WHEN ARE TWO TOOLS BETTER THAN ONE? MORTARS, MILLINGSLABS, AND THE CALIFORNIA ACORN ECONOMY

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The question investigated by this study is: how much behavioral specialization is necessary before tool specialization is worthwhile? The toolkits of hunter-gatherers vary considerably over space and through time from simple and multifunctional, to complex and specialized. The decision to use one tool over another can be modeled as a fairly straightforward consideration of costs and benefits, but the problem becomes more complex when individual tools are employed in multiple tasks. We introduce a formal model that helps explain when and why multi-use, or flexible tools, might outperform specific-use, or specialized tools, or *vice versa*. This model is used to help understand the adoption of mortars when acorns became a staple food in prehistoric California. The model suggests specialized tools win out when tasks they are designed for are performed often enough, or occur with enough certainty, to make their added cost worthwhile.

1. Introduction

More than merely serving as durable indicators of different patterned behaviors, tools are an integral part of human adaptive dynamics, both reflecting and constraining what people do. If different adaptive behaviors are made up of tasks requiring certain tools, then understanding which tools are optimal in various contexts requires addressing which behaviors are prevalent, which tools are present, and how changes in one can affect the other.

Several interrelated trends toward behavioral specialization have been documented in the Late Holocene archaeological record of California, including increased gender division of foraging labor (Jackson, 1991; Jones, 1996; McGuire and Hildebrandt, 1994), more complex settlement systems (Bamforth, 1986; Hildebrandt and Mikkelsen, 1993; Jones and Ferneau, 2002; Lebow, et al., 2007), and intensified subsistence practices (Basgall, 1987; Broughton, 1994; 1997; Codding, et al., 2012; Gould, 1964; Jones, et al., 2008; Wohlgemuth, 1996; 2004). Paralleling these trends are increases in technological specialization and in the number of tool types employed. Populations living between about 10,000 BP to 5000 BP relied on an exceedingly simple toolkit made up of about six tool types including millingslabs, handstones, cobble/core tools, flake tools, and hafted bifaces that seem to have served a wide variety of functions (Jones, et al., 2002). Starting at about 5,000 years ago, new tools with more specialized uses were introduced, but rather than replacing the old tools, much of the original toolkit remained in place. Throughout the Holocene, this same process continued, so that viewed as a whole, the dominant trend is an increase in the number of tool categories making up the technological repertoire, paired with a decrease in the functional latitude of each tool.

One of the most obvious signs of subsistence intensification in the Late Holocene archaeological record of California is the advent of the acorn economy. Available evidence suggests that sometime after 5000 years ago, the acorn assumed its place as a staple foodstuff in California (Basgall, 1987; Tushingham and Bettinger, 2013; Wohlgemuth, 1996; 2004). Stone mortars and pestles first appear in the archaeological record in large numbers after this time (Basgall, 1987; Glassow, 1996; Jones, et al., 2007; White, et al., 2002; Wohlgemuth, 1996), suggesting these implements were integral to acorn processing. However, millingslabs were never completely replaced by mortars, but instead used alongside them, presumably to process foods such as small seeds for which mortars were ill-suited. This suggests that rather than one tool form replacing another outright, there was a complex interplay between behavioral change and technological solutions (see Figure 1).

To help understand the possible mechanisms behind the California transition to mortars, as well as broader trends in technological evolution, we introduce a formal model that takes into account tool manufacture, use, and discard within the context of task performance. We focus on the trade-offs inherent in using generalized tools (useful for many tasks) as opposed to specialized tools (designed for specific tasks). Accordingly, the question guiding this study is: how much behavioral specialization is necessary before tool specialization is worthwhile? Or, put more simply: when are two tools better than one?

Technological Change and Tool Choice

Archaeologists and anthropologists have long studied how and why people use the tools they do, and how they change through time (Bettinger and Eerkens, 1999; Fitzhugh, 2001; Greaves, 1997; Hughes, 1998; Isaac, 1972; Mason, 1895; O'Brien, et al., 2001; Oswalt, 1973; 1976; Pitt-Rivers, 1906 [1875]). Many archaeologists have also focused their attention on the organization of technology, or how tools are designed manufactured, used, and discarded according to various constraints posed by the landscape and subsistence strategy (Binford, 1979; 1980; Nelson, 1991; Odell, 2001a; Torrence, 1983; 1989). The vast majority of these studies concern flaked stone (Andrefsky, 1994; Bamforth, 1991; Kelly, 1988; Parry and Kelly, 1987), but ground stone tools have also been profitably investigated (Adams, 1993; 1999; Nelson and Lippmeier, 1993).

Many of these studies have employed an optimization approach to explaining tool design and use (Beck, et al., 2002; Bettinger, et al., 2006; Bousman, 1993; 2005; Brantingham and Kuhn, 2001; Elston, 1992; Jeske, 1992; Kuhn, 1994; Ugan, et al., 2003; Wright, 1994), often explicitly employing the framework of human behavioral ecology (Bird and O'Connell, 2006; Kennett and Winterhalder, 2006; Smith and Winterhalder, 1992). Such an approach makes sense for investigating how and why technology changes because decisions about tools often involve fitness-related behavioral trade-offs that can be modeled, provided the relevant variables can be quantified. Optimization models are generally concerned with individual decision making, but the types of tools used by a culture may affect the fit of such models because the behavioral options of individuals were likely limited to varying degrees by different types of technologies. As technological traditions evolved, the tools available to an individual at any point in time would constrain his or her behavior into culturally agreed-upon task-tool combinations.

While it is true that people can make new tools if necessary and that new technologies are always available through borrowing or invention, in reality, there are limits to both short-term retooling and long-term changes to technological traditions. Over the short term, procurement and manufacturing of tools is often embedded within, and dependent on, the coordinated activities of others (Binford, 1979). Over the long term, making changes to existing technologies, and developing or adopting new technologies is as much a social problem as it is an engineering problem (Bettinger, 1999; Fitzhugh, 2001; Richerson and Boyd, 2001; Rosenberg, 1994). In other words, interdependencies between technological tradition, work organization, and individual behavior may restrict both short-term and long-term behavioral options (see Steward, 1938; Steward, 1955). Therefore, even subtle changes to tools glimpsed in the archaeological record may reflect significant behavioral changes.

Researchers investigating technological organization have long suggested people make multifunctional tools when flexibility is important and specialized tools when efficiency is important (Bleed, 1986; Nelson, 1991; Shott, 1986). Because forager mobility imposes constraints on tool design by limiting the weight and number of tools that can be carried (Kuhn, 1994), stone tool users must make trade-offs between tool flexibility (how many tasks a single tool can accomplish) and tool efficiency (how well a tool performs any particular task) (Bleed, 1986; Nelson, 1991; Shott, 1986; Torrence, 1983). Tools designed for specific tasks are more efficient, but may not perform optimally beyond the narrow range of activities dictated by their design. Tools designed to accomplish a variety of tasks reduce the number of tools needed but may not perform each task as efficiently as specialized tools.

Accordingly, a central assumption guiding this investigation is that multifunctional tools permit more flexible task performance but reduce exploitative efficiency. More specialized tools, on the other hand, increase efficiency at the level of the individual task, but limit flexibility in terms of task switching (because specific tasks require specific tools that may not always be on hand). In other words, the cost of employing multifunctional tools is reduced efficiency, while the cost of employing specialized tools is reduced flexibility.

The model we present builds on previous organization of technology models (Bamforth, 1986; Bamforth and Bleed, 1997; Binford, 1979; Bleed, 1986; Nelson, 1991; Shott, 1986; Torrence, 1983), but especially on Ammerman and Feldman's (1974) modeling of hypothetical archaeological assemblages based on how tools and their use-lives relate to work performed. Their model takes the form of a matrix made up of a set of activities or tasks, a set of tools used in performing those tasks, and the "mapping relations," or which tools are used for which tasks (herein termed *tool-task relations*). While this model is a useful illustration of how tool-use behavior may influence the archaeological record, we feel its application is limited by not including some measure of tool efficiency to be optimized. As Ugan et al. (2003) and Bettinger et al. (2006) have shown, the decision to use one tool over another can be modeled as a fairly straightforward consideration of costs and benefits. A situation not specifically addressed by these models, however, is under what situations multi-use, or flexible, tools might outperform specific-use, or specialized, tools or *vice versa*. This is the aim of the model presented here. First, the model is introduced and its behavior explored using a hypothetical dataset. This is followed by an application of the model incorporating ethnographic, experimental, and archaeological data to help explain technological changes surrounding the California acorn economy.

2. Modeling Tool Choice

2.1 Two-Task System

The model is an optimality model in the form of a Markov chain incorporating probabilities of tasks performed and payoffs of various tool/task combinations. It considers some basic economic realities of tool life histories. First, there is a cost to manufacturing tools, and tools produce benefits through work. Second, tools wear out through use and eventually are discarded and must be replaced. A convenient way of viewing the model is from the perspective of a hypothetical tool user who, by manufacturing tools and performing tasks, moves around a probability space, incurring costs and gaining payoffs along the way.

Imagine first a simple situation where the tool user needs to perform a task (Task 1) but is currently lacking the required tool (Tool "A"). The user incurs an initial manufacturing cost c_a and then accrues a benefit from using the tool, signified by b_a. The tool then either wears out over time, or breaks during use. Conceptually, a worn out tool and a broken tool are similar enough that this process is modeled with a term denoting the probability of tool wear/failure w. The probability of the tool staying intact would then be $1\text{-}w$.

The payoff Va obtained by a tool user comprises the combined payoffs from all instances of using the tool, reduced by the number of times the tool breaks and must be replaced. The time frame of tool use is undefined, but could range from a single task occurrence, to a day's work, to the entire lifetime of the tool user. Depending on the time frame, as well as other variables (e.g., risk or mobility constraints to name two), the certainty of future returns varies. To account for this, a future discounting term x is included in the model signifying that future returns are not as highly valued as present returns. If it is very likely the tool will be used again, then x approaches 1 (i.e. future discounting is low). As uncertainty of tool reuse increases, the value of x decreases (i.e., future discounting is high). A list of variables relevant to this model is presented in Table 1.

Table 1. Variables in the Single Task Model.

Variable	Definition
V_a	Payoff value of tool strategy using Tool A
c_a	Manufacturing cost of Tool A
b_a	Benefit accrued from using Tool A
w	Probability of tool wear/failure
x	Probability of accruing future returns

For a single tool and a single task, the overall payoff *Va* can be represented as:

$$V_a = b_a - c_a + x((1-w)(V_a+c_a) + wV_a) \quad (1)$$

This equation reflects three possible system states. The first part of the equation, b_a-c_a, says that in the initial state where no tool is present, the cost of making a tool must be subtracted from the benefit. The remaining terms reflect two additional states, the first where the tool does not break and the manufacturing cost is recovered $(1-w)(V_a+c_a)$, and the second where the tool breaks (or wears out) and the manufacturing cost is incurred (wV_a).

Simplified this yields:

$$V_a = b_a - c_a + x(V_a + c_a - wc_a) \quad (2)$$

And solved for *Va*, yields:

$$V_a = \frac{b_a - c_a + x(c_a - c_a w)}{1 - x} \quad (3)$$

In this simple case, the payoff to the tool user is determined by the intrinsic efficiency of the tool, defined by benefit, reduced by manufacturing cost; which is, in turn, a function of its breakage rate, or how often it must be replaced (*b-cw*).

The situation gets slightly more complicated if there are two tasks to be accomplished (Task 1 and Task 2) with a single, multifunctional tool (Tool “A”).

Variables relevant to this model are presented in Table 2. Now, we must also take into account the likelihood of performing each task, as well as how efficient the tool is at performing each task. Let *p* be the probability of performing Task 1, and *1-p* the probability of performing Task 2. Probability can range from "0" meaning only Task 2 is performed, to "1" meaning only Task 1 is performed. Intermediate values signify various combinations of Tasks 1 and 2.

Table 2. Variables in the Two Task Model.

Variable	Definition
V_i	Payoff value of tool strategy using Tool *i*
c_i	Manufacturing cost of Tool *i*
b_{ij}	Benefit accrued from using Tool *i* in Task *j*
p	Probability of performing Task 1 (Task 2 is 1-*p*)
w	Probability of tool wear/failure
x	Probability of accruing future returns

Separate benefit values for each task, b_{a1} and b_{a2}, are also necessary to model the effectiveness of the two possible tool-task combinations. The payoff function for a generalist using Tool "A" for both Task 1 and Task 2 can be represented by:

$$V_a = pb_{a1}+(1-p)b_{a2} - c_a +x((1-w)(V_a+ c_a)+wV_a) \quad (4)$$

Solved for V_a:

$$V_a = \frac{b_{a2}(1-p)+b_{a1}p-c_a+c_a(1-w)x}{1-x} \quad (5)$$

Figure 2 presents this single, multifunctional tool model graphically as a probability space. In this illustration, the lower-case letter a denotes an exhausted tool (or starting with no tool). The hypothetical forager must then incur the cost of manufacturing Tool A (c_a), then he or she performs either Task 1 according to probability *p* or Task 2 according to 1-*p*. The performance of either task either exhausts the tool according to probability *w*, or leaves the tool intact (1-w). At that point, the forager starts again with either an intact (A) or exhausted (a) tool.

Modeling the use of specialized tools is more complex. Imagine a situation involving two tools and two tasks, with Tool B used only for Task 1 and Tool C used only for Task 2. Assuming the tool user starts with no tools (or with two broken tools: (bc), he or she first manufactures each tool (incurring costs c_b and c_c). As tools break (according to w), they are replaced. In this system, there are four possible states. Moving from any one state (e.g., both tools broken, one tool broken) is dependent on the state the tool user is currently in. For example, going from two broken tools (bc) to two whole tools (BC) costs more than going from one broken tool (bC) to two whole tools (BC). Figure 3 presents this two tool model graphically.

Each of the four system states can be described by a separate equation similar to those above. The resulting system of four equations can then be solved to yield a single payoff function:

$$V_{bc} = \frac{1}{1-x}\left(p\left(b_{b1} - c_b \frac{1-x(1-pw)}{1-x(1-p)}\right) + (1-p)\left(b_{c2} - c_c \frac{1-x(1-(1-p)w)}{1-xp}\right)\right) \quad (6)$$

The leading factor $1/(1-x)$ is the time frame incorporating the future discounting rate. This factor simply scales the entire payoff that follows. The first group of terms contains all the costs and benefits of specialized tool use for Task 1. The second group of terms contains all the costs and benefits of specialized tool use for Task 2. In each case, the costs depend upon breakage rate (w), frequency of use (p, $1-p$), and discounting (x). Future discounting continues to matter inside these terms, even though it already scales the entire payoff in the leading factor, because decisions to repair a tool necessarily depend upon expectations of continued tool use to amortize the benefits of any investment in a new tool. When x is small, uncertainty/risk is high, future payoffs are heavily discounted, and repair/manufacture of expensive specialty tools will have lower payoffs.

The behavior of the model can be illustrated using a simple hypothetical scenario with two tasks and three tools (Table 3). Imagine three tools: Tools A, B, and C. Tool A is an idealized multifunctional tool that performs Task 1 and Task 2 equally well. Tools B and C represent specialized tools in that each outperforms Tool A at one of the tasks. Continuing with the logic that increased manufacturing time results in increased tool efficiency (Bettinger et al. 2006; Ugan et al. 2003), Tools B and C are also more costly to manufacture than Tool A. Thus, the basic choice revolves around a cheaper tool that is equally good at both tasks (Tool A; Eq. 5) or two more expensive tools that perform either one or the other task more efficiently (Tools B and C; Eq. 6).

Table 3. Manufacturing Costs and Benefits, Hypothetical Example.

			Benefit (*b*)		
	c	***w***	**Task 1**	**Task 2**	***b* - *cw***
Tool A	400	0.1	100	100	60
Tool B	415	0.1	117	-	67
Tool C	415	0.1	-	117	67

Figure 4 shows the payoff values of all three hypothetical tools across various values of *p, x, and c*. Recall that for this two-task version of the model, a high value of p (> 0.5) means that Task 1 is preferentially performed while a low value of p (< 0.5) means that Task 2 predominates. When $x = .95$, the multifunctional tool (Tool A) wins out in the middle while the specialized tools (Tools B and C) perform better at more extreme values of p when either Task 1 or Task 2 predominates. This means that once either threshold value of p is reached (in this case < .15 or > .85), it makes more sense to abandon the multifunctional tool and start producing *two* specialized tools, with each used exclusively for one task. Note also that as the value of x increases (i.e., certainty about future returns is high/risk is low), the range of payoffs increases as does the value of specialized tools relative to the multifunctional tool.

2.2 Multiple-Task System

The above model can be extended to cover additional tools and tasks by adding terms analogous to those above. Variables relevant to this model are presented in Table 4. The master payoff expression, when the forager begins with no tools (or with all broken/exhausted tools), takes the form:

$$V^{*} = \frac{1}{1-x}\sum_{i=1}^{n}\sum_{j=1}^{m} p_j q_{ij}\left(b_{ij} - c_i \frac{1-x\left(1-\overline{w}_i\right)}{1-x\left(1-\overline{q}_i\right)}\right) \tag{7}$$

where j indexes any of m tasks, i indexes any of n tool types, p_j is the probability (or proportion of the time) of task j (sum $p_j = 1$) , q_{ij} is the probability of using tool i for task j, b_{ij} is the benefit of using tool i for task j, c_i is cost of making tool i, and w_{ij} is breakage rate of tool i when used for task j. The symbols $\overline{w}_i$ and $\overline{q}_i$ are the average breakage rate of tool i and average use rate of tool i, respectively, defined by:

$$\overline{w}_i = \sum_{k=1}^{m} p_k q_{ik} w_{ik} \tag{8}$$

$$\overline{q}_i = \sum_{k=1}^{m} p_k q_{ik} \tag{9}$$

This general version of the model includes the same assumptions and structure of the two-task model above. In fact, the two-task model can easily be reverse-engineered from this model. Further explorations of the model should therefore start with Equation 7 (Equations 1-6 being included here to explain how the model was derived).

Table 4. Variables in the Multiple Task Model.

Variable	Definition
V^*	Overall payoff value of tools/tasks modeled
c_i	Manufacturing cost of Tool *i*
b_{ij}	Benefit accrued from using Tool *i* in Task *j*
q_{ij}	Probability of using Tool *i* in Task *j*
w_{ij}	Probability of tool wear/failure using Tool *i* in Task *j*
x	Probability of accruing future returns
w_i [bar]	Average breakage rate of Tool *i* (see Eq. 8)
q_i [bar]	Average use rate of Tool *i* (see Eq. 9)

[note to editorial staff: the last two symbols in Table 4 should be depicted with bar overhead as in Eq. 8 and Eq. 9.]

The advantage of the general version of the model (i.e., Equation 7) is that any number of tools and tasks can be modeled simultaneously but because the number of variables and system states is potentially high, it is helpful to elaborate on the structure of the model. Terms of the model can be described as either vectors or matrices, with vectors describing specific properties of tools, and matrices describing interactions between tools and tasks. First, the probability of performing each task can be represented by the vector *P*:

$$P = \begin{bmatrix} p_1 & p_2 & \cdots & p_j \end{bmatrix} \tag{10}$$

with p_1 signifying the probability of performing Task 1, p_2 the probability of performing Task 2, etc. The total of p_j sums to 1, signifying 100% of the tool user's time in all tasks. Any task requiring a tool will initially incur the cost of manufacturing the tool, which is represented by another vector, *C*:

$$C = \begin{bmatrix} c_1 & c_2 & \cdots & c_i \end{bmatrix} \tag{11}$$

with c_1 signifying the cost of making Tool 1, c_2 the cost of making Tool 2, etc. The tool-task relations, or the possible ways that tools and tasks interact, is represented by the matrix Q:

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1j} \\ q_{21} & q_{22} & \cdots & q_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ q_{i1} & q_{i2} & \cdots & q_{ij} \end{bmatrix} \tag{12}$$

In this matrix, q_{11} signifies Tool 1 used for Task 1, while q_{21} signifies Tool 2 used for Task 1, and so on. This arrangement allows considerable flexibility in the modeling of tool use as some tools may be used for more than one task (i.e, a multifunctional tool), while others may be used for only a single task (i.e., a specialized tool). The benefit the tool user gains from each tool-task interaction (b_{ij}), and the probability of tool failure (w_{ij}), can be represented by analogous matrices:

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & b_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ b_{i1} & b_{i2} & \cdots & b_{ij} \end{bmatrix} \tag{13}$$

$$W = \begin{bmatrix} w_{11} & w_{21} & \cdots & w_{i1} \\ w_{12} & w_{22} & \cdots & w_{i2} \\ \vdots & \vdots & \ddots & \vdots \\ w_{1j} & w_{2j} & \cdots & w_{ij} \end{bmatrix} \tag{14}$$

In this way, a wide variety of tools and tool uses can be modeled. For example, "expedient" versus "curated" tools (Binford 1979) may differ in several dimensions, including manufacturing time, tool-task relations, durability, benefit, and probability of reuse, with each of these variables contributing to the overall benefit accrued over the use life of the tool. Expedient tools that are manufactured quickly have a low up-front cost and, potentially, are efficient at performing a single task, but may be used only briefly, not staying in the system long enough to produce additional benefits.[1] Curated tools, on the other hand, may present a significant up-front cost, but may be used in multiple contexts over a long use life, thus recouping their higher manufacturing cost.[2] Although it could be argued that the actual values used to define tools should be based on specific ethnoarchaeological or similar data, when such data are not available (as is generally the case for prehistoric tools), hypothesized regularities in tool use, such as those previously identified in the organization of technology literature, or through experimental studies, can guide the motivation of the model.

The hypothetical tool user's job is to maximize his or her payoff by choosing q_{ij} (i.e., the tool-task relations). When the time frame is long (i.e., future discounting is low; $x \approx 1$), this payoff is maximized by choosing q_{ij} to be either 0 or 1, depending upon which i maximizes: $b_{ij} - c_i w_{ij}$. When certainty about the future is high, the choice to use any particular tool depends more on characteristics of the tool itself rather than its use context. In other words, the proportion of time devoted to each task p no longer matters when x approaches 1. At slightly lower values of x, a greater variety of tool-use strategies are possible and the proportion of time spent on each task p becomes relevant. If x is very low (i.e., uncertainty/risk is high), then wear rates become irrelevant because tools are not likely to be used more than once. So at extreme low and high values of x, the model becomes unrealistic, but at future discounting rates close to posited values for humans (less than 5%, x = .95-.99; Alvard, 1998; see also Tucker, 2006), some interesting predictions can be made.

To simulate more complex task-tool combinations, an accounting of discarded tools is useful. This allows the relative abundances of each tool type to be calculated, effectively producing a simulated archaeological assemblage. Just as Ammerman and Feldman (1974) found, the expected proportions of broken tools in an assemblage will be a function of use and breakage rates. The use rate of a tool is determined by the amount of time spent in a task p_k and the tool-task relations q_{ik} or the probability a tool is used for a particular task. The expected proportion of broken (i.e., discarded) tools in an assemblage that are tool i will then be given by:

$$\frac{\overline{w}_i}{\sum \overline{w}} = \frac{\sum_{k=1}^{m} p_k q_{ik} w_{ik}}{\sum_{h=1}^{n} \sum_{k=1}^{m} p_k q_{hk} w_{hk}} \tag{15}$$

A key question that can be addressed with this model is: under what conditions will adding more expensive specialized tools to a multifunctional tool-use strategy yield higher payoffs? To help answer this question, an archaeological example is pursued.

3. An Archaeological Example

3.1 Mortars Vs. Millingslabs

Because the model presented above requires detailed input data on tool manufacture and use, data from ethnography, archaeology, and experimental archaeology are combined along with some educated guesses to provide a workable example. We have chosen an example using ground, rather than flaked stone because archaeological ground stone tools often represent whole tools, not simply the stone portion of a complex arrangement of wood, stone, fiber, and other materials (e.g., the bow and arrow) as is often the case with flaked stone. Also, unlike flaked stone, which was quickly abandoned with the arrival of metal tools (Bamforth, 1993; Gould, et al., 1971; Odell, 2001b; Shott, 1989), ground stone tools were used into the 20th century and are still used today in many parts of the world (Bauer, 1990; Goldschmidt, 1974; Kennard, 1979; McCarthy, 1993), so data on their manufacture and use are available. That said, there is nothing that precludes modeling flaked stone or other tool classes as long as relevant ethnographic or experimental data can be located.

In California, ethnographic data suggest mortars were used to process acorns, and millingslabs were used to process small/hard seeds (Gifford, 1932; Kroeber, 1925). These tool-task relations were unlikely to have been one-to-one, however, and studies have repeatedly warned against, or shied away from oversimplification of these artifact-resource associations (Buonasera, 2013; Glassow, 1996; Jones, et al., 2007; Jones, 1996; Liu, et al., 2010; Mikkelsen, 1985; Rosenthal, et al., 2007; Wohlgemuth, 1996). Nevertheless, the well-documented archaeological pattern of mortars replacing millingslabs as the dominant plant food processing tool has long been explained in terms of the ascendance of balanophagy (Basgall, 1987; Beardsley, 1948; Codding, et al., 2012; Fredrickson, 1974; Gould, 1964; Jackson, 1991). Also, recent evidence from starch grain analysis provides support for pestles, but not handstones, being associated with acorn (Scholze, 2011).

Archaeologically, basin-shaped millingslabs and handstones constitute the first widely employed plant food processing technology in California, present at many Early and Middle Holocene sites (Basgall and True, 1985; Jones, et al., 2002; Jones 2008; Rosenthal and Fitzgerald, 2012; Wallace, 1955; 1978; Warren, 1968). There has been much speculation about which resources people were processing with these tools, but there is overall agreement that the acorn did not dominate the plant food repertoire at this early date (Basgall, 1987). Evidence from paleobotanical studies, as well as changes in material culture, suggest that between 5000 and 3000 years ago, the acorn assumed its place as a staple foodstuff, as was observed ethnographically (Basgall, 1987; Codding, et al., 2012; Tushingham and Bettinger, 2013; Wohlgemuth, 1996; 2004). Over much of central California, stone mortars and pestles first appear in the archaeological record in large numbers during this interval (Basgall, 1987; Glassow, 1996; Jones, et al., 2007; White, et al., 2002; Wohlgemuth, 1996), but rather than abandoning millingslabs, they were retained, but generally as flat, minimally-modified forms. Mortars completely replace millingslabs in some regions like the San Francisco Bay Area (Milliken, et al., 2007), but more often were used in addition to millingslabs as along the Central Coast (Jones, et al., 2007) and Central Valley (Rosenthal, et al., 2007).

To help illustrate the empirical record, a sample of 47 archaeological components from the Central Coast and interior Coast Ranges of California was assembled from regional literature. Numbers of pestles, mortars, handstones, and millingslabs in these components were recorded as well as millingslab morphologies when these were reported (Table 5). Trends through time in the proportion of mortars to millingslabs, and the proportion of different millingslab morphologies are shown in Figures 5 and 6. Given the observed archaeological patterns, it is reasonable to suggest the increased proportion of mortars at ca. 4000 cal BP was directly related to the intensified use of acorns. The retention of flat millingslabs would then be related to processing of items other than acorns, such as small seeds. This scenario is explored using ethnographic and experimental data plotted against hypothetical increases in acorn exploitation.

3.2 Input Data

Data on manufacturing times for mortars and millingslabs are scarce, but from published numbers, it is apparent that mortars required significantly more labor to produce (Aschmann, 1949; Buonasera, 2012; Leventhal and Seitz, 1989; Schneider and Osborne, 1996)[3]. Data on processing efficiency of ground stone tools are likewise scarce, but there exist some data on use of mortars for acorn processing (Bettinger, et al., 1997; Goldschmidt, 1974; McCarthy, 1993) and seed and grain processing with millingslabs (Mauldin, 1993; Wright, 1994) (Table 6). Combining these datasets yields a satisfactory initial comparison of milling tools for the purposes of this model (Table 7).

Table 6. Estimated Return Rates for Grinding and Pounding Tools.

Source	Data Type	Tool	Grinding or Pounding Rate (hr/kg)	Other Processing Rate (hr/kg)	Total Processing Time (hr/kg)	Total Processing Time (kg/hr)	kcal/kg	kcal/hr
Wright 1994	Experimental	Handstone/ Millingslab	2.0	1.1	3.1	0.32	2940[b]	948
Mauldin 1993	Experimental	Handstone/ Millingslab	0.19	3.7[a]	3.9	0.26	2940[b]	756
Wright 1994	Ethnographic[c]	Handstone/ Millingslab	-	-	4.6	0.22	3191	724
McCarthy 1993	Ethnographic[d]	Mortar/ Pestle	1.4	3.9	5.3	0.19	4443	838

[a]Mean processing rates from Simms 1985.
[b]Mean kcal/kg for Great Basin seed resources in Simms 1985.
[c]Mean of combined Alyawara/Pintubi data.
[d]Western Mono/Hupa.

Table 7. Estimated Manufacturing and Return Rates for California Plant Processing Tools.

Tool	Volume (cm^3)	Manufacturing Time (hrs)	Kcal[a] Expended	Process Small Seeds (kcal/hr)	Process Acorns (kcal/hr)
Basin Millingslab	2199	95	39710	756	754[b]
Bowl Mortar	4357	189	79002	na	838
Flat Millingslab	-	20	8360	756	na

[a]Based on net calorie expenditure for 25 year-old woman, 120 pounds; [b]Hypothetical rate based on 10% reduction of mortar rate.

For millingslabs, data from Wright (1994) and Mauldin (1993) were used to define a range of possible return rates for processing seed resources. Experimental data on seed grinding rates from these sources were used in conjunction with data on "other processing" rates (e.g., winnowing) and mean kcal/kg values for Great Basin seed resources from Simms (1985) and Mauldin (1993) to arrive at return rates. In addition to experimental data, ethnographic data aggregated by Wright (1994) for the Alyawara and Pintubi of Australia were included. The range of return rates recorded for grinding with millingslabs, despite being arrived at through very different means, are surprisingly similar, ranging from 724-948 kcal/hr (Table 6). For use in the model, the median value of 756 kcal/hr was input for processing small seeds.

Manufacturing times for millingslabs were estimated using a rate of 23.1 cm^3/hr for producing concavities in stone reported by Buonosera (2012). To approximate the manufacture of large, basin-shaped millingslabs typical of Early Holocene components in California, the mean concavity volume from a collection of complete and near-complete specimens from site CA-FRE-61 (Rosenthal and Whitaker, 2012) was used with this rate (Table 7). For flat millingslabs such as those typical of Late Holocene contexts, an estimated, but fairly conservative value of 20 hours was used for manufacturing time to account for raw material acquisition, and minimal edge trimming or other modification. For mortars, manufacturing time was estimated using the same concavity rate of 23.1 cm^3/hr and figures on mean mortar concavity volume from Buonosera (2012). The manufacturing cost value for these tools (c_i) was converted into kilocalories expended.

Data on return rates for processing acorns using mortars was taken from Bettinger et al. (1997) based on data from McCarthy (1993) and Goldschmidt (1974) on the Western Mono and Hupa, respectively. Data were not available for processing acorns on millingslabs, but it was assumed mortars supplied at least a slight technological advantage over millingslabs in terms of acorn processing because mortars should better contain the material pounded. Therefore, the known value of 838 kcal/hr for acorn processing in mortars was reduced by 10% for millingslabs, yielding a rate of 754 kcal/hr. To transform these return rates into a plausible benefit value (b_{ij}), they are multiplied by 10, signifying a 10-hour work day[4]. Wear rate, w is set at .001 for all tools and all tasks for this example. This low number is consistent with durable milling tools. These values are used to illustrate that even small advantages in efficiency, within the context of tool life cycles and changing task performance demands, can create qualitative changes in toolkits.

3.3 Archaeological Example Results

The archaeological scenario compares the efficiency of somewhat costly basin millingslabs with more expensive bowl mortars used in conjunction with cheap flat millingslabs. Assuming both small seeds and acorns are exploited in varying proportions, the choice is between using either one multifunctional tool type (basin millingslabs) or two more specialized tools (flat millingslabs plus bowl mortars).

Figure 7 illustrates this comparison across a range of values representing the proportion of time devoted to processing acorns. In this simple example, there are only two resource types, acorns and small seeds, so a reduction in one necessarily represents an increase in the other. With the future discounting term, x set at 0.95 (i.e., future discounting at 5%) , the tool with the best return is always the basin millingslab (Figure 7a). If, however, x is set at 0.99 (i.e., future discounting of 1%), the combination of bowl mortar and flat millingslab wins out once acorn proportion reaches 50% or greater (Figure 7b).

Figure 8 compares modeled proportions of milling equipment (calculated using Equation 15, Figure 8a) to the actual historical trajectory of grinding tools in Central California (Figure 8b). There is a similar pattern of mortars replacing millingslabs, and flat millingslabs replacing basin millingslabs, perhaps in both cases related to changes in the proportion of time spent processing acorns.

4. Discussion and Conclusions

The archaeological example underscores the fact that the decision to make a more expensive tool depends not only on the efficiency of the tool (b-cw), or the proportion of time spent in a particular task (p), but also on the likelihood that it will be reused repeatedly (x). Despite the slight advantage in processing efficiency of the bowl mortar and the lower manufacturing cost of the flat millingslab, when x is set at 0.95 (Figure 7a), the pair simply cannot overcome the effects of future discounting; meaning the high manufacturing cost of the bowl mortar cannot be recovered during the life of the artifact due to the uncertainty of reusing it. Conversely, when future discounting is reduced to 1%

as in Figure 7b, even the high manufacturing cost of mortars cannot stop them from outperforming basin millingslabs when acorn exploitation begins to outpace that of small seeds.

Considering the California archaeological record, an important factor favoring the adoption of mortars may have been changes in mobility, either towards sedentism or more structured seasonal moves, that provided foragers with greater assurance they would reuse tools, thus reducing future discounting (Jackson, 1991; Jones, 1996; Rosenthal and McGuire, 2004). This means Early and Middle Holocene groups that relied on large (and probably not very portable) basin millingslabs had to split the difference between acorn and small seed returns, with milling gear cached in locations where a variety of plant resources could be exploited. Later groups could instead stage mortars in locations where acorns were most productive, and separately use portable flat millingslabs in areas better suited to small seed resources. This trend is further exemplified by the later adoption of fixed processing locations (i.e., bedrock mortars) in many areas (Basgall, 1987; Jackson, 1991), signifying both the importance of acorn processing as well as the increased certainty that processing locations would be revisited. The fact that many Late Holocene millingslabs are smaller, thinner, and more portable suggests small seed processing tools were simply decoupled from the settlement calculus, thereby freeing people to map onto acorn resources and exploit the more diverse set of small seeds when and where they were available.

The model behavior explored here suggest some basic truths about the relative merits of multifunctional vs. specialized tools. First, if a multifunctional tool is cheaper to make, and has a decent return rate across multiple tasks, it can outcompete more specialized tools. Multifunctional technologies should then be favored when a range of activities are performed and no single activity dominates. Second, specialized tools, even if they are more expensive to manufacture, can outcompete multifunctional tools, but only when the tasks they are designed for are performed often enough, or occur with enough certainty, to make it worthwhile. This suggests that more focused or increasingly intensive exploitation of particular resources should favor specialized technologies.

Switching to a fully specialized strategy of tool design and use, however, also has drawbacks in that unless the work performed matches the set of tools at hand, specialized tools will not be advantageous. At first glance, this seems to fit common-sense notions of how people should make and use tools. The more a particular task is pursued, the more worthwhile investments in efficiency become (see Bettinger et al. 2006; Ugan et al. 2003). However, a counterintuitive implication of this model is that a particular task need not dominate other tasks to warrant producing a specialized tool. This is because investments in a specialized tool which is seldom used can be offset by lower tool failure and exhaustion rates (i.e., a tool that is rarely used, rarely breaks). Such a situation might arise with the use of cached specialized equipment for exploitation of a resource that is limited in time and space (see Binford, 1980; Bleed, 1986; Torrence, 1983; Zvelebil, 1984).

Behavior of the model also has important implications for technological change and how it is perceived in the archaeological record. Certain multifunctional tool design and use strategies might accommodate increasingly specialized work organization up to a point, without necessarily increasing technological diversity. When tools become more specialized, tools and behaviors should "map onto" one another with more certainty, and archaeologically recovered tools should more closely track behavior. Conversely, when tools are multifunctional, then behavior may vary within a wide "reaction norm" that is archaeologically undetectable.

That more specialized tools accompany subsistence intensification throughout the Holocene is consistent with the idea that declining foraging efficiency can be offset by technological advances that decrease handling time (Bettinger, 1999; Bright, et al., 2002; Hawkes and O'Connell, 1992; Torrence, 1983). But more specialized tools might also be expected if there were changes to the proportional representation of subsistence-related tasks, if certain tasks became more common or more predictable, or if future returns could be relied on with more certainty. Certain resources may have been ignored early in time, perhaps because of higher risk, higher technological cost, or because they required greater coordination or planning. If more "difficult" resources are rarely exploited, then perhaps a multifunctional toolkit would suffice, allowing some latitude for frequent changes in strategy. Also, if mobility was regular, or otherwise fairly unconstrained, people would have been able to move between productive patches, exploiting a limited, but reliable, set of resources as part of a wide-ranging seasonal round. But if exploiting previously underutilized taxa, or spending time in previously underutilized patches became commonplace throughout the Holocene, new specialized tool types may have been advantageous because the requisite tasks were outside the range of efficiency of existing multifunctional tools. The expense of specialized tools would have been further reduced by lower future discounting accompanying a more rigidly organized land and resource use regime. Late Holocene adaptations, including intensified foraging as well as agriculture, may have had reduced flexibility, but made up for it with an increase in certainty, and ultimately in greater provisioning ability through technological adjustments integrated with changing work organization.

In many areas of the world, the archaeological record of Holocene hunter-gatherers is characterized by a similar pattern of subsistence intensification along with increasing technological specialization. This trend is evident in regions that ultimately became agricultural such as the Levant (Bar-Yosef, 1998), Japan (Aikens and Akazawa, 1996; Aikens, et al., 2009; Imamura, 1996), and the American Midwest (Odell, 1994), and regions where hunting and gathering continued until historic contact such as Australia (Codding, 2012; Hiscock, 2007; Lourandos, 1985; Smith, 2006; Veth, et al., 2011) and western North America (Bettinger, 1999; Fitzhugh, 2001).

Similar generalized-to-specialized shifts characterize the development of human technology throughout the Pleistocene as well (Ambrose, 2001; Hayden, 1981; Isaac, 1972; Klein, 2000; Klein, 2009; Zvelebil, 1984), especially key transitions such as those occurring at the Middle Paleolithic/Upper Paleolithic transition (Bar-Yosef, 2002; Shea, 2007) and during the Middle Stone Age of Africa (Cochrane, 2008; McBrearty and Brooks, 2000; McCall, 2007). This model may therefore find fruitful application in understanding differences between the limited and generalized toolkits used by human ancestors over extremely long time spans, and the proliferation of quickly-changing, more specialized tools made by cognitively modern humans. This is not to say that technologies should always progress towards more specialized forms, as constraints present in any particular time and place might favor generalized, specialized, or even a mix of strategies. Indeed, rather than technological complexity, a more accurate measure of modern human behavior may be the ability to adaptively regulate tool-task relations.

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Notes

1. Expedient tools require little labor input to manufacture, but toolstone acquisition adds to the cost of manufacturing even simple flake knives. Such expedient tools are also exhausted quickly due to their sharp edges, meaning, that overall, their ability to provide return is reduced.

2. Whether tools are multifunctional over the course of their use lives by changing form ("flexibility" [Nelson 1991]) or maintain one form and are useful for several functions ("versatility" [Nelson 1991]) is immaterial to the model as long as manufacturing costs and task efficiency are accounted for.

3. This is also true of shallow "hopper" mortars because while the actual stone portion found archaeologically does not represent a large manufacturing input, they require the manufacture of a basketry hopper in addition to the mortar. In any case, hopper mortars are a largely post-1000 BP phenomenon in Central California (Bennyhoff, 1994; Jones, et al., 2007; Milliken, et al., 2007; Moratto, 1984; Rosenthal and McGuire, 2004).

4. "women pounded [acorn] virtually all day and sometimes for two, starting early in the morning, to produce enough…for the coming week or ten days…" (McCarthy 1993:288)

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Table 5. Regional Components Used in Mortar and Millingslab Comparisons.

Location	Site	Component	Date Range (cal BP)	Med. Date	Pestles	Mortars	Hand stones	Milling slabs	Bas.	Scv.	Flt.	Reference
Camp Roberts	CA-SLO-1834	1834A	287-historic	151	-	1	-	-	-	-	-	Basgall 2006
Camp Roberts	CA-SLO-1180	1180A	652-historic	338	2	-	5	-	-	-	-	Carpenter et al. 2007; Farquhar et al. 2010
Camp Roberts	CA-SLO-2210	2210A	638-historic	344	2	-	1	1	-	1	-	Garlinghouse and Farquhar 2005
Warm Springs Dam	Multiple	Smith Phase	700-100	500	28	4	25	17	-	-	-	Basgall and Bouey 1991
Gilroy	Multiple	Late	700-200	500	7	1	5	-	-	-	-	Hildebrandt and Mikkelsen 1993
Los Vaqueros	CA-CCO-458	West Locus	950-200	575	15	1	-	-	-	-	-	Meyer and Rosenthal 1997
Camp Roberts	CA-SLO-1169	1169A	690-540	618	-	-	2	-	-	-	-	Basgall 2006
Camp Roberts	CA-SLO-1180	1180B	906-689	771	1	-	3	-	-	-	-	Carpenter et al. 2007
Camp Roberts	CA-SLO-670	670B	918-694	802	-	-	1	-	-	-	-	Basgall 2006
Los Vaqueros Reservoir	CA-CCO-459	Upper Archaic-Emergent	1265-440	852	1	2	-	-	-	-	-	Meyer and Rosenthal 1997
Priest Valley	CA-MNT-745	745A	934-771	855	-	2	-	-	-	-	-	Hildebrandt 2006
Camp Roberts	CA-SLO-1778	1778A	1062-795	933	3	7	6	1	-	-	-	Basgall 2006, Farquhar et al. 2011
Gilroy	Multiple	M/L	1200-700	1000	5	4	13	2	-	-	2	Hildebrandt and Mikkelsen 1993
Camp Roberts	CA-SLO-2207	2207A	1297-703	1107	3	-	1	-	-	-	-	Garlinghouse and Farquhar 2005, Hannahs and Farrell 2007
Camp Roberts	CA-SLO-670	670C	1293-1016	1183	-	-	1	-	-	-	-	Basgall 2006
Anderson Flat	CA-LAK-72	72E-A1	1809-1293	1293	17	2	1	-	-	-	-	White et al. 2002
Camp Roberts	CA-SLO-1835	1835A	1527-1356	1451	-	1	2	1	-	-	1	Carpenter et al. 2007
Gilroy	Multiple	Middle	2600-1000	1700	11	11	19	2	-	-	2	Hildebrandt and Mikkelsen 1993
Camp Roberts	CA-SLO-2646	2646A	2051-1389	1704	-	-	4	-	-	-	-	Farquhar et al. 2010
Anderson Flat	CA-LAK-72	72W-A1	1750-1750	1750	2	-	-	-	-	-	-	White et al. 2002
Fort Hunter Liggett	CA-MNT-521	Middle	2450-1100	1775	2	4	12	8	-	-	8	Jones and Haney 1997a
Anderson Flat	CA-LAK-72	72W-C1	2950-1967	1967	1	-	-	-	-	-	-	White et al. 2002
Anderson Flat	CA-LAK-510	510E-B1	2430-1989	1989	-	-	2	-	-	-	-	White et al. 2002
Camp Roberts	CA-SLO-1169	1169B	3000-1000	2000	-	-	4	3	-	1	1	Basgall 2006
Los Vaqueros Reservoir	CA-CCO-696	West Locus	2765-1320	2042	32	17	-	-	-	-	-	Meyer and Rosenthal 1997
Anderson Flat	CA-LAK-881	881W1	2250-2250	2250	3	5	2	1	-	-	1	White et al. 2002
Warm Springs Dam	Multiple	Dry Creek Phase	2500-700	2500	37	26	23	16	-	-	-	Basgall and Bouey 1991
Diablo Range	CA-KER-4623	A1	3000-500	2500	1	2	4	6	-	-	6	Basgall and Giambastiani 1999
Diablo Range	CA-KER-4623	A2	2600-350	2500	3	1	5	8	-	3	5	Basgall and Giambastiani 1999

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Diablo Range	CA-KER-4623	A3	2700-400	2500	6	3	2	12	-	2	10	Basgall and Giambastiani 1999
Anderson Flat	CA-LAK-510	510W-C1	2950-2871	2871	11	-	13	8	-	1	7	White et al. 2002
Fort Hunter Liggett	CA-MNT-569	Midden A	3700-3000	3350	1	-	19	1	-	1	-	Jones and Haney 1997b
Warm Springs Dam	Multiple	Skaggs Phase	5000-2500	3500	3	-	9	10	-	-	-	Basgall and Bouey 1991
Marsh Creek	CA-CCO-548	Upper	4300-3100	3500	95	47	9	8	-	6	2	Wiberg 2010
Gilroy	Multiple	Early	5000-2600	3500	2	-	2	-	-	-	-	Hildebrandt and Mikkelsen 1993
Anderson Flat	CA-LAK-72	72E-A2	8046-4020	4020	-	-	4	8	2	4	2	White et al. 2002
Los Vaqueros Reservoir	CA-CCO-637	Middle Archaic	5795-2585	4190	13	3	-	-	-	-	-	Meyer and Rosenthal 1997
Camp Roberts	CA-SLO-1180	1180C	4528-4218	4382	-	-	1	1	-	-	-	Carpenter et al. 2007
Anderson Flat	CA-LAK-510	510W-B1	4750-4750	4750	-	-	2	2	1	1	-	White et al. 2002
Scott's Valley	CA-SCR-313	Stratum III	5935-4985	5460	-	-	3	5	-	-	-	Jones et al. 2000
Marsh Creek	CA-CCO-548	Lower	6586-6439	6500	-	-	2	2	2	-	-	Rosenthal et al. 2010
Salinas River Crossing	CA-SLO-1756	Millingstone	7162-6842	6979	-	-	21	5	5	-	-	Fitzgerald 1997
Diablo Canyon	CA-SLO-585	Millingstone	8950-5350	7150	3	1	47	31	31	-	-	Greenwood 1972
Los Vaqueros Reservoir	CA-CCO-696	Deep	9870-7400	8635	-	-	6	3	2	1	-	Meyer and Rosenthal 1997
Santa Ysabel Ranch	CA-SLO-1920	1920B	9244-8072	8700	-	-	3	1	1	-	-	Stevens et al. 2004
Vandenberg AFB	CA-SBA-246	Millingstone	9247-8759	9147	-	-	28	7	6	-	1	Stevens 2012
Cross Creek	CA-SLO-1797	Millingstone	9781-11164	10485	-	-	21	21	14	4	3	Fitzgerald 2000

Note: Med. Date = median date; Bas. = basined millingslabs; Scv. = slightly concave millingslabs; Flt. = flat millingslabs.

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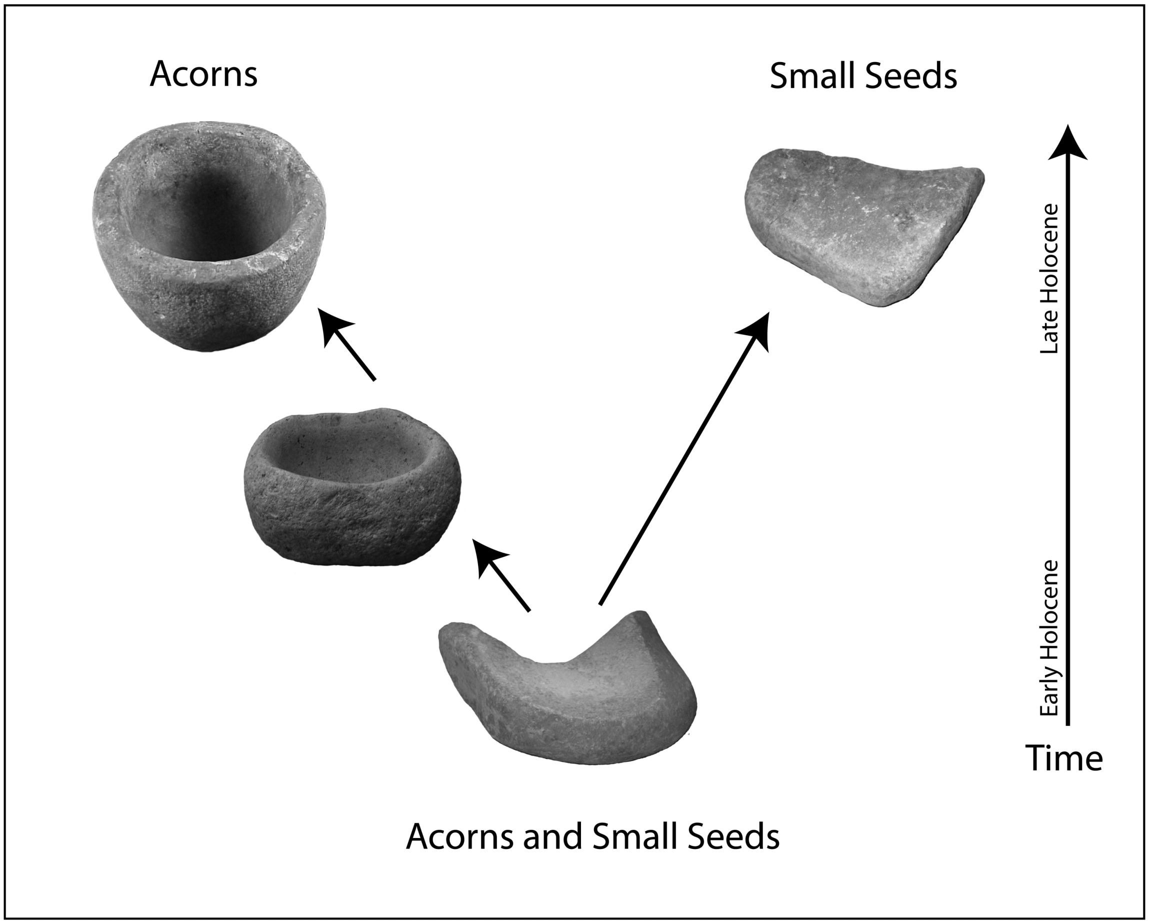

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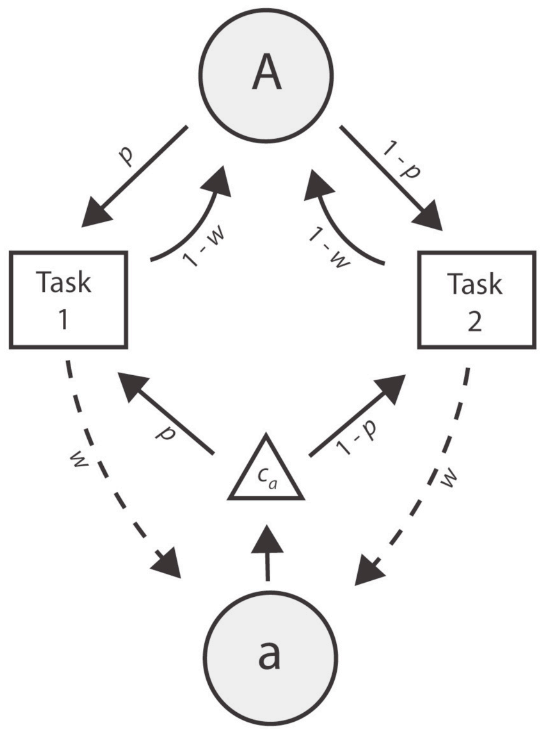

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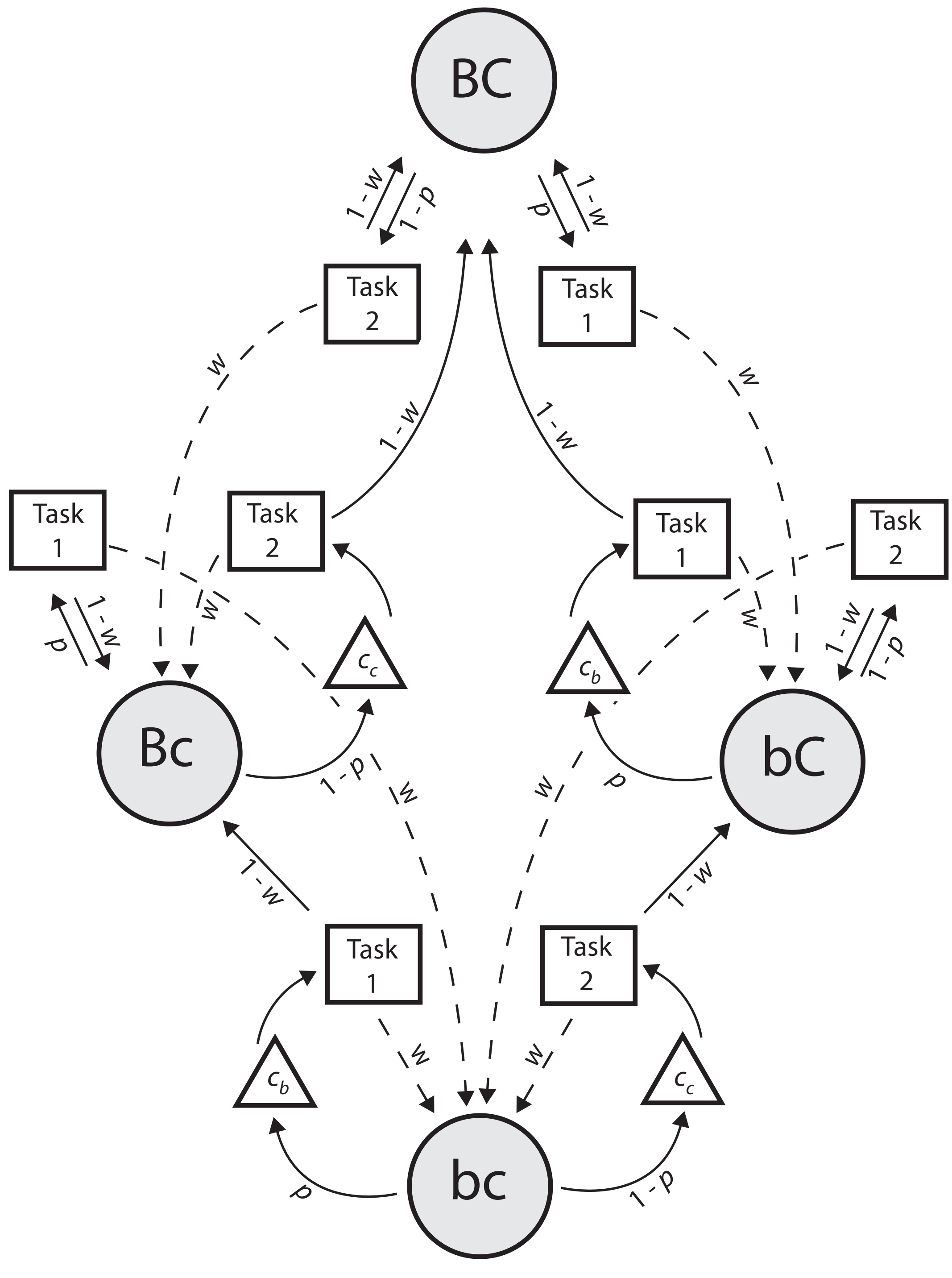

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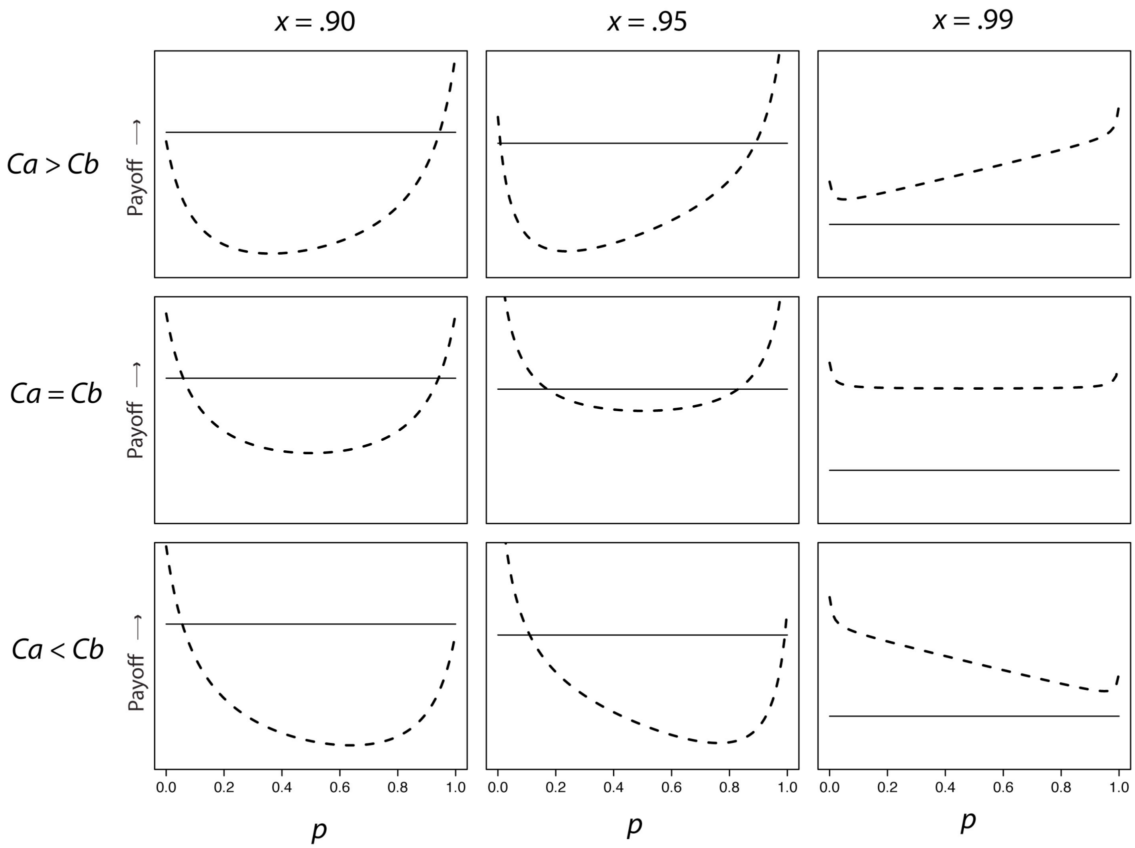

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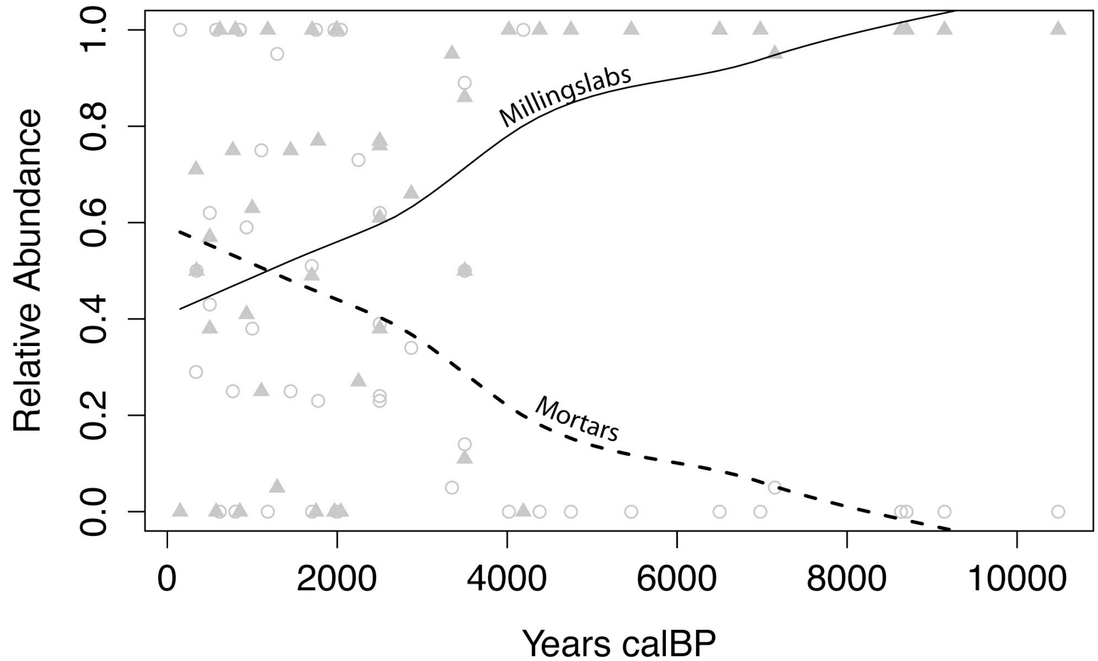

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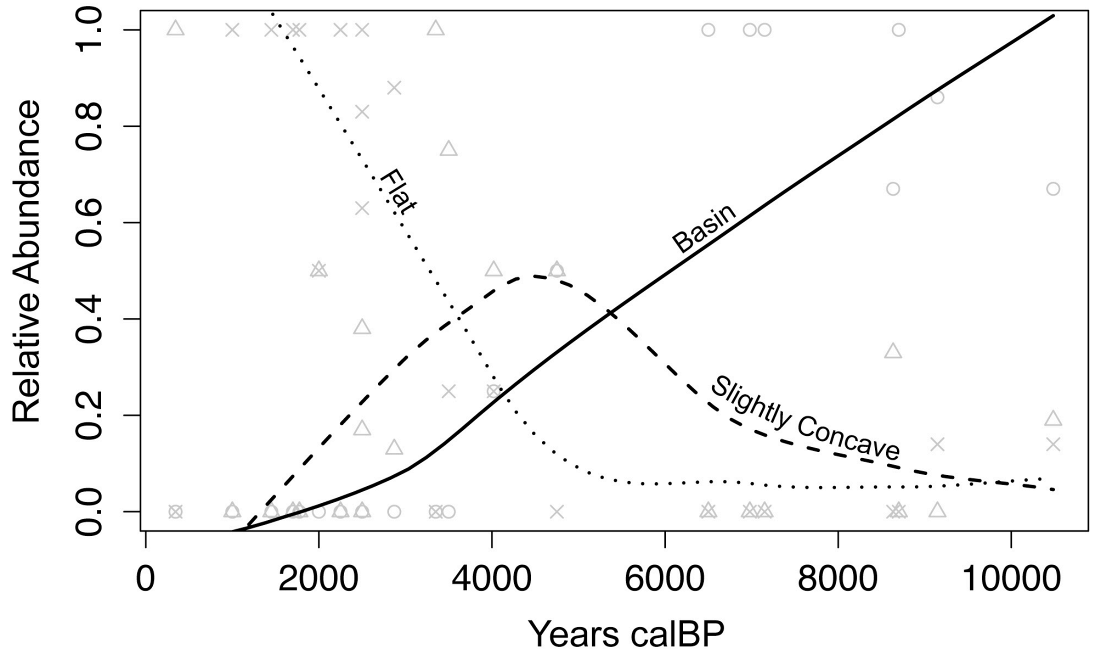

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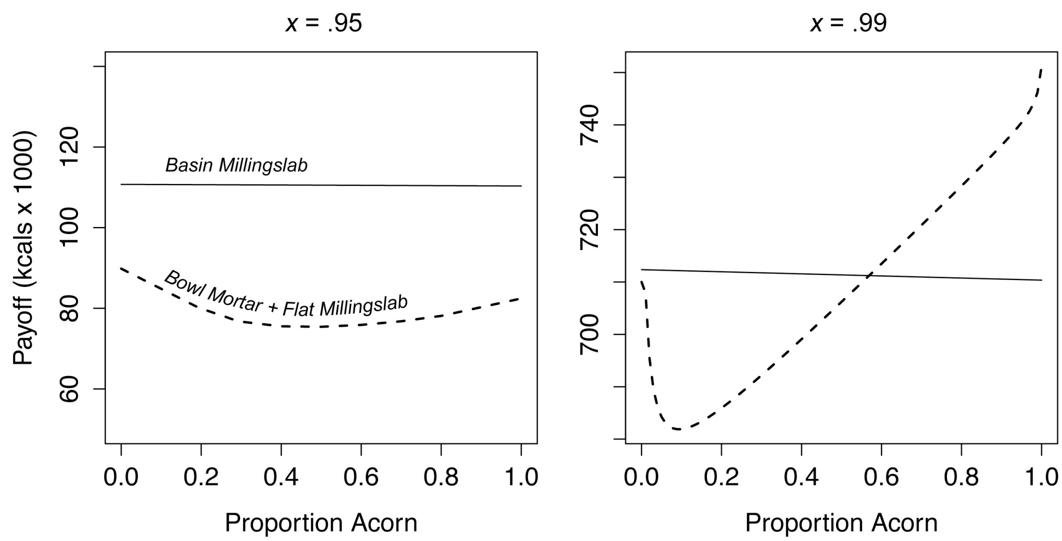

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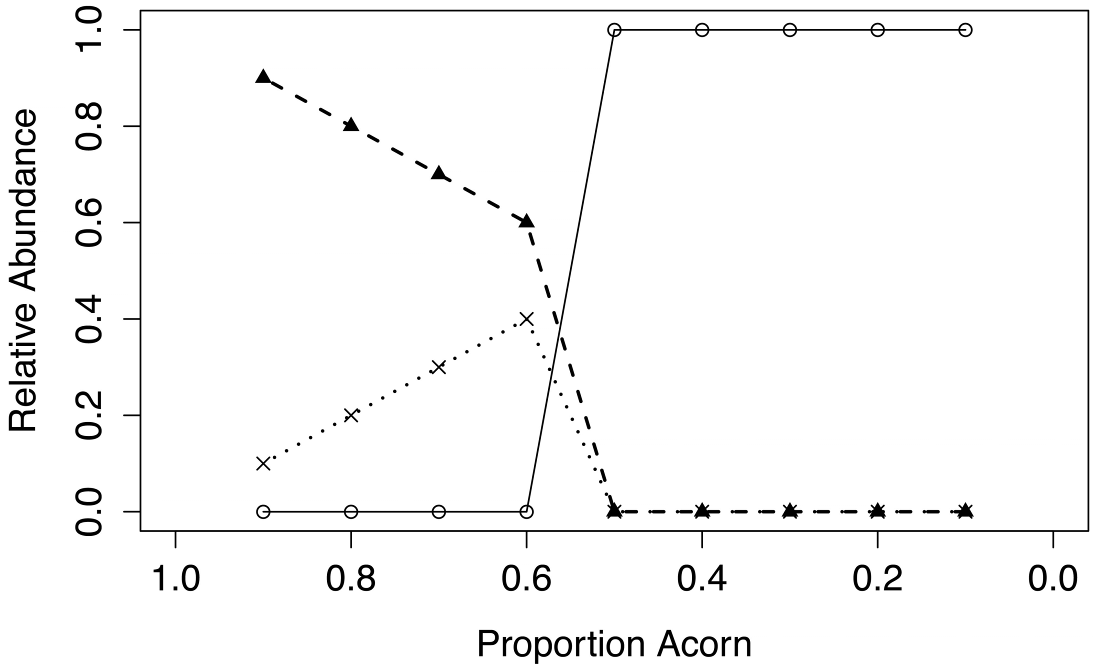

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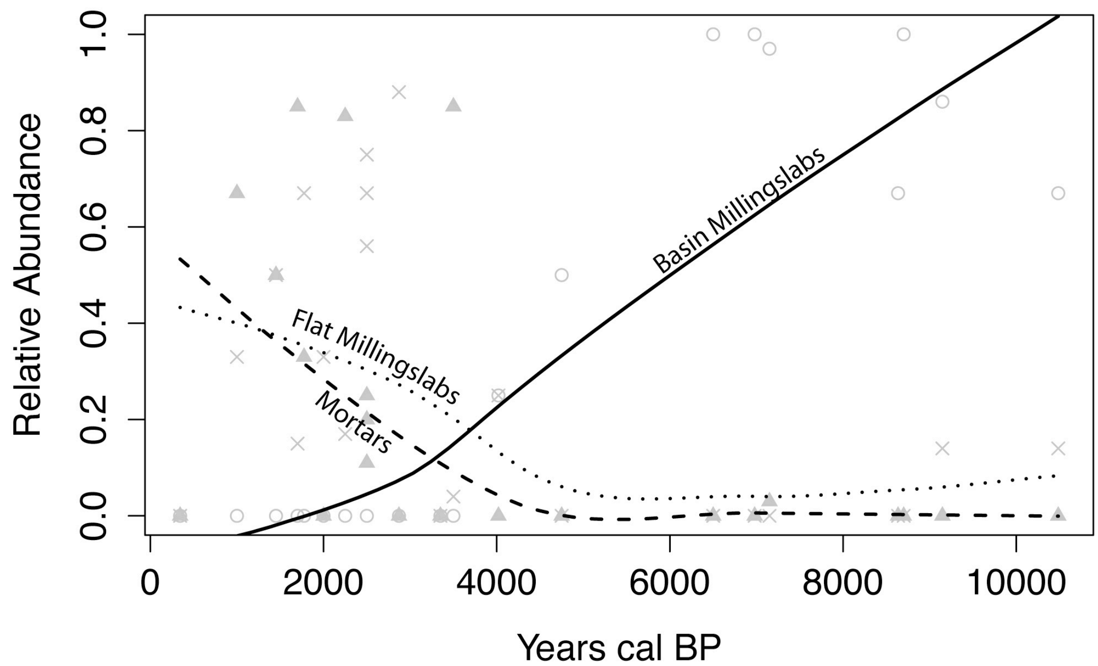

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