Archeologists have long assumed that transport considerations have been important in structuring various aspects of the archeological record. An optimality model, derived from the principles of evolutionary ecology, is presented to investigate the trade-off between field processing and transport for central place foragers. The model implicates (1) the time required to make a round-trip and (2) the relationship between time spent field processing and increase in the utility of the transported load as the two critical factors determining what parts of resources are likely to be returned to a residential camp.

Archeologists routinely develop inferences about past human behavior on the basis of patterned variation in types and quantities of refuse, especially animal bones, lithic debitage, and inedible plant parts, recovered from prehistoric sites. Fundamental to these interpretations is the assumption that some of this variation is the product of processing at or near where the resource was procured in order to eliminate parts of little utility, and thereby improve the quality of the transported load. Early explanations of this type were based on common sense notions of efficiency and limited ethnographic data. More recently, archeologists have developed scales to quantify various aspects of this problem, but to date they have never been formalized into a model that examines the full range of factors likely to influence field processing and transport decisions.

This article presents a model for exploring the optimal solution to the trade-off between field processing and transport, and this solution provides a basis for understanding the differential transport of resource parts by past and present humans. The model is basically an extension of ecological research into the economics of central place foraging (Schoener 1971; Orians and Pearson 1979) and is designed to produce testable, quantitative predictions. There are no readily available data for actual resources that allow an application of the model to a specific case, but the data required to refine this model are unlikely to be collected until their usefulness is demonstrated. Our goal is to stimulate and guide research on this problem among modern populations.

The important role of transport costs in determining the types of food waste introduced into residential sites has only recently been investigated quantitatively (Binford 1978; Drennan 1984a, 1984b; Jones and Madsen 1989; Metcalfe and Jones 1988; O'Connell, Hawkes, and Burton Jones 1988, 1990; Rhode 1990). To date, most attention has been directed toward understanding the role of transport costs in the differential transport of animal body parts. The goal of these studies has been to explore the archeological implications of the transport of only some animal carcass parts from the site of death and dismemberment to where the selected parts were consumed. Understanding of the behavioral processes that underlie this decision has advanced greatly in the last dozen years. This is due first to the work of Binford (1978), who investigated the differential transport
of animal body parts among the Nunamiut Eskimos, and more recently to similar studies among the Hadza hunter-gatherers in East Africa (Bunn, Bartram, and Kroll 1988; O'Connell, Hawkes, and Blurton Jones 1988, 1990). These studies demonstrate that hunter-gatherers can be very selective about which animal body parts are transported from kill sites to residential camps and that transport distance is an important variable in determining how many bones are transported (O'Connell, Hawkes, and Blurton Jones 1990). Although transport distance has long been argued to be an important conditioning variable (e.g., White 1953, 1954), the Hadza research is the first quantitative demonstration of its significance.

A number of investigators have suggested that the differential transport of animal body parts is conditioned by the trade-off between transport and field butchering (e.g., Jones and Metcalfe 1988; Metcalfe and Jones 1988; O'Connell, Hawkes, and Blurton Jones 1988). Unfortunately, animal carcasses are structurally complex, and are infrequently procured in large numbers, which makes the development of simple models for understanding this trade-off, and the factors that influence it, a difficult task. By structurally complex, we mean that carcasses can be divided into a relatively large number of body parts, or combinations of body parts, each of which is characterized by different amounts of edible tissue that require varying levels of effort to separate from associated inedible parts.

Precisely the same trade-off between field processing and transport should be evident for other resources procured in packages that include useful and useless (or less useful) parts. Many of these resources, such as seeds, nuts, and shellfish, are relatively simple and often are procured in large numbers. These resources are divisible into only comparatively few parts; for instance, pinyon nuts are often procured in cones and are surrounded by hulls. As will be evident, it is much easier to model the field processing/transport trade-off for these types of resources.

Field Processing

Field processing is defined here as the act of dividing a resource "package" into its constituent components at or near its place of procurement with the goal of transporting only selected, comparatively high-utility components for use elsewhere. This definition underscores three important points. First, resources are generally procured as "packages" consisting of two or more parts. When killed, an animal carcass includes skin, blood, various organs, many different bones, and meat; a chert cobble picked up from a riverbed may have a heavy cortex surrounding the usable stone; when harvested, corn kernels are attached to a cob and encased by a husk. Second, the components of a resource package are likely to vary with respect to their potential utility. Shellfish, for example, consist of an inedible shell surrounding nutritious meat. If the shellfish are procured solely for food, then the meat is valuable (high utility) and the shell is useless (zero utility). This is particularly important to archaeologists because low-utility components (e.g., nut and shellfish shells, pine cones, or animal bones) are much more likely to survive the rigors of the archeological record than are their more archeologically ephemeral high-utility counterparts. Perhaps this is the reason that the majority of work relating to the differential transport of resource components has been conducted by archeologists.

Finally, our definition emphasizes the relationship between field processing and transport. This is of particular importance to archeologists interested in predicting the probable effect of differential transport of resource components on assemblage composition. Where an independent measure of a site's position within a transport trajectory is available (Thomas and Mayer [1983:368] refer to this as the monitoring perspective), the types and frequency of resource components at the site can be used to develop hypotheses concerning the spatial distribution of those resources. Of equal importance, after determining the explanatory power of the model in modern situations, the predictions of this model may provide just such a measure.
Depending on the resource, field processing may have consequences very different from processing solely for use or consumption. For instance, cooking meat prior to consumption makes it easier to ingest, but whether that meat is attached to bone may be of little importance. On the other hand, when meat is transported before consumption, there is an advantage to removing the bone if more meat can be transported, but there is little advantage to cooking it. In general, when processing for use or consumption is reductive, there will be few, if any, differences from field processing. For example, lithic tool production is a reductive process. If stone is not reduced to useful tools before transport, it still has to be processed after transport. An interesting implication of the model is that when travel times are sufficiently large for these types of resources, processing for transport might be more extensive than required for use or consumption.

As noted above, the decision to field process and transport only selected parts of a resource has traditionally been the focus of archeological, rather than anthropological, interest. This archeological emphasis is unfortunate because ethnographers have generally failed to note the circumstances under which a particular resource is field processed prior to transport and when that same resource is transported whole. However, a cursory review of the ethnographic literature suggests that the trade-off between field processing and transport is implicated for a far wider range of resources than just large animal carcasses. Although ethnographic descriptions are open to interpretation, it is likely that the same trade-off relates to transport of shellfish (Meehan 1982:73–74), nuts (Lee 1979:193), hides (Binford 1978:461), and logs (Dodd 1992:57). In addition, archeological interpretations of lithic reduction conducted at quarry sites have long been based on implicit assumptions about the character of this trade-off (e.g., Holmes 1897:26). Taken together, existing ethnographies suggest that the trade-off between field processing and transport is a common decision faced by humans in very different environments and for a wide array of resources.

The Dilemma

Imagine a situation in which foragers have traveled some distance from their residence to gather nuts to be taken home for food. The nuts are collected in relatively simple packages consisting of nutmeat surrounded by valueless shell. The foragers must decide whether field processing the nuts—separating and discarding the shells at the nut grove—would be economically more efficient than transporting the nuts without field processing. Processing the nuts at home is essentially free to the foragers; others will be responsible for removing the shells. The advantage of field processing is that the foragers’ transported load would be composed entirely of nutritional nutmeats with no portion of the load wasted transporting useless nutsheells. But shelling the nuts takes time, time that could be spent transporting. The question is: Which strategy is the most efficient given the morphology of the resource and the distance it is to be transported? The trade-off is between transporting more loads composed of both useful and useless components (nutmeat and shell), or fewer loads made up entirely of the useful component (nutmeat).

Consider the case in which the nuts are relatively difficult to process and the shells are relatively small and lightweight. The foragers can collect, field process, and transport two loads of these hypothetical nuts in an eight-hour period, each processed load having only 10% more nutmeats than an unprocessed load because the shells compose such a small proportion of the total nut. On the other hand, if the foragers do not field process the nuts, they can collect and transport eight loads, each load containing about 9% fewer nutmeats than a processed load. Under these circumstances, we would expect only unprocessed nuts to be transported to the residential camp. Nutshells would be deposited at the residential camp, and the frequency of those shells would be proportional to the amount of nuts transported. A different nut might have very large or heavy shells that can be removed quickly from the nutmeat. Under these circumstances, the most efficient decision on the part of the foragers may be to field process these nuts. No shells would be
introduced to the residential camp; but their absence would not necessarily have any correlation with the dietary importance of this particular resource.

This simple example demonstrates the general archeological importance of the trade-off between field processing and transport and how it may vary among resources. Its implications are easily appreciated because it uses examples from opposite ends of a scale (i.e., heavy versus light shells; difficult versus easy to field process) for a resource composed of only two parts. Most resources of archeological interest are likely to fall somewhere between these extremes and will consist of at least several components. Therefore, a more formal, explicit model for calculating this trade-off is necessary.

The Model

Consider a more specific version of the same problem. Again, each nut consists of two parts, nutmeat and shell (Figure 1). Nutmeat represents 30% of the package and has a utility of 1.0, while the remaining 70% is composed of shell with no utility. Field processing these nuts is a one-step process. The shell can be cracked and the nutmeat extracted. The advantage to field processing the nuts occurs when the foragers gather and process additional nuts to replace the weight saved when the nutshell are discarded. The disadvantage is that it takes time to crack the nuts. The advantage of not field processing is that the forager (1) returns home more quickly and (2) can therefore make more trips. The disadvantage is that the transported load has only a fraction of the utility of a processed load of the same weight or volume.

The $x$-axis of Figure 1 monitors two variables. To the left of the $y$-axis, it measures the time taken to get to the grove plus the time required to return home with the load (i.e., time required for the round-trip). This is not a decision variable, because the grove is a fixed distance (measured in travel time) from home. On the right side of the $y$-axis, the $x$-axis measures procurement and field-processing time. This is the decision variable. The function at the right of the $y$-axis, labeled $U(t)$, is the relationship between utility of the

![Figure 1](image-url)

*Figure 1*  
Graphic example of field processing/transport trade-off. The points A and B on the x-axis indicate the round-trip travel times to two hypothetical residential camps.
load and time spent procuring and field processing. In this simple example, the utility function is represented by the straight line connecting \( x_0, y_0 \) and \( x_1, y_1 \). The utility of an unprocessed load is 0.3 \( (y_0) \), and the time it takes to procure the resources is \( x_0 \). Both useless shell and useful nutmeat are transported. If the foragers spend the additional time away from home to field process and procure more nuts \( (x_1) \), the utility of the load is increased to 1.0 \( (y_1) \).

If the foragers maximize the utility of the load per unit time spent transporting, procuring, and field processing, then they should decide whether to field process in a manner consistent with maximizing the value on the \( y \)-axis divided by the value of the \( x \)-axis. Graphically, the value to be maximized is the slope of the line originating from the required travel time and tangent to the utility function. Where the line touches, but does not intersect, the function indicates the appropriate decision.

Figure 1 illustrates how variation in travel time can markedly affect whether field processing is expected. Point A indicates a relatively long travel time. The line originating from Point A and tangent to the utility function indicates that the foragers' rate of return is maximized by field processing the nuts. But what if the travel time is not so great (Figure 1, Point B)? The line from this point with the maximum slope is tangent to the function where field-processing time is zero. It indicates that the foragers will maximize their rate by not field processing the nuts. The vertical dashed line (labeled \( \xi \), Figure 1) to the left of the \( y \)-axis indicates the point in travel time when field processing becomes worthwhile, and can be calculated graphically as the \( x \)-intercept of a line passing through both \( x_0, y_0 \) and \( x_1, y_1 \). Mathematically, \( \xi \) can be calculated as follows:

Let: \( \xi \) = point on transport-time axis where field processing becomes economically profitable;
\( x_0 \) = time to procure load of unprocessed resources;
\( x_1 \) = time to procure and field process load of resources;
\( y_0 \) = utility of load without field processing;
\( y_1 \) = utility of load with field processing.

\[
\xi = \frac{y_1 x_0 - y_0 x_1}{y_1 - y_0} \quad (y_1 \neq y_0)
\]

In situations where the travel time is greater than \( \xi \), it is appropriate to field process the resource; in situations where the travel time is less than \( \xi \), no field processing is expected. This equation is appropriate for a resource with only two components. A resource with \( n \) components will have a series of \( \xi \)'s related to the various transport times for the discard of the different components at the site of procurement.

Assumptions

The decision whether to field process before transport is only relevant when certain conditions are met, some of which are a function of other decisions. Accordingly, we assume that the foragers' residence and the resource in question are not in the same location, that the resource can be profitably exploited given the distance involved, and that the forager has decided to procure the resource with the goal of returning it home for use or consumption. Although these might be stated as assumptions underlying the model, they are more productively viewed as placing the decision of interest into a larger foraging hierarchy (Charnov and Orians 1973:9).

The most fundamental assumption underlying the model is that foragers will make field-processing and transport decisions in an economically efficient manner. More specifically, we assume foragers have the goal of maximizing the utility of the resource returned home relative to the time spent in procuring, field processing, and transporting that resource. Rate maximization is a reasonable goal if it can be demonstrated that there is a finite period of time that can be devoted to foraging during an individual's lifetime, or some large segment of it (Stephens and Krebs 1986:8-9).
Implicit in the rate maximization assumption is a second assumption; either processing time in camp has no cost, or no processing in camp is required for consumption or use. This is an important assumption when calculating quantitative estimates of $\varepsilon$. Fortunately, for estimating the order in which parts should be culled during field processing (discussed later), and the relative travel times at which they should be removed and discarded, it is only necessary to assume that processing time in camp is less costly per unit than field-processing time, or less time is required to process in camp than in the field, or both. This less restrictive assumption is likely to be valid in a number of circumstances and, when estimates of the costs of field processing versus processing in camp become available, the model can be modified to provide quantitative estimates of $\varepsilon$.

Access to additional personnel, facilities, and other resources will often make processing in camp less time-consuming than in the field. In the simplest case, additional processing in camp may be delegated to someone other than the forager who transported the resource, making it essentially free to him or her. If such facilities as bin mates, drying racks, or shelter from inclement weather, present in camp but not in the field, facilitate processing the resource (measured either as less cost per unit time, or less time), then processing in camp will be less costly than in the field. Last, many consumable resources are most efficiently processed with water (stewing bones or boiling mongongos to remove their skins and fruit). In circumstances where water is not available in the field, but is readily available at or near the camp, the costs of processing in camp will be significantly less than in the field.

It may also be generally true that being at camp is less dangerous than being away from home. There may also be more opportunity to share the costs of processing with other activities when conducted in camp. Depending on the nature of the processing involved, children can be attended to, equipment repaired, and information exchanged with other members of the consuming group. Under these circumstances, there may be less opportunity cost associated with processing at home.

The third assumption is that foragers are not limited in the amount of time that can be devoted to field processing and transporting during a single trip. The foragers need not return by nightfall, nor can they only be away from their residence for a fixed period of time. As discussed later, this assumption may hold for certain task groups in certain environments, but not others.

The fourth assumption of the model is that there is an optimal load size for transport that is less than the resources available. The model is most appropriate for resources that are small in size relative to the optimal load. The actual weight or bulk of the optimal load is likely to be contingent on the distance it is to be transported, the number of carriers available, condition and physical prowess of the transporters, ambient temperature—the full array of variables that have been demonstrated to condition the energetics of transport (e.g., Pandolf, Givoni, and Goldman 1977). We assume that, given the actual values of all variables relating to the energetics of transport, a load of a certain weight or size will be selected. The question that this model addresses involves the character of that load. Should it consist of unprocessed resources, partially processed resources, or completely processed resources? Either bulk or weight may be the limiting constraint defining the load. The transport of low-density resources is probably limited by bulk (only so many liters can be transported even though the weight of that load is small); loads of high-density resources are likely limited by weight (Jones and Madsen 1989). Both variables may be important for the same resource when field processing results in an increase in the density of the resource.

Finally, we also assume that the energetic cost per unit time is the same for time spent transporting the load and time spent field processing. This is undoubtedly incorrect under most circumstances. Most studies suggest that the energetic costs of transporting a relatively heavy load are likely to be significantly greater than those spent in field processing. This assumption can be relaxed in circumstances discussed later.
Exploring the Model

The quantity $\Delta x = x_1 - x_0$ is simply the time required to field process the load of resources—in the example used, the time to remove all shells from the load of nuts, and to collect and field process additional nuts to attain the optimal load for transport. It can be thought of as the cost of field processing. The quantity $\Delta y = y_1 - y_0$ is the change in the load’s utility as a consequence of field processing—the difference in the utility of a load of processed nuts versus a load of unprocessed nuts. This is the benefit of field processing. As equation 1 indicates, the magnitude of $\zeta$ is directly proportional to $\Delta x$ and inversely proportional to $\Delta y$ (Figure 2).

Two characteristics of the resource determine $\Delta y$. The first is the proportion of the various components in the complete resource package. Some resources may have very

![Diagram](image-url)
large components of low utility, others very small components of low utility. All else equal, the larger the useless (or less useful) component, the greater the increase in $\Delta y$ for field processing. The second important characteristic is the difference in utility of the various components. Removing a component that has zero utility provides a larger increase in $\Delta y$ than removing a component with some utility.

These two variables—resource component proportions and the utility of those components—combine to determine the benefit associated with field processing. There should be an inverse relationship between benefit derived from field processing and the travel time at which field processing becomes worthwhile. The larger the increase in utility from field processing, the shorter the travel time at which it becomes beneficial to field process; conversely, the smaller the increase in utility, the longer the travel time before it is worth field processing.

Since the benefit derived from field processing is conditioned by both factors, which may vary independently, it is instructive to model this relationship mathematically. Greek letters are used for resource package parameters to emphasize that these are not decision variables.

Let: $\alpha_i$ = utility of resource component $i$;
$\beta_i$ = proportion of package composed of resource component $i$ prior to field processing;
$\gamma_j$ = utility of load at field-processing stage $j$.

The utility of the resource package, and hence the load, can be calculated for any stage of field processing. Let $s_j$ equal the subset of resource components associated with the resource package at stage $j$ of field processing. Then,

$$\sum_{i \in s_j} \alpha_i \beta_i$$

$$\gamma_j = \frac{\sum_{i \in s_j} \alpha_i \beta_i}{\sum_{i \in s_j} \beta_i}$$  (2)

If field processing involves several stages (several resource components), then the increase (or decrease) in utility of the load attributable to any particular stage is $\Delta \gamma_j = \gamma_j - \gamma_{j-1}$.

Two characteristics of the resource determine $\Delta \gamma$. First is the time required to field process the resource. We might expect fairly substantial differences in the time required to remove low-utility parts from different resources, or the time required to separate different components of the same resource. Second, field-processing costs will never be the only field costs. It takes time to locate the resource package, even within a dense patch, and it takes time to capture or gather it. In addition, field processing is, as defined, a reductive process whereby resource components of low utility are culled. Therefore, when field processing occurs, additional resource packages have to be procured to attain the optimal load size for transport. For the purpose of this discussion, procurement time is the amount of time required to pursue, capture, or otherwise procure a resource package, exclusive of time spent field processing.\(^6\)

The costs of field processing, when there are significant procurement costs, can be calculated for each particular field-processing stage.

Let: $\delta_i$ = time required to remove resource component $i$ from each resource package;
$L$ = weight or bulk of optimal load size for transport;
$\phi$ = weight or bulk of each unmodified resource package;
$\lambda$ = time required to handle (locate and procure) each resource package;
$x_j$ = total handling and field-processing time required to reach stage $j$ of field processing.
Let \( S_j \) equal the subset of resource components associated with the resource package at stage \( j \) of field processing. Then,

\[
x_j = \left( \frac{L}{\phi \sum_{i \in S_j} \beta_i} \right) \left( \lambda + \sum_{i \in S_j} \delta_i \right)
\]

The first part of the expression calculates the number of resource packages that must be procured to reach the optimal load size at various stages of field processing. The second part calculates the time required to collect and field process that number of resources. If field processing involves several stages (several resource components), then the increase of field-processing and handling time attributable to any particular stage is simply \( \Delta x_j = x_j - x_{j-1} \).

It is important to note that \( x_j \) is sensitive to differences in the size of the optimal load because the weight or bulk of the optimal load for transport \( (L) \) is a variable in equation 3. This makes intuitive sense; the larger the load, the greater the time required to procure the resources, and the greater the time required to field process the resources. Therefore, since \( z \) in equation 1 is a function of both \( x_0 \) and \( x_1 \), variation in \( L \) will produce variation in \( z \).

It is imperative that data be gathered concerning the range of load sizes (measured in weight and bulk) that modern hunter-gatherers transport, and the factors that influence variation in that load size. Data from O'Connell, Hawkes, and Blurton Jones (1988) indicate that 10–20 kg is the normal load for individual Hadza transporting animal body parts. Hadza women carry home 3–5 kg loads of tubers (Hawkes, O'Connell, and Blurton Jones 1989). Lcc (1979:193, 194) suggests that !Kung women consider 10–15 kg of mongonos to be a full load, !Kung men 5–8 kg. Loads for !Kung men transporting animal body parts fall between 20 and 30 kg.

These data suggest that the range of variation in load weights is considerably less than an order of magnitude. Because of the documented variation in load size, \( z \) should not be thought of as a line, but rather as a range below which no field processing is expected to occur, within which field processing will sometimes occur, and above which field processing is always expected to occur. The range of \( z \) will depend on the amount of variability in load size for that resource, and the character of the resource's utility function \( U(t) \).

**Resources for Which \( U(t) \) is a Differentiable Function**

To this point, we have considered resources that are field processed individually—in terms of the original example, one nut at a time. As illustrated in Figures 1 and 2, their utility functions involve abrupt changes in slope, and consequently are not differentiable. This makes changing the assumptions of the model relatively complicated.

However, utility functions for some resources may be continuous and differentiable. For instance, resources that are most efficiently field processed in batches, such as seeds from which chaff is winnowed, may represent a case in point. Time spent winnowing is a continuous variable, and because the amount of chaff removed from the seed is related to how long the material is winnowed, change in utility of the load is also a continuous variable. In addition, the amount of chaff separated per unit of time is likely to decrease as winnowing continues, in which case \( U(t) \) will approximate a simple gain function that increases asymptotically to a maximum value (Figure 3).

The question here is not whether a low-utility component of a resource is expected to be transported, but rather how much of it will be transported. For the sake of illustration, \( U(t) \) can be divided into three segments, distinguished by the points labeled \( a \) and \( b \) (Figure 3). Comparatively large amounts of chaff will be transported per unit of seed in the first segment, moderate amounts of chaff per unit of seed in the second, and very little chaff per unit of seed in the third. Again, this has important archeological implications. In the example illustrated in Figure 3, the recovery of the same quantity of chaff from
Figure 5
Graph of a differentiable utility function $U(t)$. Also illustrates where various types of waste flakes are represented in the reduction sequence. Points A and B on the travel-time axis are two hypothetical residential camps.

sites A and B does not indicate that the seeds were equally important to the inhabitants of the two sites. Considerably more seed is expected per unit of chaff at site A than at site B.

Calculus can be used to determine the optimal time to spend field processing, and hence the composition of the load, when $U(t)$ is differentiable. For instance, the following is consistent with the undifferentiable model presented earlier for individually processed resources.

Let: 
- $G(t) = $ gross rate of utility returned to residence;
- $U(t) = $ utility of load after $t$ units;
- $T = $ round-trip travel time;
- $t = $ time spent procuring and field processing the resource.

\[ G(t) = \frac{U(t)}{T + t} \]  \hspace{1cm} (4)

The optimal time to spend field processing (that which maximizes $G(t)$) is calculated by differentiating equation 4 with respect to $t$ and setting the result to zero. This type of analysis is analogous to the marginal value theorem (Charnov 1976) and central place foraging theory (Orians and Pearson 1979). Once $t$ is determined, it can be related back to $U(t)$ to determine the expected composition of the transported load. Although $U(t)$ is not presently known for any resource, its characteristics will be determined by the resource parameters discussed for individually processed resources.

The advantage of differentiable functions is that various assumptions can easily be tested against empirical data. For instance, under some circumstances it might be reasonable to predict that maximizing the net rate of energetic return is the appropriate goal of transport and field-processing decisions. Similarly, as noted earlier, the energetics of transport may be quite different from the energetics of field processing. In this case,

Let: 
- $N(t) = $ net rate of energy returned to residence;
- $\epsilon_T = $ rate of energetic expenditure during transport;
- $\epsilon_s = $ rate of energetic expenditure during procurement and field processing.
\[ N(t) = \frac{U(t) - (T\delta + \omega)}{T + t} \] (3)

The optimal time to spend field processing is calculated as described for equation 4. The goals of maximizing gross utility versus net utility can be posed as competing hypotheses and examined empirically.

**Structured versus Unstructured Resources**

When considering specific resources, it will be necessary to understand the effect of the resource's morphology on field-processing options. For instance, while acknowledging that we are dealing with a continuum, it is useful to distinguish "structured" from "unstructured" resources. By "unstructured," we mean that the morphology of the resource package does not dictate the order with which the various resource components must be removed. A "structured" resource, on the other hand, is one in which the morphology of the resource package determines that order.

It is relatively easy to demonstrate that unstructured resources have a ranking for the order according to which we can expect resource components to be removed by field processing. All else being equal, the component that yields the greatest \( \Delta y / \Delta x \) should be culled first, the component with the second highest \( \Delta y / \Delta x \) second, and so forth. Consequently, unstructured resources consisting of several or more components are likely to have utility functions that approximate diminishing-return curves, rather than either linear or positively accelerating functions.8

In many cases, this economic ranking will also apply to simple, structured resources because their structure does not impose a different culling sequence. For instance, nuts frequently have inner and outer shells. Both are inedible, but the outer shell is often thick and heavy, the inner thin and light. The morphology of nuts requires that the outer shell be removed before the inner shell, but this might be exactly what would be predicted even if nuts were unstructured (i.e., if the inner shell could be removed before the outer).

However, it appears that the more complex the resource package, the more important it is to understand its underlying structure. In these cases, the morphology of the resource package may dramatically affect the costs or benefits of field processing various components. For instance, Lee states that "If the flesh of the mongongos has been eaten away, the collectors may crack and eat a portion of their nuts on the spot" (Lee 1979:193, emphasis added). While extrapolating from specific passages can be dangerous, this statement can be interpreted to mean that when the flesh has not been eaten away, collectors do not field process mongongos. The model and the characteristics of the mongongo fruit provide insights into why this might be so. In addition, this case illustrates the importance of understanding the structure of the resource, and how that structure can influence field-processing and transport decisions.

Mongongo fruit has a fairly complex structure composed of five layers, only two of which are edible (Lee 1979:185, Fig. 7.2). The outer surface of the fruit is an inedible skin covering the edible flesh that surrounds the mongongo nut. The mongongo nut consists of inedible outer and inner nutshell that contain the edible nutmeat. The structure of the mongongo changes after it drops from the tree. Initially the whole fruit is present, but as time passes, insects remove the skin and flesh, leaving only the nut with its two shells and inner nutmeat.

The most dramatic saving from field processing mongongo is the removal and discard of the inner and outer nutshell. Together they comprise, by weight, 0.518 of the package when the skin and flesh are still present, and 0.852 of the package when the fruits have lost their flesh to insects. The benefit derived from culling the shells is greatest after the flesh has been lost (\( \Delta y = 0.85 \) for nuts alone versus \( \Delta y = 0.24 \) for intact fruit).8 Assuming that the cost of removing the nutshell is not influenced by the presence or absence of the surrounding fruit, the travel time at which the !Kung would be expected to field process mongongos when the fruits are present is over three times that for the nuts alone.
However, because of the structure of mongongos, the skin and fruit, when present, must be removed before the nutshells can be culled. This undoubtedly increases the required field-processing time, and as a consequence reduces the benefit-cost ratio for field processing the fruits. In addition, it is possible that the fruit cannot be as effectively transported once separated from the package, further increasing the costs of field processing. Field processing mongongos when the fruit is present is likely to be a low-benefit, high-cost exercise. We would predict that the !Kung would only field process intact fruits when exploiting mongongo groves very far from home, perhaps at distances so great that mongongos are not worth collecting given the transport costs (Jones and Madsen 1989; Rhode 1990).

**Mixed Loads and Time Constraints**

The economic trade-off between field processing and transport has been considered in situations where there are no time constraints on individual foraging trips. This may seldom be the case. For instance, in some environments, it may be considerably more dangerous to be away from one's residential base after dark than it is during the day. Increased carnivore activity and a decreased ability to defend oneself if attacked at night may well be important factors limiting extra-residential mobility in areas where large terrestrial carnivores are present. Similarly, it is likely that all-female task groups in some environments may face different dangers than all-male, or mixed male and female, task groups. Lee notes that !Kung women never remain out overnight (1979:123), but that males will occasionally remain away from camp overnight when tracking large animals.

The field processing/transport model does not predict that "mixed loads" will ever be transported. The term "mixed load" is defined here as resources field processed to two or more stages—in the simplest case, the transport of both processed and unprocessed resources. The portion of \( U(t) \) in Figures 1 and 2 for mixed loads is the straight line connecting \( x_0, y_0 \) and \( x_1, y_1 \). There can be no line tangent to this portion of the function. The same is true when \( U(t) \) is a differentiable function; the resulting prediction is that the load will consist of uniformly processed (or unprocessed) resources.

However, mixed loads may be expected if for any reason there is a limit on the length of time that can be devoted to a single procurement and transport event. For example, speaking of the !Kung, Lee notes:

> If time is short, they may crack and eat a few nuts raw, . . . And if the gatherers have an afternoon to spend, they crack up to half their nuts, eating all those that crack imperfectly and saving all the nuts that crack neatly with the inner shell intact. . . . This preliminary cracking can reduce the weight of nuts to be carried home by 75%. [1979:193, emphasis added]

Lee emphasizes that the time available for field processing is an important factor determining whether women field process mongongos, and if so, how many. The same appears to be true for a variety of resources among the Hadza (Kristen Hawkes and James F. O'Connell, personal communication, 1990) and the Alyawara (James F. O'Connell, personal communication, 1990). Since !Kung women never remain away from camp overnight (Lee 1979:123), the amount of time remaining before nightfall appears to affect strongly whether they field process collected mongongos, and if so, how many (i.e., what proportion of their load). Under these circumstances, transported loads will consist of both processed and unprocessed resources. This suggests that when there are time constraints on individual foraging trips, there will be a travel-time threshold. When travel time is high relative to time available, the amount or extent of field processing will be low. Either a smaller amount of the load will be processed, or the entire load will be processed to a lesser extent. This travel-time threshold will be reached when the time available for a foraging trip equals the time required for the round-trip plus the time necessary to process the optimal load (process to an extent predicted by the model). When resources are procured at distances for which the travel time is greater than this threshold, we can expect that mixed loads will be transported back to the residential base.
Archeological Applications

Although the model, or rather the assumptions on which it is based, have not been tested ethnographically, a relatively simple archeological application can be suggested. The best resources to examine will be those with limited and known sources, and those that are procured as relatively unstructured packages consisting of a number of low-utility components that survive well in the archeological record. Stone quarried for lithic tool production may fulfill these criteria.

Lithic tool production is likely to be associated with a $U(i)$ that approximates a function similar to that illustrated in Figure 3. The waste flakes produced during the manufacture of a stone tool can be conceptualized as resource components, and the finished tool as the resource component with the highest utility. Because flintknappers can vary the size of the flakes removed during the reduction sequence by controlling force and technique, they are in effect determining the value of $\beta$, the proportion of the original piece of stone that is removed by striking each waste flake. Because waste flakes have no utility in themselves ($\alpha = 0$), the model predicts that the largest possible flakes should be removed within the limits set by the form of the desired tool. Many authors (e.g., Newcomber 1971; Stahle and Dunn 1982) have noted the correlation between flake size and manufacturing stage of bifacial stone tools; generally, larger flakes are struck earlier in the sequence, smaller flakes toward the end. This aspect of the reduction sequence is the basis for using size as an important attribute in distinguishing between primary, secondary, and tertiary waste flakes. This allows the tentative assignment of different types of waste flakes to the utility function (Figure 3). For this example, the point on the utility function labeled $c$ indicates the division between primary and secondary flakes, and that labeled $d$ the division between secondary and tertiary flakes.

In this example, because the travel time between site B and the source of toolstone is comparatively small, toolstone should be transported after only limited processing and thedebitage at site B should represent all stages of reduction. In contrast, site A is more distant from the source and more field processing is expected prior to transport; as a consequence, only the latter stages of reduction are expected to be represented by the debitage at this site. An interesting archeological exploration of the utility of this model would be to conduct experimental work at a prehistoric stone quarry that would allow an estimate of $U(i)$, and then examine prehistoric sites at varying distances from the quarry. Changes in the proportional frequency of the different flake types represented by the quarried stone could then be compared with the predictions. Studies of this type have already been undertaken (Elston 1989, 1990).

This example raises two important points for archeologists. First, the model predicts, and therefore potentially explains, the archeological consequences of variation in the types of resource components transported by central place foragers. The archeological pattern of interest might be variation in the types of waste flakes representing different stone sources recovered from a particular site, or variation between sites in the types of waste flakes of a single source. The emphasis is on explaining variation; using the implications of the model to interpret some invariant aspect of an assemblage (the presence or absence of a particular resource) is not likely to be profitable. To do so with any rigor would require estimating the various parameters of the model with a level of precision unlikely ever to be available from the archeological record.

Similarly, resources that are procured in packages consisting of many components with different utilities are likely to provide the best inferences about past human behavior. We have relied on simple, two-component resources when discussing various features of the model for simplicity. These are unlikely to be of much interest to archeologists, because the model only predicts the presence or absence of the single low-utility component, and the high-utility component will often be used or consumed, or will decay if abandoned. When the low-utility component is present, little is added to conventional interpretations by employing the model. When absent, archeologists will generally be unable to deter-
mine if its absence indicates that the resource was not utilized, or that the low-utility component was culled during field processing. Predictions for multi-component resources will, however, concern the array of resource components expected in relation to transport distance; these should be more amenable to archeological study.

For this reason, understanding the field processing/transport trade-off as it relates to the differential transport of large-animal body parts is likely to be extremely important to archeologists. Although the parameters identified in relation to simple resources also relate to the economics of field butchery, the formal model presented in this article does not strictly apply to animal carcasses. For large animal exploitation, the effects of variation in the size of the transported load cannot be minimized, as we have done in the model, by assuming an optimal load that is relatively large in comparison to the size of the resource package. As discussed earlier, animal carcasses are structurally complex, consisting of a relatively large number of body parts that can be divided into an even larger number of combinations of body parts, each with a different utility and requiring a different amount of work to separate from adjacent parts. What bones actually get transported, the character of the load, is therefore at least partially a function of how much of the carcass can be moved. A subtle but important shift in the question addressed by the model needs to be made: Given varying transport constraints, what is the order with which parts should be removed and transported from the kill-butcher site to the residential camp? The simple model presented here provides an avenue for addressing this question, and developing an appropriate methodology is currently a priority of our research group (Metcalf 1990).

Summary and Discussion

This article presents a simple model for exploring the trade-off between field processing and transport. Field processing has been defined rather narrowly as the activity of dividing a resource package into its constituent components, at or near where the resource was procured, in order to cull low-utility parts and transport only comparatively high-utility parts. This definition is consistent with the traditional archeological interest in behavioral decisions that structure prehistoric assemblage composition. Other types of processing in the field certainly can and do occur; for instance, resources may come in packages too large to transport as a unit (i.e., elephants). In this case, processing in the field might involve dividing the resource into transportable pieces. Alternatively, the value of the resource might decrease significantly during the time required to transport it. If such processing techniques as gutting or drying can retard the decay process, then foragers might decide to process a load of fish before transporting it any great distance. Neither of these two types of processing in the field will affect assemblage variability unless they also result in the differential transport of certain parts. If an animal is divided into a number of parts for transport, and all those parts are transported, the resulting assemblage will be identical to that produced by the same animal killed at the door of the prehistoric residence.

Given its underlying assumptions, the model implicates transport time between the place of resource procurement and use, and the character of the resource's utility function $U(t)$, as the critical factors in structuring the types and amount of waste components culled and discarded in the field. Both the proportion of the various components that make up the complete resource, and their utilities, determine the benefits associated with field processing. The time spent separating the various resource components from the resource package, and the time required to procure additional resources, determine the cost of field processing.

It is interesting, and encouraging, to note that all of the factors implicated by the model as important in structuring field-processing and transport decisions are intuitively reasonable. In fact, all were nominated by T. E. White (1953, 1954) as important in determining which bones were returned to residential sites by prehistoric hunters. This sug-
gests that the various assumptions underlying the model are not so restrictive, even in combination, that they are unlikely to be met in "real" situations. In one sense, the model can be seen as explaining White's and others' intuition; in another, it can be seen as expanding their insights by demonstrating how those factors should interact to influence the decision.

Collection of data necessary to calculate the utility functions of resources commonly recovered from prehistoric contexts in the Great Basin and elsewhere is under way (Barlow 1990; Elston 1989, 1990; Metcalfe 1990; O'Connell and Marshall 1989). Although archeological questions provided the stimulus for developing the model presented here, studying living populations will provide the best—perhaps the only—avenue for testing and refining it. Field observations will allow accurate estimates of the various resource and situational parameters that have been implicated in the trade-off between field processing and transport. Predictions can then be tested against directly observable behavior, and the model either refined or discarded, as appropriate.

When the explanatory limits of this model are understood in terms of directly observable behavior within a variety of observable environmental and social contexts, its strengths and weaknesses for reconstructing past human behavior from the archeological record can be explored. As noted earlier, one of the principal goals of this article is to encourage and guide studies of the differential transport of resource components among modern populations.

Notes

Acknowledgments. The origins and development of this article can be traced to discussions with Robert Elston, Kristen Hawkes, David Madsen, Kevin Jones, James O'Connell, and Alan Rogers. We wish to thank Joan Coltrain, Kathleen Heath, Steven Simms, John Speth, Tony Schurr, David Zeana; and especially Don Grayson, Kristen Hawkes, Kim Hill, Charles Keckler, Eric Smith, and an anonymous reviewer for comments on various drafts. Debra Gillett and Jennifer Graves provided editorial assistance. An early version of this article was presented by the senior author at the 1989 Society for American Archaeology meetings in Atlanta.

1 Utility is scaled from 1.0 to 0.0; 1.0 indicates the highest possible utility, 0.0 no utility at all. This is a scale of proportional utility; the resource component with the highest utility is given a value of 1.0 and the values of other resource components are scaled down toward zero accordingly. For instance, Lee (1979) presents the calories/gram of the different components of mongongo fruits. Two components are eaten; nutmeat provides 6.41 calories/gram and flesh 3.12 calories/gram. As defined here, the utility of these components is 1.0 for nutmeat, 3.12/6.41 = 0.49 for the fruit. These values are used later in the text.

This scale of utility is heuristic; useful because the utility of resource packages at a particular field-processing stage equals the utility of the load at that same stage, when all resource packages are processed equally. It also simplifies the equations presented later. However, proportional utility is only useful for developing expectations about the differential transport of the resource components of a single resource; it does not allow comparisons between resources. For this reason, when actual measures of utility become available (e.g., calories per load), they should be preferred.

2 $U(t)$ does not originate at $y = 0$ because the $y$-axis is scaling utility between 0.0 and 1.0, rather than employing a direct measure of utility. There is no change in the utility of the load while procuring resources—if one nut has a utility of 0.3, then 100 nuts have a utility of 0.3. If a direct measure of the load's utility were used, say calories, then the function $U(t)$ could be expanded to include procurement times.

3 These are actually a series of step-functions that can be approximated by straight lines when the number of resource packages to be transported is large.

4 We originally calculated $z$ by solving the point-slope equation for the $x$-intercept $(z, 0)$. Charles Keckler (personal communication, 1991) suggested a more intuitive solution. The slopes of the lines originating from $z$ to $x_0$, $y_0$, and to $x_1$, $y_1$, are equal. Therefore,

$$
\frac{y_0}{z + x_0} = \frac{y_1}{z + x_1} \quad (z \geq 0)
$$

Solving for $z$ yields equation 1.
This is strictly true only when the forager does not procure enough of the resource initially so that field processing reduces it to the optimal load size. We do not know whether procurement and field processing are likely to take place as two sequential activities or as a series of alternate activities. Therefore, for developing $U(t)$, foragers are only credited for those resources that could be transported at any particular moment during the course of procurement and field processing.

Ecologists use the term handling time to refer to the time spent pursuing, capturing, and consuming a prey item. We have distinguished between procurement (handling time required to procure the unmodified resource item) and field processing (handling time required to modify the resource package) for clarity.

O’Connell, Hawkes, and Blurton Jones (1988:129) note that dividing the average carcass weight of giraffe by number of Hadza carriers results in a value of about 45 kg per carrier. This should not be confused with the weight of loads actually transported, because the calculation includes bone and meat abandoned at the kill-butcher site.

There is an additional reason to expect that many resources’ utility functions will approximate diminishing-return functions. Most resource patches are likely to be finite, and continued exploitation will deplete those patches. Under these circumstances, increasingly greater amounts of time are required to acquire additional resources—even without field processing, this is likely to produce a diminishing-return function.

These values were calculated using equation 2 and the data presented in Lee (1975:Fig. 7.2) after converting caloric values to utility (see Note 1).

Mixed loads are only expected for resources that have utility functions similar to those represented in Figures 1 and 2. When the utility function is smooth and continuous, time constraints on individual foraging events should result in the transport of loads that are less, but uniformly, processed than predicted by the model.

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