability, the archaeological and ethnographic records show that small seeds were also an important part of the subsistence economy late in time, when mortar-pestle technology was used almost exclusively.

So why was there an expansion in small seed use late in time, especially given that acorns and small seeds never competed with one another due to their differential seasonal availability? We think this pattern probably reflects the growing importance of the storage of off-season resources, rather than simply the importance of one type of plant food relative to another (e.g., acorns versus small seeds). As human population densities increased in central California, labor throughout the entire year shifted towards surplus production of plant foods for use during winter and early spring, when all types of foods were scarce. Previously, the storage of acorns, pine nuts, and other fall-ripening nuts was sufficient to bridge seasonal deficits in productivity. As populations increased during the Late Holocene, and foraging territories decreased (i.e., with increasing territorial circumscription), it was necessary to extend the period of surplus production throughout the year (including small seeds), emphasizing the extent to which storage of off-season resources became an important component of prehistoric economies through the Late Holocene in central California.

With these considerations in mind, it seems probable that the adoption of the bowl mortar and pestle in central California marked a significant economic transformation that began in lowland regions during the Middle Holocene. Although archaeobotanical evidence does not show that specific plant foods were correlated with diachronic changes in milling technologies, it seems certain that the nature of plant exploitation did indeed change, reflecting increased storage and the use of off-season resources. This transformation appears to track with evolving patterns of labor organization, increasing residential stability, and the overall intensity of plant use. The shift identified in milling technologies, therefore, represents a transition from time-minimizing to energy-maximizing adaptations, a development which did not occur in all regions of central California at the same time, reflecting local thresholds in population density and resource productivity. If this is correct, residentially-tethered adaptations began much earlier in central California than traditionally assumed, first in productive coastal and interior valley habitats, and later in the mountains of the Coast Ranges and the Sierra Nevada.

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