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Modeling the costs and benefits of manufacturing expedient milling tools

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A R T I C L E I N F O

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A B S T R A C T

It is often assumed that use-surfaces on informal or expedient milling tools were formed strictly through use. Informal or expedient milling tools lack clear evidence of exterior shaping and are often associated with short-term occupations or temporary, task-specific sites. Here, a simple model of technological intensification outlined in Bettinger et al. (2006) is adapted to predict minimum use times necessary to profit from time spent improving the use-surface of milling tools. The costs and benefits of making and using improved milling surfaces for two types of raw material (sandstone and granite) are compared using experimentally derived estimates of grinding rates and manufacturing costs. Experiments indicate that shaping a milling surface increases seed-grinding efficiency. Modeling these data along with manufacturing costs predicts that manufacturing effort should be expected sooner than often assumed—in fact, little more than one and a half hours of seed grinding are necessary to profit from time spent manufacturing a shallow basin in sandstone. It also predicts that sandstone should be selected over granite for short-term seed grinding due to its ease of shaping. These results imply that there are many cases where mobile hunter–gatherers who processed seed resources could have reduced their overall handling time by selecting certain materials and investing time in shaping milling surfaces. This highlights the need for greater attention to physical evidence of manufacturing among expedient milling tools. Documenting raw material selection and degree of manufacturing effort expended on such tools can increase the visibility of gendered economic decisions among prehistoric hunter–gatherers.

1. Introduction

Little theoretical inquiry has been directed to the manufacture of milling tools lacking exterior formalization – tools that are often referred to as expedient or "unshaped". Reasons for this lack of investigation may include the apparent simplicity of such tools as well as tendencies to view women (arguably, the primary users of these tools) as passive actors in prehistory. Though a number of optimality models have been applied to decisions affecting flaked lithic technology (Bettinger et al., 2006; Brantingham and Kuhn, 2001; Kuhn, 1994; Metcalfe and Barlow, 1992; Surovell, 2003, 2015; Torrence, 1989; Ugan et al., 2003), similar models have rarely been applied to ground stone tools (Buonasera, 2013a; Stevens and McElreath, 2015). Here, I discuss a simple optimality model designed for procurement related technologies (Bettinger et al., 2006) and show how it could be used to predict raw material preference and manufacturing effort for ground stone milling tools in mobile settings. These settings are envisioned to include a range of short-term residential sites, as well as temporary, task-specific sites.

Applying optimality models to technology assumes that people seek to minimize their work efforts and/or maximize energy gain. Although social and ideological factors also affect choices, optimizing assumptions provide a rational starting place from which to build and improve investigations. A benefit of using formal models is that "constraints, currencies and goals" are explicitly defined, allowing logically derived predictions to follow (Surovell, 2003:14). Although the assumptions of optimality models over-simplify the bases of human decision-making, the interplay between a simple predictive model and experimental or empirical evidence can sometimes reveal relationships that were previously overlooked, and thereby provide additional hypotheses for testing.

The costs and benefits of manufacturing grinding tools in mobile settings are often considered to be self-evident and have received little formal consideration by archaeologists. Along these lines, it is commonly assumed that mobile foragers should expend little or no

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effort manufacturing food grinding tools. Yet, people engaged in seed grinding should spend time improving milling tools when it will reduce the total handling time for those resources. Even in mobile settings, time spent manufacturing a better grinding surface could decrease overall processing times for resources like seeds.

Though little ethnographic detail exists about the manufacture and use of grinding tools among hunter–gatherers, some information indicates that users of informal milling tools took time to manufacture desirable attributes. Among historically Pintubi and Kukatja speaking people in the Western Desert of Australia, Cane (1989:99, 112) recorded that "a great deal of work" went into manufacturing seed grinding dishes out of sandstone slabs. Walsh (2003:265–266), also working in the Western Desert of Australia, noted that among the Mantjiltljarra a "husband or a son would shape milling stones by removing lumps and shaping edges under the direction of the mother/wife."

In the southern Sierras of California, Native women are credited with the manufacture of bedrock mortars (Jackson, 1991:307; McCarthy et al., 1985). "Mono consultants said that new mortars were made [by relatives who used the mortars] with steel chisels in historic times, but thought they had probably been made with a hard rock in pre-contact times" (McCarthy et al., 1985:325). Bennett and Zing (1935) reported that among the Tarahumara of the Sierra Madre Occidental, traditional farmers and pastoralists who practiced seasonal transhumance, women were known to spend a few hours manufacturing a simple basin metate and mano when it was necessary.

> Nothing is more important in the household routine of a Tarahumara woman than the metate, which she calls *matáka*... Since it is too heavy for her to carry about in the numerous journeys she takes to pasture the animals, she learns how to make a *matáka* in short order. First, she finds a large, smooth, flat rock that she knows is very hard. She chips it with a much harder piece of volcanic *piedra lumbrosa* to form the groove for the mano, or handpiece (*matásola*). This is similarly chipped with a piece of flat, hard stone. [pp.79–80]

Grinding efficiency of simple milling tools can be increased in several ways. Shaping stone surfaces using pecking or other percussive techniques to remove high points increases the contact between upper and lower stones. Pecking also creates an abrasive surface. Additionally, creating even a very shallow depression can help to retain material on the surface and reduce grinding time over an unmodified surface. Finally, increasing the size of grinding surfaces has been shown to increase grinding efficiency (Hard et al., 1996; Mauldin, 1993). To better assess when an individual should invest time in shaping a milling surface, costs and benefits of manufacturing improved milling surfaces are modeled here using experimentally derived estimates of grinding rates and manufacturing costs.

Throughout the following paper, the term "metate" is used synonymously with "grinding slab" or "milling slab" to indicate the lower stone of a pair of processing tools used predominantly for grinding. Likewise, the terms "handstone" and "mano" are used interchangeably to indicate the upper stone of this pair. Where it is necessary, particular shapes are indicated by appropriate modifiers (e.g., basin, flat, troughed, shaped or unshaped).

1.1. Evaluating technological investment with the point-estimate model

Several models of technological intensification, or "tech-models", have been proposed for evaluating changes in procurement and processing technology (Bright et al., 2002; Ugan et al., 2003; Bettinger et al., 2006). These models predict the minimum amount of use time required for one technology to provide an advantage in time or energy over another. If gains in efficiency can be realized with increased investment in manufacturing time, but more efficient tools are costlier to produce (especially if manufacturing time competes with total use time), then the decision to use the costlier or cheaper version of a technology can be viewed as an optimization problem that depends on the amount of time a particular technology will be used.

Here, a simple model of technological intensification proposed by Bettinger et al. (2006)—the point-estimate model—is adapted to predict threshold use times that make investment in improving milling surfaces on different raw materials worthwhile. The point-estimate model is a variation of a widely applicable optimality model that compares rates of return with additional investments of time (Bettinger et al., 1997; Charnov, 1976; Metcalfe and Barlow, 1992). The point-estimate model assumes each category of technology has its own cost-benefit curve and plots returns associated with each specific technology as discrete points rather than as part of the same function. This allows comparisons to be made between alternative categories of technologies within a class of subsistence technology (e.g., fishing hooks versus fishing nets) as well as among variations within a particular category of technology (e.g., larger or smaller fishing nets). Bettinger et al. (2006) define a *category* of technology as "a structurally related set of forms which can be envisioned as modifications of one another occupying a single, continuous gain function", whereas a *class* of technology is made up of alternate categories of a technology "applied to a particular subsistence pursuit" (p. 540). Given enough data, a continuous curve might be constructed to describe changes in the rate of gain for versions of a particular category of technology. Bettinger et al. (2006:541) note that the point-estimate approach may work better for many archaeological cases because it requires fewer assumptions and less extensive data sets than are necessary to derive accurate cost-benefit curves.

The point-estimate model requires that a cheaper alternative be compared with a more productive, but costlier version of the same technology. A graphical representation is shown in Fig. 1, with the X-axis representing time. The portion of the X-axis to the right of the Y-axis is manufacturing time, while the portion to the left of the

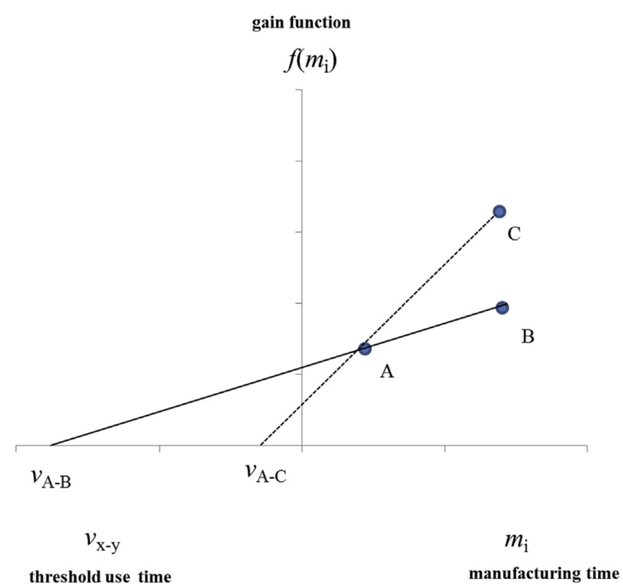

Fig. 1. After the point-estimate model (*Journal of Archaeological Science* 33, Bettinger et al., 2006, p. 542).

Y-axis represents use time. The Y-axis represents the rate of gain, which is a function of manufacturing time. The initial state of a technology (point A) and a more productive but costlier version (point B) are plotted, and a linear function connecting the two is constructed. The X-intercept of this line shows the threshold use time for shifting from tool A to tool B, where the cost of making the improved version of the tool has been recouped. For use times beyond this threshold, net returns are increased by shifting from technology A to technology B. Different categories of a technology with unique gain functions can also be compared. If a technology like C enters the picture and is more productive than B, then B is likely to be abandoned in favor of C. However, technology A, the cheapest technology, may be retained specifically for short-term incidental uses (Bettinger et al., 2006:544).

Examples of formal tech models thus far have focused on food-getting technology—nets versus spears or hooks for fishing, or atlatls versus bows for hunting. This kind of gear must be replaced or maintained continually, implying that time spent manufacturing can compete with the time available for maximizing food capture or collection. The models assume that time spent making an improved tool is limited by the amount of use it is expected to receive. Because it is possible to use ground stone tools for many years, in some cases on the order of decades (Horsfall, 1987), their potential utility can greatly exceed manufacturing costs. This fact would seem to preclude any predictive value for the model since under these conditions it would always be optimal to manufacture the more costly and more productive version of a tool.

However, potential use time also depends on land-use patterns and site function. A milling tool can have a great deal of utility in the sense of lasting a long time, but the manufacturer/user can only realize the maximum utility under circumstances favoring continued or repeated use of the same tool—such as sedentary situations or, where re-occupation of particular sites follows a very predictable seasonal schedule. The modeling applications shown here assume that milling tools (especially larger, heavier lower stones) were left behind when people moved from a site. In situations of high to moderate residential mobility, the benefits of devoting time to tool manufacture would be limited by the amount of time spent at a location and by expectations for returning to the same location in the future. In these contexts, the point-estimate model could be formulated to show the maximization of processing time as a trade-off between time spent making tools, and time spent grinding resources. Specifically, manufacturing an improved grinding tool should be favored when the time spent making a better tool, combined with the time it takes to grind a quantity of seeds with the improved tool, is less than the time it would take to grind the same quantity of seeds with an unimproved tool. The following modeling exercise uses experimental data on grinding rates and manufacturing costs to estimate the minimum grinding times required to make time spent improving grinding surfaces worthwhile. Improvements are accomplished by: 1) shaping a shallow basin in a natural, flat surface and, 2) increasing the surface area of a shaped, pecked surface. The relative costs of different raw material choices are also compared.

2. Methods

2.1. Manufacturing grinding tools

To compare grinding productivity, four grinding slabs with shallow depressions of the same depth (0.5 cm) and elliptical shape, but increasing length and width were manufactured from commercially purchased, quartz arenite sandstone slabs (Fig. 2). Manos were manufactured from the same material. Grinding slab and mano dimensions are within the range of sizes reported for one-hand, expedient manos and metates reported for various informal milling tools in the literature (e.g., Bayham et al., 1986; Fitzgerald, 1993; Hale, 2001; Nelson and Lippmeier, 1993). Manos were made to fit comfortably in one hand and within their corresponding grinding slab basin (Fig. 2). An unshaped mano and unshaped grinding slab were also used in the grinding experiments. Dimensions for all grinding slabs and manos are listed in Table 1. Most grinding surfaces were manufactured using a combination of power tools and stone tools, though grinding slab #3 and mano #3 were made entirely with stone tools. Grinding surfaces made by the former method were initially shaped using an angle grinder fitted with a diamond-embedded steel grinding pad. The stone grinding surfaces were then finished by hand pecking. Pick-shaped handstones, made from very hard metamorphic cobbles, were used to remove all marks of mechanical manufacturing. Grinding slab #3, manufactured entirely by pecking, provided volume and time measurements for manufacturing grinding surfaces in sandstone (Table 2). Manufacturing time was measured only as time spent pecking the stone surface. Time spent locating raw materials and manufacturing pick-shaped handstones was not included in manufacturing time.

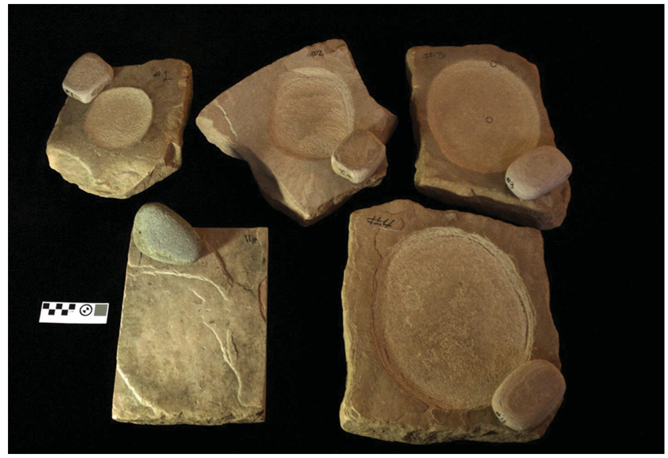

Fig. 2. Five experimental sandstone grinding slabs after two hours and twenty minutes of use. Four shallow basin grinding slabs of increasing surface area (#1 - #3 top row, left to right, and #4, lower right) and an unshaped, flat grinding slab (#11, lower left). Scale is in cm.

Additional data on manufacturing costs were obtained from published sources (Table 2). Grouped by material type, estimated manufacturing rates (volumes of stone removed per unit of time) were very similar across experiments conducted by different individuals. For granite, volume per hour rates from Leventhal and Seitz (1989), and Schneider and Osborne (1996) were averaged and used to calculate manufacturing times for shaped grinding surfaces. Because Schneider and Osborne (1996) used a different method to peck their sandstone mortar (a central mass was isolated by pecking, and then removed by indirect percussion), their results were not averaged with the volume per hour rate for sandstone obtained in the present study.

2.2. Grinding experiments

Rates of flour produced by grinding Indian ricegrass (*Oryzopsis hymenoides*) on four shallow basin grinding slabs (metates) of various sizes and one unshaped grinding slab were obtained during a recent experimental seed grinding session conducted as a field trip during the 34th Great Basin Archaeological Conference held in Boise, Idaho. Participants included college students, professional archaeologists, and avocational archaeologists. The session was

Table 1
Tool dimensions, surface areas and volumes.

Tool	Shaped	Raw material	Dimensions (l, w, h)		Surface area[a] (cm^2)	Volume[b] (cm^3)	Grinding rate[c] (g/h)
			Entire tool (cm)	Grinding surface (cm)			
metate #1	Y	Sandstone	25.2, 22.0, 5.5	12.5, 11.0	108	54	37.6
mano #1	Y	Sandstone	8.5, 7.0, 3.2	7.5, 6.0	35	n/a	
metate #2	Y	Sandstone	30.0, 29.5, 5.7	19.2, 14.5	219	110	63.7
mano #2	Y	Sandstone	8.5, 7.1, 3.8	7.6, 6.0	36	n/a	
metate #3	Y	Sandstone	33.0, 23.2, 6.0	23.7, 18.7	348	174	89.3
mano #3	Y	Sandstone	10.6, 7.4, 3.9	10.0, 6.8	53	n/a	
metate #4	Y	Sandstone	36.5, 31.4, 6.3	29.3, 23.5	541	271	188.9
mano #4	Y	Sandstone	11.2, 7.2, 3.7	10.1, 6.7	53	n/a	
metate #11	N	Sandstone	30.5, 21.3, 5.8	17.2, 15.0	203	n/a	26.8
mano #11	N	Basalt	11.7, 7.7, 5.1	11.0, 5.9	51	n/a	

[a] Surface area = πab.
[b] Volume = surface area $\times$ 0.5 cm.
[c] Measured grinding rate based on <500 μm fraction from Table 3.

Table 2
Experimental manufacturing times for ground stone concavities.

Study	Method	Material	Volume (cm^3)	Time (h)	Rate (cm^3/h)	Number of blows
Schneider and Osborne (1996)	Central plug[a]	Sandstone	215	3.8	56.0	37,200
Buonasera (present study)	Pecking	Sandstone	168	3.4	49.4	n/a
Schneider and Osborne (1996)	Pecking	Granite	140	8.0	17.5	67,200
Leventhal and Seitz (1989)	Pecking	Granite	275	17.2	16.0	46,000

[a] This mortar depression was made by pecking a groove around a central mass, which was then removed by indirect percussion.

part of a larger, ongoing, NSF funded project comparing efficiencies of different ground stone tool designs for reducing wild grass seeds and other resources to finer particles (award number BCS-1452079). Participants were novice grinders and worked in teams of two. Following a 20-min practice period, each participant processed Indian ricegrass seeds into flour for two, non-consecutive, 30-min segments. Samples of Indian ricegrass flour were provided to each team as a visual aid to determine when grinding was complete. One member of each team kept track of start and stop times and recorded observations, while the other ground seeds into flour. After 30 min, team members switched roles. This allowed flour production on each tool to be measured over a total of two hours (four, 30-min grinding segments).

To ensure consistency in comparisons, the flour produced on each tool set was subjected to a 20-min sieve analysis following methods outlined in ANSI/ASAE S319.4 for hand sieving. A set of nested sieves 1000 μm, 710 μm, and 500 μm, was used to classify fractions of different particle sizes. Fractions were weighed to the nearest tenth of a gram using a triple-beam balance (Table 3). Whole and partially crushed seeds were too large to pass through the 1000 μm sieve, while coarsely ground particles were retained on the 710 μm and 500 μm mesh (Fig. 3). Fraction weights are listed in Table 3. Flour production was measured as the weight of the fraction passing through 500 μm mesh and retained in the pan (Fig. 3, Table 3).

2.3. Modeling grinding efficiencies

The point-estimate model was used to compare gains in grinding efficiency with the cost of manufacturing an improved grinding surface on two different types of stone—sandstone and granite. Gains obtained by manufacturing a shallow basin in sandstone, and by increasing the area of a manufactured surface in sandstone, were modeled using values derived from the grinding and manufacturing experiments described above. Costs of shaping granite were modeled using experimentally determined manufacturing rates provided in the literature (Table 2). Grinding rates for manufactured surfaces with the same surface area and shape were assumed similar for sandstone and granite and were held constant here. Experimental grinding rates for granite will be included in future experimental comparisons.

The point-estimate model shown in Fig. 1 was adapted to compare the manufacture and performance of milling tools, with manufacturing time represented by the right side of the X-axis and use times on the left side of the X-axis. The Y-axis is the rate of flour production. The X-intercept on the left side of the X-axis shows the threshold use times required to shift between the cheaper, less productive form and the more productive but more expensive form. The initial metate surface of either an unshaped slab, or a smaller basin-shaped surface, could be used as found, with no improvement, or could be improved by: 1) manufacturing a shallow basin,

Table 3
Sieve analysis.

Aperture size μm	Portions retained after sieve analysis									
	Tool set #1 (g)	%	Tool set #2 (g)	%	Tool set #3 (g)	%	Tool set #4 (g)	%	Tool set #11 (g)	%
1000	26.6	13	47.7	18	11.1	4	44.3	7	11.0	11
710	29.8	15	29.9	12	26.3	9	72.6	12	15.5	15
500	71.4	35	55.8	21	61.8	22	112.4	19	21.6	21
<500	75.1	37	127.3	49	178.6	64	377.7	62	53.5	53
Total	202.9	100	260.7	100	277.8	100	607.0	100	101.6	100

Fig. 3. Fractions from sieve analysis of Tool Set #1. From top to bottom, fractions retained in sieves with openings of 1000 μm, 710 μm, 500 μm, and the pan. Fractions retained in the pan (the portion less than 500 μm) were compared as flour. Scale is in cm.

or 2) increasing the area of a smaller basin surface. The grinding rate of the initial state is plotted as point A. The grinding rates and manufacturing costs of the improved granite surface (point B) or sandstone surface (point C) are then plotted.

Adapting the terminology of the Bettinger et al. point-estimate model (2006:541) for ground stone manufacturing and food processing, a more costly grinding tool that increases processing returns will be favored over a cheaper tool when:

$$\frac{f_2(m_2)}{m_2+v}>\frac{f_1(m_1)}{m_1+v} \tag{1}$$

where

v = use time
m_i = manufacturing time
$f_i(m_i)$ = the rate of flour production

The threshold processing time at which the more and less costly technologies produce equivalent returns is given by

$$v_{1-2}=\frac{f_1(m_1)m_2-f_2(m_2)m_1}{f_2(m_2)-f_1(m_1)} \tag{2}$$

Here, the costs and benefits of using tools as found, versus improving them, were compared. Tools used as found were assumed to have no manufacturing time, setting m_1 to zero.

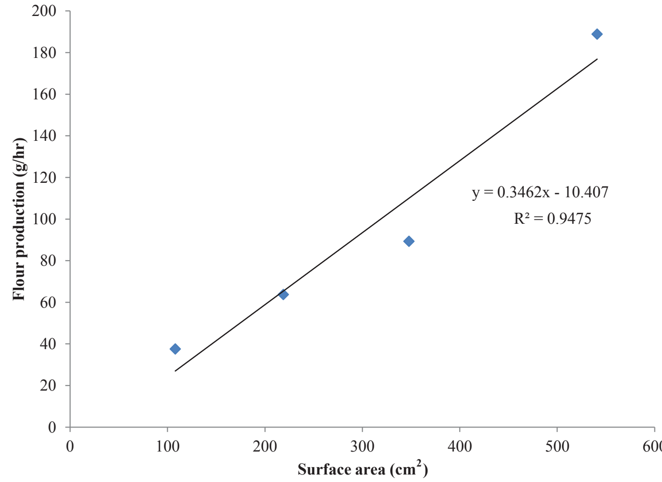

Fig. 4. Flour production on four basin shaped sandstone metates with increasing surface area.

$$v_{1-2}=\frac{f_1(m_1)m_2}{f_2(m_2)-f_1(m_1)} \tag{3}$$

Equation (3) can also be solved to compare flour production, as shown below.

$$f_2(m_2)(v_{1-2})=f_1(m_1)(m_2+v_{1-2}) \tag{4}$$

To recoup the cost of manufacturing an improved grinding surface, an individual would need to anticipate grinding at least as much flour as could be processed on the improved grinding surface in the threshold use time. This amount is given by $f_2(m_2)$ (v_{1-2}) in Equation (4).

3. Results

Fig. 4 is a plot of surface area to flour production on the shallow basin tool sets. Flour production is based on the <500 μm fraction combined from 2 h (four, 30-min sessions) of grinding (Tables 1 and 3). Fig. 4 shows a strong, positive relationship between increasing surface area and increasing rate of flour production ($R^2 = 0.95$). Though variation was apparent in individual grinding ability (see

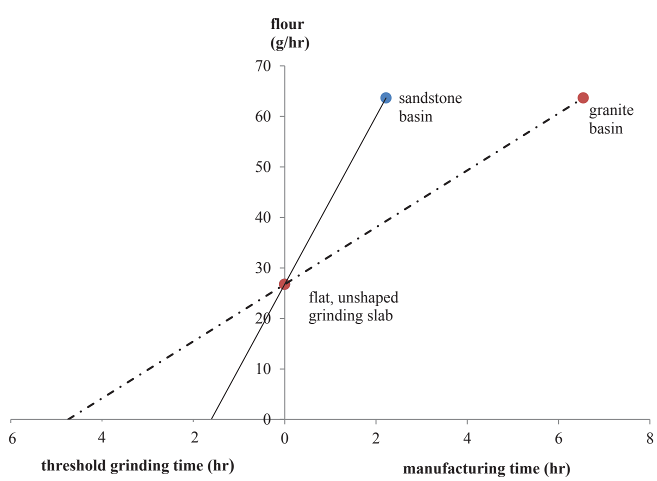

Fig. 5. Point-estimate model for manufacturing a shallow basin from a flat, unshaped slab.

Table 4
Unshaped versus shaped grinding surfaces, assuming a depth of 0.5 cm.

Grinding surface (cm^2)	Manuf. time sandstone (h)	Grinding rate (g/h)	Manuf. time granite (h)	Grinding rate (g/h)
Unshaped metate #11 (203)	0	26.75	0	26.75
Shaped metate #2 (219)	2.22	63.65	6.54	63.65

Manufacturing time = volume/manufacturing rate of raw material.
109.5/49.4 = 2.22.
109.5/16.75 = 6.54.

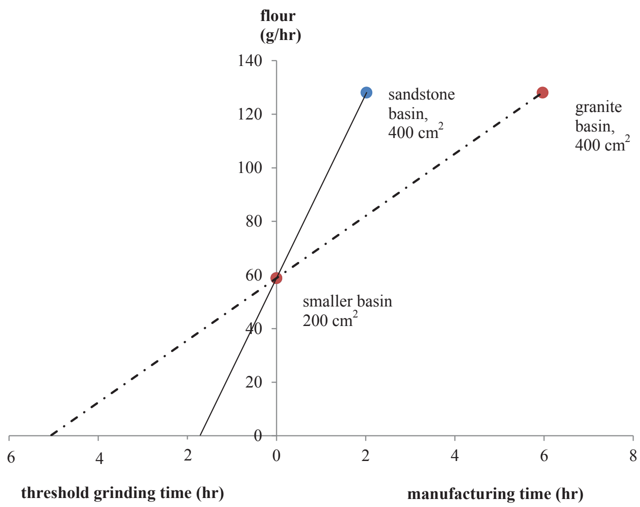

Fig. 6. Point-estimate model for increasing the surface area of a shaped basin metate.

Supplemental data), surface area is clearly an important factor governing rates of flour production.

Fig. 5 compares rates of flour production with costs of manufacture for an unshaped flat surface and a manufactured shallow basin made from sandstone or granite (Table 4). Total surface area used on the unshaped grinding surface (determined from extent of use-wear) was 203 cm^2. Total surface area on the shaped experimental surface was similar at 219 cm^2. Based on experimental results, it would be worthwhile to spend time manufacturing a shallow basin out of sandstone if more than 1.6 h of grinding time on the improved surface could be anticipated. In contrast, it would take more than 4.7 h of seed grinding before it would be beneficial to manufacture a shallow basin out of granite.

Fig. 6 compares increasing rates of flour production with costs of manufacture for shaped shallow basin surfaces made from sandstone or granite (Table 5). Based on these experimental results, it would become profitable to spend time increasing the surface area of a shallow sandstone basin metate from 200 cm^2 to 400 cm^2 if more than 1.7 h of grinding time could be anticipated. For granite, it would not be beneficial to increase the surface on a similarly shaped basin until more than 5.1 h of grinding could be anticipated.

4. Discussion

Fig. 4 indicates a positive, linear relationship between the rate of flour production for Indian ricegrass and increasing surface area on four shaped basins, ($R^2 = 0.95$). Mauldin (1993:319) noted a similar relationship for a set of larger, flat, shaped grinding slabs (surface areas of 716, 807, 1735 cm^2) used in conjunction with two-handed manos and agricultural grains (maize, wheat, and quinoa). Though gains in grinding rates must ultimately decline as the physical limits of arm reach, hand size, strength or endurance are approached, neither experiment used sizes that reached those limits. Rather, Mauldin's experiments and those presented here, both opted to compare sizes typically encountered in archaeological contexts. For tools within this intermediate size range, other factors are expected to come into play, such as raw material availability and characteristics, manufacturing costs, lengths of expected use, and types and amounts of resources that will be processed. Under conditions of mobility, or where short-term use is expected, contrasting the cost of manufacture with gains in productivity can provide estimates of minimum use times needed to benefit from shaping expedient milling tools.

The experimental values modeled here indicate that just a few hours of seed grinding can make it worthwhile to shape a milling surface, particularly where sandstone is available as a raw material. The model represented in Fig. 5 predicts that manufacturing a shallow basin in sandstone would be preferable to using an unshaped surface if more than 1.6 h of seed grinding on the improved surface could be anticipated. Stated another way, this threshold would be reached in the time it takes to process about 102 g of flour. The rates of gain depicted in Fig. 6 are similar to those in Fig. 5, though they are slightly less steep, producing a threshold grinding time of 1.7 h for increasing the surface area of a shaped sandstone basin.

While the increase in grinding productivity shown in Fig. 6 is due primarily to increasing surface area, the increase in Fig. 5 is probably the result of several factors. First, shaping makes the overall topography more even than an unshaped surface by bringing the high points into the same plane. This overall leveling of topographic highs can increase the effective surface area by allowing a greater portion of the upper and lower stones to be in contact during grinding. Second, pecking helps to roughen or “sharpen” the grinding surface. Third, creation of a shallow basin helps retain material on the grinding surface. This is important

Table 5
Increase in shaped surface area by 200 cm^2, assuming a depth of 0.5 cm.

Shaped surface area (cm^2)	Manuf. time sandstone (h)	Grinding rate (g/h)	Manuf. time granite (h)	Grinding rate (g/h)
200	0	58.83	0	58.83
400	2.02	128.07	5.97	128.07

Y = 0.3462X − 10.407.
X = surface area, Y = grinding rate = rate of flour production.
Manufacturing time = volume/manufacturing rate of raw material.
100/49.4 = 2.02.
100/16.75 = 5.97.

because it reduces time spent returning partially ground material to the grinding surface. That the rates of gain depicted in Figs. 5 and 6 are so similar, may be coincidental. The unshaped grinding surface was fairly flat and regular over the used portion of its surface (Fig. 2). If the unshaped surface had been slightly more rugged or uneven, the rate of gain would probably have been steeper, decreasing threshold grinding time. On the other hand, if the unshaped surface had been flat and regular over a larger area, this would have made the rate of gain less steep, increasing threshold grinding time.

At use times beyond the thresholds modeled in Figs. 5 and 6, the linear model shows that increasing productivity associated with ever-larger surface areas will continue to pay for increases in manufacturing costs. This would seem to predict that once use time thresholds are met, ground stone surfaces should be manufactured to be as large as physically possible. However, a number of factors can act to diminish the returns from additional manufacturing effort. As mentioned earlier, limits of human strength and arm reach will certainly act to reduce returns at extremely large sizes. Also, diminishing returns could be expected when increasing the surface area of very irregular surfaces because some portions of the stone surface may require removal of significantly greater volumes of stone for equivalent increases in surface area.

Another limit to expanding the size of manufactured grinding surfaces in short-term use contexts could be anticipated flour needs. As surface area increases, threshold use times remain the same, but the amount of flour production necessary to justify increased manufacturing costs will continue to increase. This relationship is shown in Equation (4) from Section 2.3 At some point, the amount of flour needed to justify additional manufacturing costs might be greater than the amount of seeds mobile foragers can reasonably anticipate collecting or using. For example, the amount of flour that would be produced on progressively larger grinding surfaces can be calculated using the threshold use times for sandstone or granite metates in Fig. 6 and the grinding rates for the improved surfaces. As surface area increases, the amount of flour produced in the same amount of time will increase. Increasing the surface area of a sandstone metate by 200 cm^2 (from 200 cm^2 to 400 cm^2) would be repaid if more than 220 g of flour could be anticipated. On the other hand, increasing the surface area of a granite metate by 1000 cm^2 (from 200 cm^2 to 1200 cm^2) would be repaid if more than 2054 g of flour were needed. While the former amount is likely to be met in one grinding session,[1] the latter could exceed the amount needed over a short stay and/or have a greater risk of not being met due to variability in daily foraging returns. It must also be remembered that these are experimental values, intended for comparison. While they can be used to compare the relative performance of different tools, they do not necessarily represent absolute grinding rates that might have been achieved by individuals in the past.

Figs. 5 and 6 also show that longer use thresholds are required before it is worthwhile to modify granite surfaces. This implies that granite basin metates should not be economically preferred for manufacturing basin grinding slabs where sandstone is also available as a raw material, unless another factor, like durability, becomes an important consideration. This is because it costs much more to manufacture a basin out of granite than it does to make one from sandstone, but granite basins are not expected to be much better at processing seeds than sandstone basins over the short term. In fact, it is often assumed that sandstone is better for reducing seeds to flour than finer-grained rocks such as basalt or granite (Schneider, 2002), though this has not been demonstrated in controlled experiments. It was assumed here that pecked surfaces have similar abrasiveness over the short term, though sandstone and granite are expected to wear at different rates. Differences in grinding rates due to relative abrasiveness and durability are the subject of ongoing research and will be included in future models. Results presented here, however, show that surface area alone is an important factor in increasing grinding efficiency and that differences in manufacturing rates for sandstone and granite are quite large.

In situations where a softer, more easily worked stone type and a harder, less easily worked stone type are both present and of suitable dimensions, either raw material might be selected for unshaped milling tools. As use time increases, better grinding returns will be realized sooner by investing time in shaping the more easily worked material. Unless other factors such as durability or perhaps grit reduction become paramount, the more easily shaped material should be energetically preferred for manufacturing basin-shaped metates. This means that grinding surfaces with evidence of intentional shaping should be biased towards more easily shaped materials like sandstone. On the other hand, grinding surfaces that appear to have been used as found, should vary more directly with the local availability of different lithic raw materials.

Formalization of this relationship between tool form, material, and use time is echoed in the results of a technological study of the Milling Stone Pattern (Hale, 2001). The Milling Stone Pattern (better known as the Milling Stone Horizon) is characterized by an abundance of milling tools (basin and flat metates/millingslabs and manos/handstones) as well as battered core and cobble tools, and relatively few formal flaked-stone tools. One assessment of 31 known sites in Southern California puts the average ratio of ground stone to flaked stone tools at 27 to 1 (McGuire and Hildebrandt, 1994:43). Of interest are the rather early dates associated with many of these sites (Early to Middle Holocene) and a highly mobile orientation, combined with a heavy dependence on plant foods and, in coastal locales, shellfish utilization (Fitzgerald and Jones, 1999; Jones, 1996; Rosenthal and Fitzgerald, 2012). Although early discoveries of this pattern were confined to southern California (True, 1958; Wallace, 1955; Warren, 1968), it has since been noted in central and northern Californian contexts (Fitzgerald and Jones, 1999), and has even been reported at some Late Holocene sites in southern California (Kowta, 1969).

Hale analyzed ground stone morphology, use-wear, and tool material for a sample of 256 artifacts selected from several well-documented Milling Stone sites in southern California (2001:37). He found that locally available sandstone was the most frequently chosen material for grinding implements (metates and manos), although other, harder, more durable types of rock were also available at the same locations. He also found that basined metates significantly outnumbered flat metates. “Overall, material profiles were dominated by relatively soft stone comprised mostly of sandstone (54%), followed by schist (41%); just nine specimens made from granite and two from volcanics. Granite and volcanic stone was common enough … that if material selection was random, then these would be better represented” (2001:191). Hale suggested that the Milling Stone Pattern represents a flexible, generalized processing strategy and that sandstone and schist were selected because they were abrasive and more easily shaped than other types of stone.

[1] Cane (1987:430–431) estimates that no more than 20 percent of daily caloric needs (estimated at 2000 Kcal per person) are met by grass seeds among foragers who rely on seeds. Based on this estimate (roughly 400 Kcal per person/day) for seeds, and the caloric value of Indian ricegrass (2740 kcal/kg, from Simms, 1985), an individual might expect to grind 146 g for themselves or 438 g for a small family (estimated here as the amount for three adults) per day.

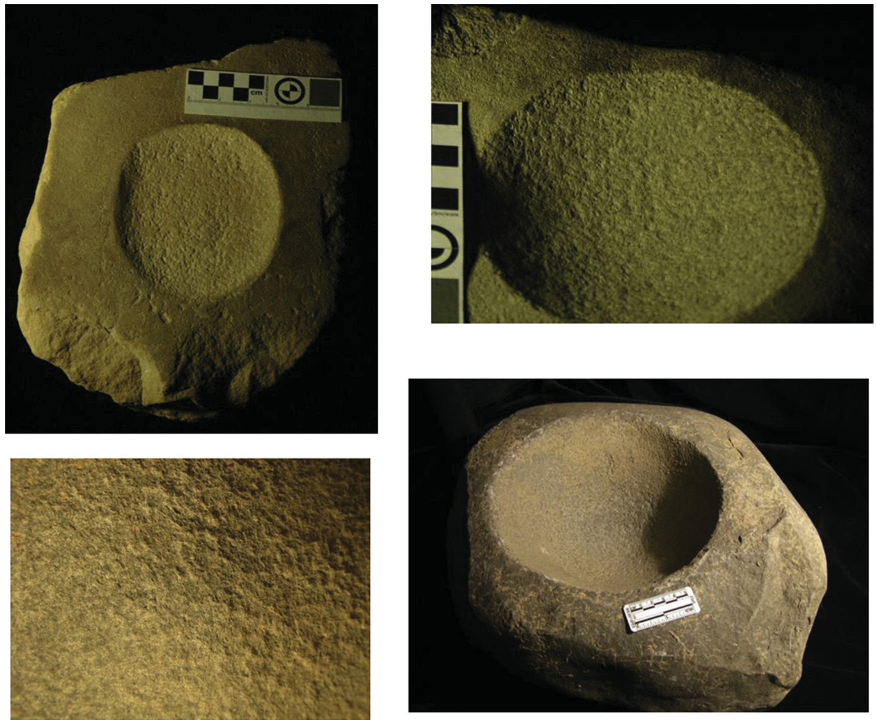

Fig. 7. Densely clustered pecking marks visible on experimental and archaeological tools. Top row, left to right: experimental small sandstone basin and shallow sandstone mortar after two hours and twenty minutes of use. Bottom row, left to right: close-up of interior and overview of an "unshaped" greywacke mortar from an archaeological site in central California.

In another study, Nelson and Lippmeier (1993) found that the presence or absence of intentionally shaped metates, and raw material type varied with the regularity of site occupation between fortuitously used rock shelters and architectural sites in the eastern Mimbres region of New Mexico. These authors make a distinction between fortuitously used places and sites that are used regularly such that access to resources and facilities can be anticipated (p. 291). At fortuitously used sites, 93% of metates were unshaped, while at the regularly used sites only 53% of metates were unshaped. Further, only the regularly occupied sites contained metates manufactured from the most durable materials available such as quartzite and granite (p. 295). For ground stone tools, then, material choice and morphology may be factors that are responsive to anticipated durations of use, which in turn is affected by patterns of mobility. Hence, optimality modeling of economic costs and benefits related to choice of tool stone and manufacturing effort may be useful for evaluating mobility and duration of site use in highly and moderately mobile contexts.

Working surfaces on grinding tools that lack exterior shaping are often assumed to have formed entirely through use rather than through deliberate manufacturing effort. Yet, the experimental data modeled here indicate that less than two hours of seed grinding will make it beneficial to manufacture a sandstone basin, or to increase the surface area on a basin grinding slab. Rock-on-rock grinding, especially with food as an intermediary material, removes stone at a much slower rate than deliberate pecking (Hayden, 1987; Wilke and Quintero, 1996). For example, after more than two hours of grinding, pecking was still clearly visible on the grinding tools used in the current experiments (Figs. 2 and 7). In a different experiment, Wright (1993) reported that marks from pecking were still visible on a sandstone metate that was used to grind hard field corn for more than 53 h! Considering these relatively low rates of attrition from use, threshold grinding times for manufacturing milling surfaces would be greatly exceeded before an equivalent grinding surface could form through use. This also illustrates that physical evidence for manufacturing, in the form of densely clustered pecking (Fig. 7), should be detectable on many expedient milling tools from archaeological contexts.

Rather than assuming that users of grinding tools would have passively waited for a better surface to form through use, it is more informative to ask when we should expect investment, and how much investment we might expect in expedient milling tools. In many, perhaps most contexts, it seems that the handling time for seeds would have been reduced by investing some time in shaping milling surfaces. This implies that where the encounter rate for higher ranked plant resources was low enough that seed use fell into the optimal diet, a preference for easily shaped raw material or the presence of pre-existing grinding tools on the landscape could have influenced site selection or resource use because of the time-saving advantages and reduced handling times they would have represented for processing seeds.[2]

Once seeds are in the diet, how much time people invest in shaping milling tool surfaces should depend on the amount of flour production needed or expected. This, in turn, depends on: 1) the length of stay, 2) the proportion of dietary energy needs met by seeds, and 3) the number of individuals that need to be fed per grinder.

It is also worth asking when manufacturing investment might *not* be expected for use-surfaces. Tool surfaces should be unshaped when time spent grinding seeds is very low, where manufacturing

[2] A study on Alyawara plant use by O'Connell and Hawkes (1981) found that in most cases, seeds were not added to the diet when caloric returns for a patch fell low enough that their inclusion would have increased overall energy returns for the patch. They explained this observation by noting that the plant collecting kit used by the women in their study did not include milling tools, and suggested that the handling costs of seeds had been significantly underestimated by not taking into account the costs of manufacturing or maintaining grinding tools (pp.109–110).

costs are very high, or where benefits from shaping are less apparent. For example, shaping will be more expensive where only very hard, less easily shaped raw materials are present, or might be less beneficial where large and naturally very flat raw materials are abundant. Also, resources other than seeds might have very different relationships to grinding surface texture and area. While increasing surface contact and surface area is beneficial for seed grinding, naturally rugged surfaces might be more desirable for grinding dried meat or for processing pulpy, fibrous plant resources.

Because of this, it is important to emphasize that analysis of surface areas and manufacturing effort should not be used in isolation, but as part of a larger analytical framework that includes use-wear analysis (Adams, 2002; Adams et al., 2009; Dubreuil and Savage, 2013; Dubreuil et al., 2015), and analysis of raw materials. Use-wear analysis can supply crucial information about the types of resources that were processed on grinding tools and the intensity of processing (Adams, 1988; Buonasera, 2013b; Dubreuil, 2004; Dubreuil and Grosman, 2009; Hamon, 2008). Combining data about types of resources that may have been processed and intensity of use, along with data on raw material selection, and physical evidence for or against manufacture, would allow formal considerations of manufacturing costs and benefits to inform us about economic decisions made by people who used these tools in the past.

5. Conclusions

Ground stone tools have served crucial roles in subsistence economies for millennia, increasing both the quantity and the quality of available foodstuffs by removing indigestible material, reducing cooking time and fuel requirements, and reducing toxicity (Stahl, 1989). Despite their importance to past hunting and gathering societies, the costs and benefits of manufacturing grinding tools in mobile settings have received little formal consideration by archaeologists. Unless tools exhibit clear evidence of exterior shaping, it is commonly assumed that little or no effort was spent manufacturing the working surface of food grinding tools; instead, use surfaces are assumed to have formed entirely through prolonged or repeated use. With a broad stroke, this common sense assumption reduces the value of an entire category of technology to inform us about economic decisions made by users of grinding tools (typically, women) in prehistory.

Controlled experiments and formal modeling can be combined in productive ways to provide new insights into decisions affecting ground stone tool design. This paper has focused on one type of simple optimality model that considers manufacturing costs of different raw materials and returns from increased grinding productivity to predict how much use is needed to profit from modifying grinding surfaces. Experimental values modeled here suggest that pre-shaping of seed grinding tools would have been optimal in many mobile settings. It also illustrates that greater returns would be achieved considerably sooner by increasing the surface area of sandstone grinding tools versus granite tools. Where both materials are available, and use time will be great enough that overall handling time can be reduced by shaping a grinding surface, it suggests that sandstone should be selected over granite unless other factors, such as a need for increased durability, are important. Material choice and manufacturing investments in less formalized milling tools can provide information on expected durations of use by mobile hunter–gatherers. By contrasting expectations with physical evidence of manufacturing and use, we can learn more about motivations and decisions made by people who used ground stone tools in the past.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2015.03.018.

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