Selective Transport of Animal Parts by Ancient Hunters: A New Statistical Method and an Application to the Emeryville Shellmound Fauna

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When deciding which parts of a prey animal to transport home, hunters may be more or less selective. In our vocabulary, unselective hunters are those who usually bring home most of the carcass; selective hunters are those who usually abandon all but the choicest (and/or lightest) parts. This paper uses the abcml statistical method to develop a means of estimating transport selectivity from the frequencies of skeletal parts in a faunal assemblage. It then applies the method to artiodactyl data from the Emeryville Shellmound in order to test the local depression and distant patch use hypothesis. This hypothesis predicts that selectivity should decline during the early part of the Emeryville sequence and rise during the later part. The initial analysis did reveal such a pattern, but this pattern disappeared when samples were pooled in order to produce acceptably narrow confidence intervals. Although this result weakens the hypothesis, it does not firmly refute it, because the model fits the data imperfectly in the critical middle portion of the sequence. Abcml also provides estimates of the intensity of attrition, which indicate that attrition was most severe in early strata and least severe in later ones. Substantial attrition (50% of bones surviving) is indicated even from samples that show no indication of attrition using conventional methods. These conclusions are based on assumptions about the processes of transport and attrition that are more reliable in qualitative outline than in quantitative detail. Consequently, the paper's qualitative conclusions are more trustworthy than its quantitative estimates. © 2001 Academic Press

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The Problem

Once a prey animal has been killed, the central-place forager must decide which parts to carry home. These decisions are presumably influenced by the values of the various parts, the difficulty of disarticulating parts from one another, and the difficulty of carrying each part home. This insight has spawned a long tradition of research within zooarchaeology (reviewed by Lyman, 1994). Presumably, transport decisions will be more selective in some circumstances, less selective in others. For example, hunters may be highly selective—abandoning all but the most valuable and lightest parts—if they have killed prey far from home. They may be less selective if the prey was killed closer to home. It should be possible to learn about the circumstances that influenced ancient transport decisions by estimating the selectivity of these decisions.

Unfortunately, we have no satisfactory means of doing this. The method in general use was developed in the late 1970s and 1980s (Binford, 1978; Thomas & Mayer, 1983; Lyman, 1984, 1985; Grayson, 1988). It bases inference on the association between the frequencies of skeletal parts within an assemblage and

their economic utilities. Since the statistical distributions of these variables are unknown, inference is usually based on some non-parametric measure of association such as Spearman's *r* (Kendall & Stuart, 1979). This approach has several drawbacks: first, it violates the assumptions of the statistical methods that are used. Even non-parametric measures of association make two distributional assumptions: They assume that the counts of different skeletal parts are statistically independent and that they share the same (unknown) statistical distribution. Neither assumption is satisfied here. The independence assumption fails because bones are not deposited in a site independently—unwanted parts may be deposited simply because they were attached to something that was wanted (Binford, 1981: 3). The assumption of identical distributions fails because some parts are represented more times in an animal than others and thus provide a larger sample and a smaller sampling variance. Second, we have no theory relating an estimate of (say) Spearman's *r* to any particular level of selectivity. We cannot infer the selectivity of transport from an estimate of *r*. Neither can we infer much from comparisons between assemblages. Spearman's *r* may differ significantly from zero in one assemblage but not another for any of several

reasons. The difference may reflect an increased selectivity of transport decisions, but it could also reflect a larger sample size or a lower level of attritional damage.

A simpler approach, which avoids the worst of these problems, is to use some measure of the mean utility of bones within an assemblage as a measure of transport selectivity (Broughton, 1999). If hunters select parts for transport on the basis of their food utility, then the mean food utility should be higher the more selective the hunters are. This approach violates no statistical assumptions because it makes none. It does, however, have drawbacks of its own. Mean food utility is, at best, only a relative measure of transport selectivity: we don't know what level of this variable corresponds to any particular degree of selectivity. For this reason, it is only useful in comparisons between samples. But differences between samples are hard to interpret because they may have various causes. For example, they may reflect differences in the intensity of attrition or simply the effects of random sampling. It is difficult to control for these factors because existing methods provide only a crude means of controlling for attrition and because we have no statistical theory for mean food utility.

Outline of a Solution

We develop here an alternative method for estimating the selectivity of transport decisions. It is based on a statistical method called abcml, which is described in some detail below. Abcml is designed to estimate simultaneously the contributions to a faunal assemblage made by each of several agents of deposition. In addition, it estimates the number of animals contributing to the assemblage and the intensity of density-mediated attrition. Along with these estimates, it provides confidence intervals and a measure of goodness of fit. It avoids the statistical problems outlined above.

In the present paper, we show how abcml can be extended in order to estimate the selectivity of human transport decisions—the tendency of human hunters to abandon carcass parts of low value at the kill-site, and to carry home only the parts of highest value. In extending the method, we will in various places encounter a need for information that we do not have. Where this happens, we will resort to heroic assumptions, establishing by fiat whatever parameter values are unknown to us. These assumptions will be designed to conform as closely as possible to conventional wisdom.

We apply our new measure of transport selectivity to a problem in California prehistory. Using the artiodactyl fauna from the Emeryville Shellmound, a hypothesis is tested involving local resource depression and the use of distant resource patches.

Rationale

In lieu of detailed information about transport and attrition, we propose to rely on unsupported assumptions. As a result, there will be room for doubt about every conclusion that we draw. What is the value of this procedure?

We would defend it in several ways. First, we hope that our approach to inferring the selectivity of transport decisions will ultimately be of value even if our initial application is based on faulty data. As the field learns more about the processes of transport and attrition, our statistical method will provide increasingly accurate estimates of the history of transport selectivity at specific archaeological sites.

Second, our assumptions will mimic conventional views about transport and attrition, views that underly many recent attempts to deal with these issues (Grayson, 1988; Lyman, 1994; Broughton, 1999). Consequently, our analysis will answer an important question even in the short run: it will tell us what these conventional views imply about the history of transport selectivity at the Emeryville Shellmound.

Third, our assumptions are more likely to be accurate in broad outline than in quantitative detail. Our conclusions about transport selectivity are thus more likely to be correct qualitatively than in quantitative detail.* Although there will always be room for doubt, we would argue that our qualitative conclusions are worth taking seriously.

Fourth, our results will illustrate the kinds of inferences that would be possible given a detailed understanding of transport and attrition. We hope that they will encourage ethnographic and experimental research on these issues.

Finally, it is worth pointing to a distinction between the unsupported assumptions that we will make below and those that we criticized above. Each of the unsupported assumptions that we will make reflects a shortcoming that could be remedied through empirical research. The same cannot be said of the problems identified above. Those problems are intrinsic to the statistical methods employed, and no amount of empirical research would remove them.

Estimating the Selectivity of Transport Decisions

Our measure of transport selectivity is based on a statistical method called abcml, an acronym for Analysis of Bone Counts by Maximum Likelihood (Rogers,

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*While it is usually true that the qualitative conclusions of a model are as reliable as its qualitative assumptions, it is not always true. To verify this claim for our own model, it would be necessary to perform a sensitivity analysis, varying each assumption in order to find out how the answers change in response. We have done a little of this, as we describe below in the Discussion, but we have not attempted any comprehensive sensitivity analysis. Thus, we claim only that our conclusions are "more likely to be correct qualitatively than in quantitative detail".

Table 1. *Configurations and agents of deposition*

		→→Increasing utility→→						
Configuration	Feet	Head	Axial	Front limbs	Rear limbs	Unselective	More selective	Most selective
1	+	+	+	+	+	0·80	0·04	0·04
2	−	+	+	+	+	0·08	0·40	0·08
3	−	−	+	+	+	0·08	0·40	0·08
4	−	−	−	+	+	0·02	0·08	0·40
5	−	−	−	−	+	0·02	0·08	0·40

2000*a*). Abcml requires detailed information about the "agents of deposition" that are thought to be responsible for an assemblage. Any process that contributes bones to an assemblage can be construed as an agent of deposition. For example, we might wish to distinguish between the bones that are contributed by hyenas at a kill site and the bones contributed by human hunters at a home-base site. We might further distinguish between hunters who have killed an animal near their home base, and hunters whose kill is farther away. Each of these might be construed as an agent of deposition. Each agent must be described in detail, as we discuss below.

In addition, abcml requires information about the sensitivity to attrition of each skeletal part that is tabulated. We assume that sensitivity to attrition is inversely proportional to a bone's density, and we estimate the density of each part by averaging the relevant values in Lyman's (1994: Table 7.6) photon densitometer (PD) results for deer (*Odocoileus* spp.), the taxon of primary interest here.*

Given this information about transport and resistance to attrition, abcml uses skeletal part counts to estimate: (1) the fraction of the faunal assemblage contributed by each agent of deposition; (2) the intensity of attritional processes, such as gnawing by carnivores and leaching by ground water or acidic sediment; and (3) the number of animals in the assemblage. These estimates are obtained using the method of maximum likelihood, which underlies many familiar statistical methods and has a number of desirable statistical properties (Kendall & Stuart, 1979). Maximum likelihood estimates make efficient use of data, and their sampling distribution is approximately normal (the approximation improving with sample size). This makes it easy to test hypotheses and generate-confidence regions.

Our problem here is to adapt this method to the problem of transport selectivity. When a prey animal is killed, the hunter must decide which parts of the carcass to discard and which parts to transport home. Following long tradition, we assume that parts of lowest food utility will be discarded first. To approximate this behaviour, we define three hypothetical agents of deposition:

● Unselective: The hunter usually transports the entire prey animal.
● More selective: The hunter usually discards some parts of low utility before transporting the carcass.
● Most selective: The hunter usually transports parts of highest utility only.

Thus far, our model is imprecise. It is intended merely as a restatement of the now-conventional view of transport selectivity that was first articulated several decades ago (White, 1954; Perkins & Daly, 1968).

To make these characterizations useful, we must make them precise by replacing vague terms such as "usually" and "low utility" with numerical values. But this precision will not imply realism, for our numerical values will be guesses that are constrained only by (1) the conventional view of transport that we have just described, and (2) empirical data on the food utility of portions of carcasses (Binford, 1978; Metcalfe & Jones, 1988). Our agents will not be accurate descriptions of any real-life agent of deposition; they will be caricatures whose sole purpose is to provide a scale of transport selectivity that agrees qualitatively with the conventional view of transport selectivity.

Imagine that it were possible to tally the skeletal parts added to an assemblage each time an animal was deposited there. For some animals we would get the whole skeleton; for others only a bone or two. Each of these constitutes what we will call a "configuration"—a list of skeletal parts contributed to the assemblage when one prey animal (or portion thereof) is deposited. For simplicity, we assume that only five configurations are ever transported, as shown in Table 1. The first configuration there consists of all the bones in an entire skeleton. The second is the entire skeleton minus a low-utility part (the feet), and so on. An extremely unselective hunter might always transport the first configuration. An extremely selective one might always transport the last.

*Recently, new estimates of density based on Computed Tomography (CT) have begun to appear in the literature (Lam, *et al.*, 1998). It is not yet clear whether the CT estimates predict sensitivity to attrition better than PD estimates, since the requisite experimental work has not yet been done on CT estimates. In the present paper, this issue is moot since no CT estimates of density are available for deer.

Next, we must specify the probability with which each agent transports each configuration. The probabilities we used are given in the three right-most columns of Table 1. As these probabilities show, the "unselective" agent is quite likely to transport an entire carcass and quite unlikely to transport only limbs. The "most selective" agent, on the other hand, is unlikely to transport an entire carcass and likely to transport just limbs. Thus, our hypothetical agents of deposition provide a scale of increasing selectivity in transport decisions.

This model is qualitatively consistent with the conventional view (described above) that hunters are most likely to transport those skeletal parts that carry a great deal of meat. This view recieves only mixed support from the ethnographic record: it is supported by Binford's (1978) observations of meat transported by Nunamiut eskimo but not by ethnographic observations of the Hadza (Bunn, Bartram & Kroll, 1988; O'Connell, Hawkes & Blurton Jones, 1988, 1990) or the Kua (Bartram, 1993), human foragers in eastern and southern Africa. These African samples do however support several assumptions that underlie our model: in the Hadza data, configurations can be arranged into a uni-dimensional scale, and in the Kua data the fraction of the bones that are transported decreases with the time spent processing the carcass in the field. Both observations suggest the importance of selectivity in transport decisions. Yet of the three ethnographic data sets, only the Nunamiut data support our assumptions about which skeletal parts are discarded first. Nonetheless, it is useful to have a model that mimics the conventional view of transport selectivity. This will allow us to compare our results with Broughton's earlier work, which was also based on the conventional view.

Given the agents of deposition defined in Table 1, abcml estimates the following parameters for each faunal assemblage:

α_0 = the fraction of the animals in the assemblage contributed by the "unselective" agent of deposition.

α_1 = the fraction contributed by the "more selective" agent.

α_2 = the fraction contributed by the "most selective" agent.

K = the number of animals deposited in the assemblage.

κ = the expectation of K implied by the stochastic process that produced the assemblage. An estimate of κ is also an estimate of K, but the confidence interval of κ is larger than that of K. Thus, an estimate of κ can be viewed as an estimate of K with a conservative confidence interval. For further discussion of the distinction between κ and K, see Rogers (2000a).

β = a measure of the intensity of attrition. Abcml assumes that a copy of the ith skeletal part survives attrition independently with probability $e^{-\beta s_i}$, where s_i measures the sensitivity of part i to attrition and is assumed to be inversely proportional to the density of part i. The constant of proportionality is chosen so that on average half the bones in a complete skeleton would survive attrition when $\beta = 1$.

Finally, we define a univariate scale that measures the selectivity of transport:

$$S = \alpha_1 + \alpha_2$$

In words, S equals the sum of the frequencies of the two selective agents of deposition; it thus measures the tendency for transport decisions to select in favor of high-utility parts of the carcass.*

Resource Depression and the Emeryville Shellmound Vertebrate Fauna

Anthropologists have long emphasized the abundance of resources available to native peoples of California (Kroeber, 1925). This has given a decidedly utopian quality to traditional descriptions of California prehistory (see a recent version in Fagan, 1995: 253). Yet certain foods that served as staples in the region at contact (especially acorns [*Quercus*, *Lithocarpus*]) are expensive to process relative to their caloric returns (Basgall, 1987). As the human population of California increased in size during the last 4000 years, acorns became increasingly important (Basgall, 1987; Wohlgemuth, 1996). This suggests that the increase in population size was accompanied by a decline in overall foraging return rates (Basgall, 1987; Bettinger, 1991). If so, we should find evidence that foraging efficiency declined for other resources, including vertebrates. Recent zooarchaeological work has examined this issue (Broughton, 1994a,b, 1995, 1997, 1999; Hildebrand & Jones, 1992; Jones & Hildebrandt, 1995; Raab *et al.*, 1995). It was also examined by one of us (Broughton, 1995, 1999) using the Emeryville Shellmound vertebrate fauna. That analysis used non-parametric statistical methods to examine trends in taxonomic composition, skeletal part representation, and bone damage. It provided support for human-induced declines in vertebrate foraging efficiency across the late Holocene occupational history of this site.

The Emeryville Shellmound (CA-ALA-309) was located on the east shore of San Francisco Bay, California, before it was destroyed in 1924 (Figure 1). The mound was excavated three times, each time in a different location. Most of these excavations were conducted stratigraphically, and 10 primary strata were revealed. The excavations provided 17 faunal samples that could be placed into stratigraphic context.

*The reader may be wondering why we defined three agents of deposition only to collapse two of them into the single parameter, *S*. This procedure allows the model to adapt more flexibly and results in a better fit of model to data.
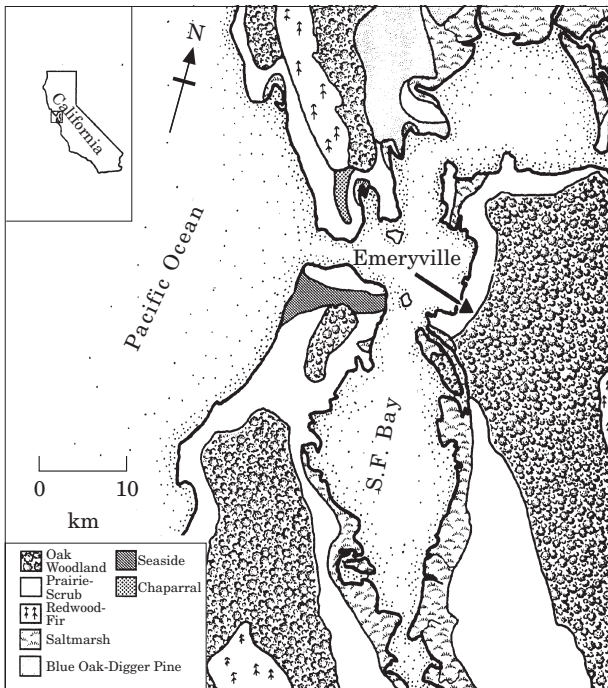
Figure 1. Map of San Francisco Bay area indicating the location of the Emeryville Shellmound and early historic period vegetation. (Vegetation redrawn from Küchler (1977).)

Fourteen radiocarbon dates range from ~2600 to 700 ^{14}C years BP and exhibit no stratigraphic inconsistencies. The Emeryville deposits thus allow a fairly fine-grained ordinal-scale analysis of change in verte-brate foraging across ~1900 years of occupation (see Broughton, 1995, 1997, 1999). During this time, the East Bay region appears to have witnessed significant human population growth, at least to judge from the increase through time in the number of dated site components (Broughton, 1999). Thus the Emeryville region follows the more general California trend of expanding human population densities during the late Holocene.

In a rich environment, it would be foolish to waste time on prey that are small, hard to catch, and/or hard to process once caught. These low-ranked prey will be ignored because one can get more to eat in less time by concentrating on prey that are large, easy to catch, and easy to process. (This insight is formalized in the "diet-breadth model" MacArthur & Pianka, 1966; Stephens & Krebs, 1986.) Consequently, foragers in rich environments should produce archaeological deposits that are rich in high-ranked prey. And the prey of highest rank tend often to be those that are largest in size. Thus, in a deteriorating habitat, large prey should make up a smaller and smaller fraction of the resources derived from local patches.

At Emeryville, this is clearly the case for sturgeon (Broughton, 1997, 1999). The white sturgeon (*Acipenser transmontanus*) is an enormous fish—big ones can reach 6 m in length and weigh 700 kg. The Emeryville deposit does not contain monsters of this size, but it does contain big fish. For example, a sturgeon with an 11mm dentary width would have been 1·7 m long and weighed over 50 kg. The largest fish in the Emeryville fauna would have been a third
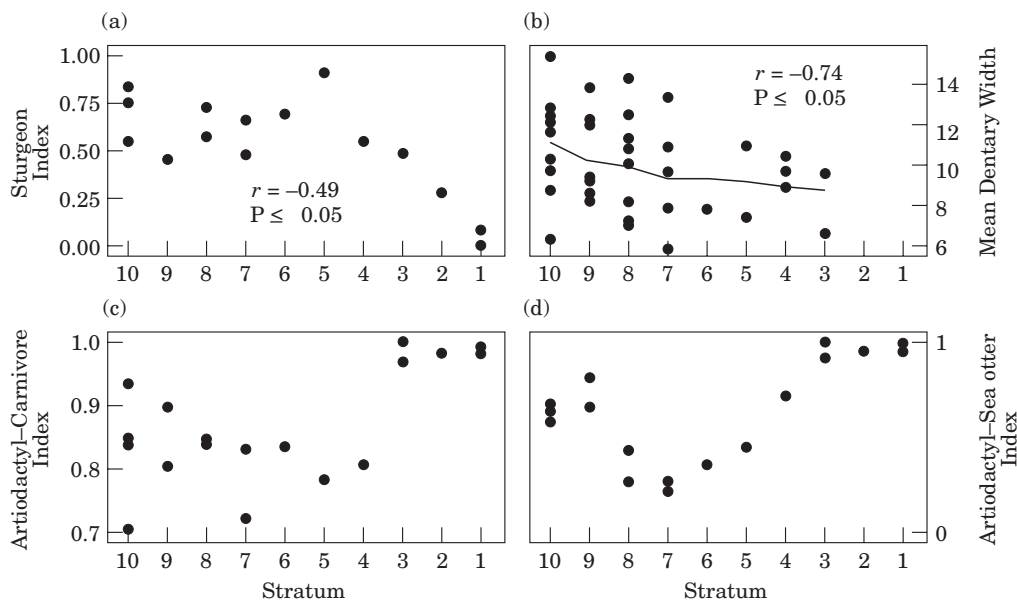

Figure 2. Panel a: Relative frequency of sturgeon (*Acipenser* sp.). Sturgeon index is (NISP sturgeon)/(NISP fishes). Panel b: Width of sturgeon dentaries. Line was fit using the lowest algorithm (Cleveland *et al.*, 1992). Panel c: Frequency of artiodactyls relative to small carnivores. The artiodictyl/carnivore index is (NISP artiodactyls)/(NISP artiodactyls + small carnivores). Artiodactyls include black-tailed deer (*Odocoileus hemionus*) and tule elk (*Cervus elaphus*). Small carnivores include coyote (*Canis latrans*), racoon (*Procyon lotor*), and striped skunk (*Mephitis mephitis*). Panel d: Frequency of artiodactyls relative to sea otters (*Enhydra lutris*). The artiodactyl/sea otter index is (NISP artiodactyls + sea otters). Data from Broughton (1999).

again as long and would have weighed close to 140 kg. Changes in the abundance of sturgeon across the Emeryville sequence are illustrated in Panel a of Figure 2. The horizontal axis there ranges from stratum 10 (the most ancient stratum in the site) to stratum 1 (the most recent). Sturgeon remains become rarer and rarer as we move from early strata to late strata of the site. Not only do sturgeon get rarer: Panel b of the figure shows that the ones that are caught decline in size. Both patterns suggest an increase in harvest pressure. (These changes are not correlated with salinity, the most potent influence on the current sturgeon population in the Bay.)

Other estuarine resources show similar patterns. For example, the surface-dwelling mollusks of largest size (California oyster, *Ostrea lurida*, and bay mussel, *Mytilus edulis*) decline significantly ($r = -0.54$; $P < 0.05$) across the Emeryville strata relative to the smaller bent-nosed clam (*Macoma nasuta*) that dwell beneath the surface (Broughton, 1999: 71, data from Gifford, 1916: table 15).

The largest common mammalian prey in the Emeryville data are artiodactyls (black-tailed deer and tule elk). Panel c of Figure 2 graphs the abundance of these prey relative to small mammalian carnivores such as coyotes, racoons, and striped skunks. Over the early portion of the site (strata 10–6 or 7), artiodactyls decline relative to small carnivores. But then the graph reverses direction in the later portion of the record. (The resurgence reflects an increase in the frequency of deer; elk are virtually non-existant in the upper strata.) A similar pattern is seen in Panel d, which graphs the frequency of artiodactyls relative to sea otters.*

Collectively, these data sets suggest the following hypothesis:

Hypothesis 1 (Local depression and distant patch use)

Encounter rates with prey animals declined throughout the occupation of the Emeryville Shellmound. As the region near the site became depleted of prey, the human residents of the site travelled with increasing frequency to more distant (and less depleted) patches. In these less depleted patches, the optimal diet would include fewer low-ranked prey (MacArthur & Pianka, 1966; Broughton, 1999).

This hypothesis accounts for all of the data shown in Figure 2. To test it, Broughton (1999) introduced several ancillary hypotheses. Two of these, which deal with the selective transport of artiodactyl parts, are central to our analysis:

Ancillary hypothesis 1 (Game density opportunity cost)

When an animal is killed, a hunter must decide whether to carry the entire carcass home, or to leave certain

*The similarity of these patterns is interesting since sea otters and artiodactyls do not inhabit the same patches and would not be taken in the same hunts. In this case, it doesn't seem to matter whether different hunt types are analysed separately (see Smith, 1991; Broughton, 1994a: 374; Broughton, 1995, 1999; Cannon, 1999).
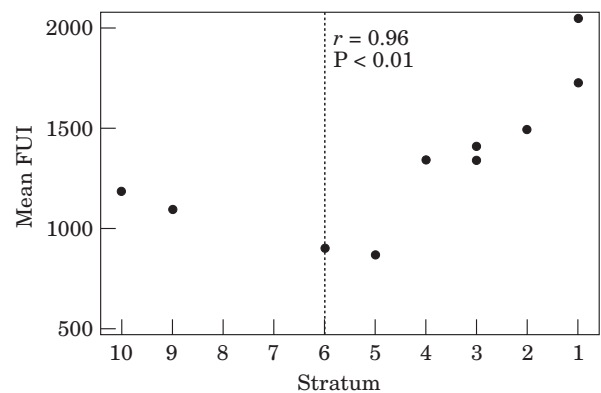

Figure 3. Mean utility of artiodactyl skeletal parts. Samples showing a significant correlation between part density and part representation have been excluded. The Food Utility Index (FUI) is defined by Metcalfe & Jones (1988). Spearman's r (and associated P-value) were calculated on strata 1–6.

heavy and/or low-utility parts at the kill to lighten the load and speed the trip back. The opportunity cost associated with the first option is high if game are common but low if game are scarce. As game becomes scarcer, less and less will be discarded at each kill site. Transport decisions will become less and less selective (see Bettinger, 1991: 107; Broughton, 1999: 17).

Ancillary hypothesis 2 (Travel cost)

When prey must be transported over long distances, it makes sense to lighten the load by abandoning carcass parts that are heavy and/or low in utility (Metcalfe & Barlow, 1992; Barlow & Metcalfe, 1996). Transport selectivity should increase as greater use is made of distant patches.

Taken together, these hypotheses predict a decline in transport selectivity across the shellmound's early strata and an increase across the later strata. Before looking for this pattern, however, it was necessary to exclude samples damaged by density-mediated attrition (Lyman, 1985; Grayson, 1988, 1989). Broughton (1999) calculated non-parametric correlation coefficients between deer bone density values and relative skeletal abundances for each of the 17 artiodactyl samples. Seven of the samples in the lower strata of the deposit exhibited significant correlations and were therefore eliminated from further analysis, in accordance with standard practice. The cause of this attrition is unclear. Carnivore damage is extremely rare in the Emeryville fauna and does not vary across strata. It is possible that leaching from saline ground water may be the cause. Ground water was encountered by the excavators in the lower strata (Broughton, 1999). The role of leaching by saline ground water in density-mediated attrition has not been explored experimentally.

To assess transport selectivity within the remaining samples, Broughton examined the relationship between the relative frequencies of artiodactyl body parts and

their economic utilities as indicated by the Food Utility Index (FUI) (Binford, 1978; Metcalfe & Jones, 1988). Where transport selectivity is high, he reasoned, mean FUI should also be high. Thus, Broughton (1999) expected the mean utility of artiodactyl skeletal parts to decline across the early strata of the site and then to increase across the later strata. As Figure 3 shows, this is exactly what he found. Although too few samples remained in the lower strata to evaluate a trend, the mean FUI increased significantly across the upper six strata.

Patterns were also sought in data from the Emeryville Shellmound concerning bone fragmentation and cutmarks, artiodactyl and sea otter age structure, and the taxonomic composition of the birds. In each case, the results were consistent with the hypotheses. The Emeryville fauna provides support for the view that foraging returns declined across the occupational history of the site.

Re-analysis of the Emeryville Artiodactyl Skeletal Part Frequencies

Broughton's analysis of artiodactyl part frequencies from Emeryville (just described) suffers from several of the problems that we summarized in the introduction to this paper. To reiterate briefly, the mean FUI is an imperfect measure of transport selectivity and Spearman's correlation procedure makes assumptions that are violated when data points are based on samples of differing size. Our new transport selectivity scale avoids both problems.

Unfortunately, however, it encounters another. The Emeryville artiodactyl data consist of tabulations of the number of identifiable specimens (NISPs) for each skeletal part considered. Since bones are often fragmented, a single skeletal part may be counted in the NISP several times. Abcml makes no allowance for this. It assumes that each skeletal part is counted either once (if it surivivied attrition) or not at all. To avoid violating this assumption, it would be necessary to re-tabulate the bones, basing all counts on landmarks—recognizable features that are (ideally) so small that they are unlikely to be counted twice even in heavily fragmented bone.* For the present, we will simply live with any error that is introduced by using NISPs.

We used abcml to estimate the parameters of our model in several different ways. The results are all shown in Figure 4. In the upper row of panels within this figure, each bold dot shows an estimate of S, the transport selectivity scale. In the middle row, each dot shows an estimate of β, the intensity of attrition. In the lower row of panels, each dot shows a value of χ^2,

which measures how badly the model fits the data. If the model is correct, roughly 95% of the dots should be below the dotted line.

In the upper row of panels, the vertical "whiskers" attached to most of the dots show 95% confidence intervals. Where there are several points for a single stratum, the vertical whiskers overlap. In some cases, there is no confidence interval at all, either because the estimate is at a boundary or because the likelihood function was poorly behaved.*

Consider first the figure's left column of panels. There, each of the 17 faunal samples is analysed separately. If we set aside one high value (in stratum 7), it appears that S declines smoothly from stratum 10 through stratum 6 and then rises from stratum 6 through stratum 1. This is exactly the pattern that is predicted by the three hypotheses stated above. Since our hypotheses predict a different pattern in strata 10–6 than in strata 6–1, we analyse these segments of the sequence separately. In each case, Spearman's r detects a significant trend: r is -0.7 ($P<0.05$) across levels 10–6 and 0.75 ($P<0.05$) across levels 6–1. Yet this analysis is less than convincing because the data points have very different sample sizes. These differing sample sizes violate the assumptions of Spearman's r because they imply that the data points are not drawn from identical distributions.

An alternative approach to the problem relies on the confidence intervals (shown as vertical whiskers) of the estimates themselves. Unfortunately, those in the upper-left panel are so broad that they are of little use.

To increase the precision of the estimates, we first tried pooling the samples from each stratum to obtain one sample per stratum. Analysis of the resulting 10 samples produced the results shown in the middle column of panels in Figure 4. With these data, several of the confidence intervals are smaller, but there is less evidence of the pattern predicted by our hypotheses. The pattern is mostly flat except for a couple of high points in the early period and one low point at level 6. This low point agrees with our hypotheses, which predict low values in strata 6 and 7. But there is no consistent decline in the early period and no consistent rise in the later period. The confidence intervals are broad, especially in the middle strata that are most critical to the hypothesis.

The confidence intervals are broad because several of the samples are small, as shown in Table 2. For example, the sample from stratum 6 includes only 37 bone fragments and yields an MNI of 2. We are

*One reviewer suggested that the skeletal parts be tabulated using the Minimum Number of Elements (MNE). However, the MNE is also inconsistent with abcml for reasons that are discussed by Rogers (2000a).
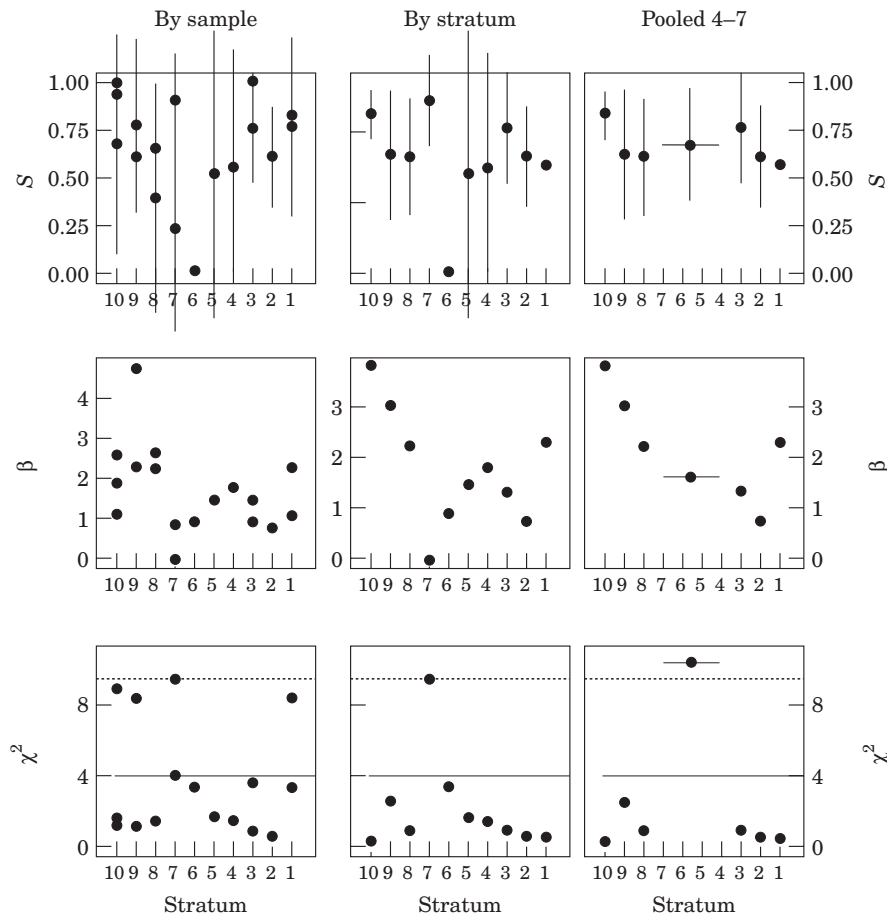
*Standard methods for inferring confidence intervals rely on the fact that maximum likelihood estimates occur at points where the derivatives of the likelihood function are zero. This is not the case when estimates are at boundaries, such as the estimates of S for stratum 6 in the upper-left and upper-middle panels. When estimates occur at interior points, the sampling variances and covariances are obtained by inverting the Jacobian matrix. When this matrix is singular, no sampling variances (and no confidence interval) can be obtained. This is what happened with stratum 1 in the upper-middle and upper-right panels.

Figure 4. Estimates of transport selectivity (S), intensity of attrition (β), and badness of fit (χ²). Left column: Each sample analysed separately. Middle column: Samples pooled to achieve one per stratum. Right column: Strata 4–7 are pooled. Top row: Estimates of S, the selectivity of transport. Vertical bars show 95% confidence intervals. Horizontal bars show the strata covered by each estimate. Middle row: Estimates of β, the intensity of attrition. Bottom row: χ², a measure of badness of fit of the data to the model, which approximates a chi-squared random variable with 4 degrees of freedom. The mean value, 4, is shown as a horizontal solid line; the 0·05 critical value is shown as a dotted line.

Table 2. Size of sample from each stratum, after pooling samples from the same stratum

Stratum	NISP	MNI	$\kappa \pm$ S.E.
1	294	8	7·6 ± ?
2	1545	32	19·2 ± 5·5
3	593	17	11·6 ± 5·3
4	181	7	2·9 ± 1·9
5	112	5	1·3 ± 1·2
6	37	2	0·09 ± ?
7	292	15	5·2 ± 1·9
8	353	8	12·6 ± 4·6
9	274	9	15·59 ± 4·9
10	596	18	52·9 ± 8·2

Note: NISP is the Number of Identified Specimens. MNI is the Minimum Number of Individuals, calculated as described by Rogers (2000a). κ estimates the number of animals contributing to the assemblage, and s.e. is the standrd error of κ. Both estimates are provided by abcml.

dealing here with a small sample of transport decisions, so it is not surprising that our estimate of selectivity should be poor.

To improve the confidence intervals in the middle part of the sequence, we pooled strata 4 through 7 to obtain the results shown in the right column of panels in Figure 4. All confidence intervals are now reasonably small, and the estimates are of roughly equal value throughout the sequence. Taken at face value, this result is inconsistent with our hypotheses. Before discussing this result, we must consider the other parts of Figure 4.

The panels in the middle row of Figure 4 show estimates of attrition. Apart from stratum1 (which had a poorly-behaved likelihood function), the results show a progressive decline in the intensity of attrition, in agreement with Broughton's previous analysis (see above). The most heavily damaged assemblages are those in the lowest strata. Within these strata, estimates

of attrition are truly severe. For example, in stratum10 abcml estimates that $\beta \approx 3.79$. This implies that roughly 10% of the bones originally deposited have survived.

Even in the later strata, several of the estimates are close to unity, implying that about half of the bones originally deposited have been lost. This is surprising, since these strata showed no significant correlation between the abundances of skeletal parts and their densities. On this basis, Broughton inferred that density-mediated attrition was not important. The present results suggest that the conventional method of detecting attrition is extremely insensitive. It can fail to detect attrition even when the sample size is large and a large fraction of the bones originally deposited has been destroyed.

The χ^2 values graphed in the lower panels measure the goodness of fit of the model to the data. When the model is correct, these statistics approximate a chi-squared random variable with 4 degrees of freedom. The expected value, 4, is shown as a solid line in the figure, and the critical value for $P = 0.05$ is shown as a dotted line. Even when the model is correct, χ^2 values will fall above the dotted line 0.05% of the time, so the single high values in the lower-middle and lower-right panels are not conclusive evidence that the model is inappropriate. They are, however, cause for concern. In strata 4–7, the model does not appear to fit the data very well. This poor fit may have introduced bias, so we should be skeptical of the parameter estimates from these strata even though their confidence intervals are narrow.

Discussion

There are grounds for scepticism about all of our empirical results because they rest on unsupported assumptions about transport and attrition. For the moment, however, let us set these doubts aside and discuss results as though we had full confidence in the underlying assumptions.

Taken together, the three hypotheses stated above lead us to expect a V-shaped pattern in selectivity: selectivity should decline during the early part of the Emeryville sequence and increase during the later part. When all 17 samples are analysed separately (as in the left column of Figure 4), the results appear to support this view, yet this support evaporates when the samples are pooled to increase the precision of the estimates. The V-shaped pattern in our stratum-by-stratum estimates is produced mainly by the low estimate of S in stratum 6, and this low estimate may reflect nothing more than the small size of the sample from that stratum.

Although these results offer little support for our hypotheses, they do not firmly reject them either. In the first place, it is easy to draw a V-shaped line that lies entirely inside the confidence intervals in any of the panels in the top row of Figure 4. Thus, we cannot reject the hypothesis that the V-shaped pattern exists. In the second place, the large χ^2 value for strata 4–7 means that we cannot place great confidence in the estimates for these strata. Finally, we may have obscured the pattern we are seeking by pooling strata 4–7. Because of these problems, we cannot exclude the possibility that selectivity dipped to a low value in the middle portion of the sequence.

Although we cannot reject our hypotheses conclusively, our results do weaken the case in favour of them. It is worth asking what revisions are reasonable. We see no reason to revise the view that foraging returns declined across the period represented in the Emeryville deposit. This inference is supported not only by the data on mean food utility, but also by a host of other indicators (reviewed above). It is supported not only at Emeryville but also at numerous other sites in this area (Broughton, 1994a, 1999). The portion of the Emeryville story that may need revising has to do with the changing roles of near and distant patches in the local foraging economy.

That portion of our argument has assumed that the Emeryville sequence can be divided into two intervals—an early interval during which prey encounter rates declined near the site, and a later interval that saw increasing use of distant patches. We have proposed that transport selectivity declined during the first interval and increased during the second. But perhaps these processes were simultaneous: Each reduction in local encounter rates may have increased the use of distant patches. If so, then selectivity would have been affected in opposite ways at the same time: It would have been pushed downward by declining productivity within the local patch and upward by increased use of distant patches. The result might have been an absence of change in selectivity—the pattern suggested by the upper-right panel of Figure 4.

It is also possible that either or both of our ancillary hypotheses are false. The game density opportunity cost hypothesis assumes that hunters in rich habitats sacrifice low-ranked body parts in order to gain additional foraging time. This hypothesis would fail if the time spent removing parts exceeded the travel time saved, or if no habitat were ever rich enough to make this sacrifice worthwhile. The travel cost hypothesis assumes that hunters in distant patches spend time processing the carcass in order to lighten the load that must be carried and/or maximize the calories contained within it. This hypothesis would fail if for some reason (perhaps warfare) it were unsafe to spend time processing carcasses in distant patches. In short, these hypotheses may be satisfied never, always, or only under certain circumstances. Ethnographic research is needed to address these questions.

Our results on attrition are in much closer agreement with those of Broughton (1999) than are our results on transport selectivity. Like Broughton, we find that attrition is more intense in the early strata than in the recent ones. But the new analysis also adds new insight.

First, it indicates that attrition in the early strata is so severe that roughly 90% of the bones in some strata have been lost. It is remarkable that any information can be extracted from such severely damaged assemblages. Second, it indicates that attritional damage may be moderately severe even in assemblages that show no trace of damage using conventional methods. For example, neither of the samples from stratum 3 showed a significant correlation between part representation and part density, so both samples were included in Broughton's earlier analysis (Figure 3). Yet the new analysis indicates that $\beta = 1\cdot31$ in stratum 3, and this implies that roughly 60% of the bones originally deposited were destroyed. If this estimate is accurate, then conventional methods of controlling for attrition do a very poor job. This conclusion echoes that of Rogers (2000*b*), who both demonstrates and explains the low power of conventional methods.

Having discussed our results as though we had full confidence in the underlying assumptions, we now turn to the problems that would arise if one or more of these assumptions were wrong. We argued above that our assumptions are more likely to be qualitatively correct than they are to be correct in quantitative detail. This distinction is nicely illustrated by our model of transport selectivity. That model embodies both qualitative and quantitative assumptions. The qualitative assumptions consist of what we have called the conventional view of transport selectivity: the view that carcass parts of low food utility are discarded first. The quantitative version of this assumption consists of the numerical values collected in Table 1. It is entirely possible that the quantitative assumptions are wrong even if the qualitative assumptions are right.

What effect would this have on our results? We have experimented with various alternatives to the values in Table 1, all of which are consistent with the verbal theory. These led to somewhat different estimates of S and (to a lesser extent) to different estimates of β. But in all cases the qualitative pattern was the same: the estimates of β decline as one progresses up the sequence, and there is no significant evidence for a V-shaped pattern in the estimates of S. Thus, we are confident that our qualitative conclusions are not artifacts of the particular numerical values that we present in Table 1.

There are also both qualitative and quantitative versions of our assumptions about attrition. The qualitative version claims only that dense bones are more resistant to attrition than are less dense bones. The quantitative version of our assumption agrees with this claim but also stipulates a particular functional form for the relationship between density and resistance to attrition. The qualitative version has broad empirical support support (Brain, 1967; Marean *et al.*, 1992) and is unlikely to be wrong; the quantitative version is merely a guess. Once again, our qualitative assumptions are more reliable than our quantitative ones. It follows that our qualitative conclusions should be taken more seriously than our quantitative ones.

With the Emeryville data, our qualitative conclusions include the absence of a strongly V-shaped pattern in the selectivity estimates and the decline in intensity of attrition as one moves from early to late strata within the site. Although there is still room for doubt, these inferences are worth taking seriously. Our quantitative inferences include the numerical estimates of S and the claim that 90% of the bones in some strata have been lost. These inferences should be viewed with greater caution.

We turn finally to the unhappy possibility that our assumptions are fundamentally wrong: wrong not only in quantitative detail but also in qualitative pattern. Such errors would seriously undermine our empirical conclusions, but that is not all they would do. They would also undermine the work of many other scholars whose conclusions rest on the same qualitative assumptions about transport or about attrition (Brain, 1967, 1968, 1969; Binford, 1978; Thomas & Mayer, 1983; Lyman, 1984, 1985; Grayson, 1988; Broughton, 1999). But even in this least fortunate of cases, the work we have done is not without merit, for the statistical method introduced here is of value in its own right. As improved information about the processes of transport and attrition become available, the new method should provide increasingly accurate estimates of the history of transport selectivity in archaeological bone assemblages.

Acknowledgements

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