A model of central place forager prey choice and an application to faunal remains from the Mimbres Valley, New Mexico

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Abstract

Drawing on models from foraging theory, many researchers have used assemblages of animal bones from archaeological sites to document cases of resource depression and reduced foraging efficiency. This paper presents a model of central place forager prey choice that unifies several issues that these previous studies have addressed through the use of separate models. In comparison to the models usually employed, the model presented here makes assumptions that more closely match the ways in which human hunting is often carried out, and it also makes it easier to determine how decisions about the processing of prey at their point of capture will combine with decisions about prey choice to influence overall foraging efficiency for central place foragers. The benefits that arise from the use of such a model are illustrated by applying it to archaeofaunal data from the Mimbres Valley, southwestern New Mexico, where it appears that people experienced depression of large mammal resources, and declining hunting efficiency, during the period between about AD 400 and AD 1200.

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Many researchers have used assemblages of animal bones from archaeological sites to document cases of resource depression (Charnov et al., 1976), or reductions in the prey capture rates of human foragers that were the result of their own harvesting of those prey (e.g., Bayham, 1979; Broughton, 1994a,b, 1997, 1999; Cannon, 2000; Grayson, 1991; Hildebrandt and Jones, 1992; Janetski, 1997; Nagaoka, 2000, 2002; Szuter and Bayham, 1989; also see Broughton, 2002a,b; Grayson and Cannon, 1999; Hildebrandt and McGuire, 2002; Jones and Hildebrandt, 1995; Lyman, 1995; Lyman and Wolverton, 2002; Ugan and Bright, 2001). These studies have important implications for our understanding of the ways in which people have structured our planet’s ecosystems, particularly through their effects on populations of large-bodied vertebrates (e.g., Broughton, 2002b; Grayson, 2001; Kay, 1994, 1998).

Also important is that these studies provide an archaeologically operational measure of foraging efficiency, or the efficiency with which people obtained calories from their environments through the harvest of wild resources. Reductions in for-
aging efficiency have been suggested to have led to several changes that are evident in the archaeological record of various parts of the world, ranging from increases in the importance of agriculture (e.g., Barlow, 1997, 2002; Cannon, 2000, 2001a; Winterhalder and Goland, 1997) to increases in the degree of violent conflict (e.g., Broughton and O’Connell, 1999). By providing an empirical measure of foraging efficiency, resource depression studies offer a means of testing hypotheses about the causes of major changes that occurred in the human past.

In this paper I present a model of central place forager prey choice that unifies several issues that have previously been addressed in archaeological resource depression studies through the use of separate models. In comparison to the models invoked in most resource depression analyses, the model that I present here makes assumptions that more closely match the ways in which human hunting is often carried out. Perhaps more important, however, is that, in comparison to the approaches taken in previous studies, the model that I present makes it easier to determine how decisions about the processing of prey at their point of capture will combine with decisions about prey choice to influence overall foraging efficiency for central place foragers. I illustrate the benefits that arise from the use of such a model by applying it to archaeofaunal data from the Mimbres Valley, southwestern New Mexico, where it appears that people experienced depression of large mammal resources, and declining hunting efficiency, during the period between about AD 400 and AD 1200.

Resource depression and central place foraging

Most previous archaeological resource depression studies have drawn explicitly on the prey model—also known as the prey choice or diet breadth model—from foraging theory (e.g., Kaplan and Hill, 1992; Stephens and Krebs, 1986). This model shows that, given certain assumptions (see Broughton, 1994a, 1997; Smith, 1991; Stephens and Krebs, 1986), the most energy-efficient foraging strategy is to pursue resources with higher post-encounter caloric return rates whenever they are encountered, and to pursue lower return resources only when higher return resources are encountered relatively infrequently.

Since post-encounter return rate is positively correlated with body size for most vertebrate prey, it is argued that, if energetic returns were important as a decision-making currency among a group of foragers, larger-bodied taxa should have been pursued by those foragers whenever they were encountered (e.g., Bayham, 1979; Broughton, 1994a,b, 1997, 1999; Szuter and Bayham, 1989). From this it follows that a decline over time in the relative abundance of a larger-bodied taxon in an archaeological assemblage would indicate a reduction in the rates at which individuals encountered that taxon (Broughton and Grayson, 1993). Assuming that other causes of the reduction in encounter rates such as climate change can be ruled out (see Grayson and Cannon, 1999), the decline in relative abundance would indicate that people experienced resource depression, or a reduction in per capita prey capture rates resulting from the effects of their own predation on the taxon involved. In addition, because the resource whose availability was reduced was one that provided a high caloric return rate, the decline in its relative abundance would indicate a decline in overall foraging efficiency.

Foraging theory models, however, make very specific assumptions about the real-world cases to which they are applicable, and their use in situations in which their assumptions are not met may not provide a valid test of any hypotheses derived from them (e.g., Stephens and Krebs, 1986). Some researchers have recognized that most archaeological situations likely violate a key assumption of the prey model (e.g., Broughton, 1994a, 1999; Nagaoka, 2000), and they have dealt with this by employing other foraging models in conjunction with it. As I describe next, though, this approach is less than ideal when research goals include documenting changes over time in foraging efficiency, particularly in cases involving people who hunt from a central place to which they return with captured prey.

The aspect of the prey model that has been acknowledged to be problematic is its assumption that the probability of encountering any prey type is independent of previous encounters either with it or with any other prey type. This “fine-grained search assumption” will be violated, for example, when individuals of a given prey type have a better than random chance of being found close to one another within certain areas of a habitat; that is, when prey exhibit “patchy,” or heterogeneous, distributions (e.g., Broughton, 1994a; Smith, 1991, pp. 206–207, 228). In such instances the prey model applies to a forager while foraging within a homogeneous resource patch, but another model
is required to address the issue of which patches to exploit in the first place (e.g., Smith, 1991).

Most archaeofaunal assemblages are likely to have been deposited over long periods of time by multiple individuals who hunted in a variety of resource patches (e.g., Broughton, 1994a; Broughton and Grayson, 1993), and for this reason the fine-grained search assumption of the prey model will be violated unless the model is applied only to sets of resources that could have been collected within a single patch. Archaeologists who have recognized this have appropriately dealt with the nested decisions of patch choice and prey choice by using models designed to address each decision independently (e.g., Broughton, 1999; Nagaoka, 2000). These researchers have first divided their study areas into patches: for example, a coastal setting might be divided into a marine resource patch and a terrestrial resource patch. They have then used the prey model to address the decision of which prey to pursue within a patch, the solution to which depends on the abundances of high-return prey within that patch, and a patch choice model (based on the marginal value theorem; see Charnov, 1976) to address the decision of how much time to spend foraging in each patch, the solution to which depends both on the marginal rate of energetic gain obtained from each patch per unit time spent foraging within it and on the average amount of time that it takes to travel between patches.

Because this approach uses separate models to address what are conceptualized as separate decisions, it is difficult to determine what effects prey choice and patch choice will combine to have on overall foraging efficiency. In addition, because the patch choice model used in these studies assumes that patches are encountered in the same manner in which prey are assumed to be encountered by the prey model, it is not appropriate for cases involving central place foragers who begin each foraging trip from a single point on the landscape. For central place foragers, patch choice will affect overall foraging efficiency because different patches will be located at varying distances from the central place and will thus entail varying costs in terms of travel and resource transport time. Using the approach taken previously, however, it is difficult to integrate travel and transport costs, prey encounter rates, and prey post-encounter return rates into a single theoretical measure of foraging efficiency for central place foragers.

As a potential solution to these problems, I have argued that a more appropriate foraging theory model for use in most archaeological situations is Orians and Pearson’s (1979) model of central place forager patch choice (Cannon, 2000). This model assumes a habitat that consists of some number of internally homogeneous resource patches located at varying distances from a central place, and it asks which of the available patches will maximize the rate of energy delivery to the central place. The decision variable in this model is which patch to exploit, but the solution to this decision depends both on the time that it takes to travel to each patch and on the energetic gain function provided by each patch, which depends in turn on the abundances and post-encounter return rates of the various prey types found within each patch. Thus, this model allows direct analysis of the combined effects on foraging efficiency of both transport costs and the availability of different prey types within patches.

I do not go into the details of the Orians and Pearson patch choice model here because I have done so elsewhere (Cannon, 2000). In this paper, I am primarily concerned with one factor that may be extremely important in cases of central place foraging that the Orians and Pearson model does not explicitly take into account. Foragers may often be able to increase their rate of energy delivery to a central place by processing resources at their location of acquisition in such a way that parts of low caloric “utility” are left behind (e.g., Binford, 1978; Perkins and Daly, 1968; Thomas and Mayer, 1983; White, 1954). Metcalfe and Barlow (1992) (see also Bettinger et al., 1997) have developed a theoretical model of the trade-off between transport costs and field processing costs that is central to this issue, and implications of this model have been explored using both ethnographic and archaeological data (e.g., Barlow and Metcalfe, 1996; Beck et al., 2002; Bettinger et al.,
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One of the main points to be taken from this work is that an efficiency-minded forager should spend more time processing prey at the point of capture as the distance back to the central place increases. In turn, this relation between transport distance and optimal field processing time has been used in archaeological resource depression analyses to draw inferences about changes in patch use based on the abundances of different parts of vertebrate prey carcasses recovered at residential sites (e.g., Broughton, 1999; Nagaoka, 2000; Rogers and Broughton, 2001; also see Rogers, 2000). The logic behind doing so is simple. If a hunter spends more time processing a carcass in the field, then more parts of low food value should be removed from the load that is taken home so that the utility of that load, measured in calories per unit weight, is increased. If more time is spent field-processing carcasses as transport distance increases, then a smaller proportion of low utility parts should be taken home when more distant patches are used.

It is possible to combine a model of field processing like the one developed by Metcalfe and Barlow (1992) with a model of central place forager prey choice that is similar to the patch choice model presented by Orians and Pearson (1979), and I do so next. The model that I present facilitates exploration of the combined effects of prey selection, transport distance, and field processing on overall foraging efficiency. This model can also be used to develop predictions about the patterns that should be observed in archaeological faunal assemblages deposited at residential sites over spans of time during which central place foragers were experiencing resource depression, and I apply these predictions to the Mimbres Valley case below.

The central place forager prey choice model

As with the Orians and Pearson (1979) patch choice model, the model that I present here assumes that the goal of a central place forager is to maximize his or her “delivery rate,” or the amount of energy carried back to the central place per unit foraging time. The decision that I model here, however, is different from the one that Orians and Pearson model: rather than “what patch should I forage in on my next foraging trip?” it is, “what kind of prey, and what parts of that prey, should I bring home from my next foraging trip?” Central place foraging will often require foragers to choose between prey with different post-encounter return rates that they can expect to encounter at different distances from home, and what follows is an attempt to model decisions of this sort.

The delivery rate in this model is essentially a measure of foraging efficiency, or the amount of energy obtained per unit of time spent foraging. As I illustrate below, this rate is affected by the abundances of prey, by transport time, by the post-encounter return rates of prey, and by the amount of time spent processing prey in the field. As a result, all of these variables are incorporated into the measure of foraging efficiency that the model provides.

I first present the basic elements of the model and then discuss them in greater detail. My presentation is geared towards the mammalian prey that I consider in my analysis of Mimbres Valley faunal assemblages: large-bodied artiodactyls like deer (Odocoileus spp.) and pronghorn (Antilocapra americana) and small-bodied leporids like jackrabbits (Lepus spp.) and cottontails (Sylvilagus spp.). It should require little modification, however, for the model to be applicable to other kinds of resources.

Central to this model is the assumption that there is a maximum load size, measured in units of weight, that a forager will transport home (e.g., Jones and Madsen, 1989; Zeannah, 2000), and I designate this parameter “Lmax.” In addition, there are four characteristics of resources that are important in the model: (1) the number of calories provided by a prey item, (2) the weight of a prey item, (3) the length of time that it takes to encounter a prey item, “handle” it, and transport it back home, and (4) the manner in which the utility of a load of a prey type can be increased through field processing. The variables that reflect these characteristics are defined in Table 1, and the relations between these variables are depicted graphically in Fig. 1.

Regarding the assumption of a maximum load size (Lmax), it is obvious that some resources, such as large mammals, come in packages that are too

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2 I use the terms “prey type” and “prey item” as they are used in Smith (1991, p. 205), though the model that I present requires slight modification of the definition of a prey type: a prey item is a single unit of harvest, and a prey type is defined by the variables e, m, and c, and by the processing function E(p).
heavy to be carried by a single person or perhaps even by several people. A central place forager who harvests such a prey item will have to make a decision about which parts of it to take home and which to leave behind, and the model that I present here integrates this decision into the decision about prey choice. It is not necessary to know the precise value of the maximum size of the loads transported by foragers in order to apply this model: archaeological predictions derived from it can be tested qualitatively—that is, by considering the directions of changes in various aspects of resource acquisition (see Kaplan and Hill, 1992)—if certain assumptions can be made. First, it must be assumed that \( L_{\text{max}} \) remained relatively constant over time, or, more exactly, since different individual foragers may well have had different \( L_{\text{max}} \) values, and since different numbers of people may have been involved in different foraging trips, it must be assumed that the distribution of \( L_{\text{max}} \) is.

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**Table 1**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_i )</td>
<td>The delivery rate provided by a unit of the ( i )th prey type, or the average amount of nutritional energy taken home per unit of foraging time when an item of this prey type is harvested</td>
</tr>
<tr>
<td>( E_i )</td>
<td>The energy of a load, or the average amount of energy contained in a load of prey type ( i ) that is transported home from the place where it is acquired and processed; I use this term interchangeably with the term utility&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>( e_i )</td>
<td>The average amount of energy contained in one complete unit of prey type ( i )</td>
</tr>
<tr>
<td>( m_i )</td>
<td>The average weight of one complete unit of prey type ( i )</td>
</tr>
<tr>
<td>( s_i )</td>
<td>Search and transport time, or the average amount of time that it takes to find a unit of prey type ( i ) once search has begun plus the average amount of time that it takes to transport a load of that prey type home</td>
</tr>
<tr>
<td>( h_i )</td>
<td>Handling time, or the average amount of time that it takes to pursue and obtain a unit of prey type ( i ) following encounter plus any additional time that is required to initially prepare the prey item for transport</td>
</tr>
<tr>
<td>( c_i )</td>
<td>Capture time, which equals ( s_i + h_i )</td>
</tr>
<tr>
<td>( p_i )</td>
<td>Processing time, or the amount of time spent processing a load of prey type ( i ) in order to increase its utility after any initial processing necessary to prepare it for transport (i.e., ”handling”) has been completed</td>
</tr>
<tr>
<td>( T_i )</td>
<td>Total foraging time, which equals ( c_i + p_i )</td>
</tr>
</tbody>
</table>

<sup>a</sup>As used here, “energy” is similar to the concept of “utility” employed in previous field processing models (e.g., Bettinger et al., 1997; Metcalfe and Barlow, 1992), but it is expressed in units of energy (e.g., kilocalories) rather than in units of energy per unit of weight or volume (e.g., kcal/kg or kcal/L).

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**Fig. 1.** The central place forager prey choice model. Prey type 1 is a “small” prey type \( (m_1 \leq L_{\text{max}}) \), and prey type 2 is a “large” prey type \( (m_2 > L_{\text{max}}) \). See text for details.
values across foraging trips did not change substantially over time. It must also be possible to make assumptions about whether the package sizes of important resources fell above or below the maximum load size, and I note that the weight of the large mammal resources that I consider below certainly must have fallen above this size for hunters in the Mimbres Valley.3

Because this model assumes that there is a maximum load size that a forager will transport home, prey types can be divided into two classes that I will call “small” and “large”: small prey types are those for which the weight of a complete prey item is less than or equal to the maximum load size (i.e., \( m_i \leq L_{\text{max}} \)), and large prey types are those for which the weight of a complete prey item is greater than the maximum load size (i.e., \( m_i > L_{\text{max}} \)). I discuss small prey types first, and in order to develop the model I make the unrealistic assumption that only one unit of a small prey type will be harvested per foraging trip. In other words, I assume that a forager will return home as soon as the first prey item is captured and “handled,” even if that item is small enough that additional items might easily be collected and transported home on the same trip. I present this model in greater detail elsewhere (Cannon, 2001a), and I show there that relaxing this assumption has no effect on the qualitative predictions that can be derived from it.

Prey type 1 in Fig. 1 is an example of a small prey type that is harvested singly. When a central place forager leaves home to forage, a certain amount of time will pass before a unit of prey type 1 is encountered. The average amount of this “search” time is included in the variable \( s_i \), and I envision this to be search time averaged over a relatively short period, perhaps on the order of days or weeks. The average amount of time that it takes to encounter a unit of a given prey type might vary for many reasons, but the abundance of that prey type on the landscape, or at least its abundance in areas close to a forager’s central place, should be especially important.

This model makes no specific assumptions about such issues as whether search time consists of time spent traveling to a distant location to harvest prey or whether it consists of time spent searching or waiting for prey close to home. However, in addition to search time, the average amount of return trip “transport” time for a prey type is also included in the variable \( s_i \). Thus, if a forager does travel a long distance, on average, to harvest prey type i, \( s_i \) will be greater than it would be if the resource could be obtained closer to the central place.

This model also makes no specific assumptions about the distribution of prey on the landscape. It does not necessarily assume that a forager searches for all prey types simultaneously, as the standard prey model does, and it entails no “fine-grained search assumption”; search time is treated as a distinctive characteristic of each individual prey type and is not distributed equally among all prey types. Likewise, the model does not assume the existence of discrete resource patches, although it is compatible with them.

If a forager decides to pursue a prey item once it is encountered, “handling” time \( (h) \) begins. For now, I use the term handling time in a manner similar to its usual usage in foraging theory (e.g., Stephens and Krebs, 1986, pp. 13–24), and I consider it to include time spent pursuing, capturing, and preparing a prey item for transport. If a prey item is smaller than the maximum load size, and if only one such prey item is acquired per foraging trip, then it is relatively straightforward to calculate the delivery rate because processing time, as defined in this model, can be disregarded. It makes no sense for a delivery rate-maximizing forager to “process” such a prey item after “handling” it because any time spent doing so cannot increase the amount of energy taken home: it can only lower the delivery rate by increasing the amount of time spent in the field. As I discuss below, however, this is not the case for large vertebrate prey types.

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3 In his model of optimal site location for central place foragers, Zeanah (2000) assumes a maximum load weight of 30 kg. O’Connell et al. (1988) (see also O’Connell et al., 1990) found that Hadza foragers in East Africa usually carry loads of meat that average 10–20 kg per person, though when they kill or scavenge the carcasses of giraffes (which weigh more than twice as much as the next largest prey species regularly taken), loads might weigh as much as 45 kg per person. For plant resources, Bettinger et al. (1997) have analyzed ethnographically collected baskets from California, and they suggest that the average load size transported on daily “residential” foraging trips was approximately 15 kg, while the average load size carried on longer distance “logistical” foraging trips was approximately 36 kg (see also Barlow et al., 1993). Even if the largest value of 45 kg were used as an estimate of maximum load size for Mimbres Valley hunters, most individuals of the artiodactyl species that are the subject of this study would fall above this value (see weights in Chapman and Feldhamer, 1982, for example).
For a small prey item that is acquired singly, the delivery rate is simply the amount of transported energy provided by that prey item \( (e_i) \) per total amount of time spent foraging. In this case total foraging time is just “capture” time \( (c_i) \) which equals \( s_i + h_i \), and the delivery rate for a unit of prey type \( i \) is given by

\[
R_i = e_i / c_i. \tag{1}
\]

This rate can also be represented by a line that begins at the origin and then passes through the point defined by \( c_i \) on the time axis and \( e_i \) on the energy axis: the steeper the slope of this line, the higher the delivery rate.

I now turn to large prey types, an example of which is provided by prey type 2 in Fig. 1. The concepts of search and transport time and handling time apply to these prey types just as they do to small prey types. With large prey types, however, the issue of processing time becomes important.

If the weight of a unit of a prey type is greater than the heaviest load that a forager will transport (i.e., if \( m_i > L_{\text{max}} \)), then that prey item must be processed in the field in order to reduce its weight before it can be taken home. Adult male mule deer, for example, can weigh over 150 kg, which is far too heavy for a single person to carry. Thus, when one of these animals is killed, its carcass will have to be prepared to some degree before any of it can be transported, and even if several people are available to carry the carcass, some butchery may be required to divide up the load.\(^4\) In terms of the model presented here, the time that it takes to perform such processing is considered to be “handling time” rather than “processing time.”

However, it may be possible to increase the utility of a load by spending additional time processing the prey item beyond the minimum amount of time required initially to prepare it for transport. Consider, for example, two loads of equal weight: one consists of two complete deer hind limbs, and the other consists of a section of ribs plus two hind limbs with phalanges, metatarsals, and tarsals removed. Because the lower limbs provide fewer calories than ribs (e.g., Metcalfe and Jones, 1988, Table 3), less of the weight in the second load will be taken up by low calorie body parts, and the utility of this load will be higher than the utility of the first load. On the other hand, it will also take longer to prepare the second load because time must be spent removing the section of ribs from the carcass and disarticulating the tarsals from the tibiae. In the model presented here, any such “extra” time spent processing a load in order to increase its utility constitutes “processing time” rather than “handling time.”

More generally, for any prey type for which a prey item consists of parts that vary in caloric content per unit weight, the way in which the utility of a load of that prey type changes with processing time can be described by a “processing function.”\(^5\) I denote this function as \( E_i(p_i) \) because a processing function will be specific to the \( i \)th prey type. In Fig. 1 the processing function for prey type 2 is represented by the curve labeled \( E_2(p_2) \), and Fig. 2 is a more detailed depiction of such a function. If a prey item weighs more than the maximum load size, then it will provide no transportable utility to a forager until handling is complete because it is only at this point—when a load of size \( L_{\text{max}} \) is produced—that any of the item can be carried home. In Fig. 2, the utility of a prey item after handling is denoted as \( E_0 \). If the utility of a load can be increased further through processing, then this can be described by a processing function, \( E_i(p_i) \). Eventually, however, a point should be reached at which processing no longer increases the utility of a load (utility may even decline with further processing), and the utility of the load at this point is designated \( E_{\text{max}} \).

Many prey types should exhibit processing functions that take the shape of a diminishing returns curve, as shown in Fig. 2. Barlow and Metcalfe (1996) and Bettinger et al. (1997) have shown that the processing functions for at least some plant resources approximate diminishing

\(^4\) Large-bodied vertebrates, of course, are not the only kinds of resources that might fall into this class of prey types. For example, if individuals of a smaller-bodied vertebrate taxon are encountered and harvested simultaneously, then the entire group of harvested individuals is the relevant prey item (e.g., Madsen and Schmitt, 1998), and such aggregate prey items might also exceed \( L_{\text{max}} \). In cases like this foragers will have to do one or both of two things: leave some of the individuals that are collected behind, or process at least some of them so that a load of the maximum size is obtained (see Cannon, 2001a for further details on this and related points).

\(^5\) This is similar to the “utility function” of Metcalfe and Barlow (1992), but I have changed the name to distinguish this function from the overall energetic delivery rate in the model that I present here \( (R_i) \), which could also be considered to be a “utility function.”
returns curves, but data are not currently available to determine empirically whether this is the case for vertebrate resources. However, Metcalfe and Barlow (1992, pp. 350–351) present a logical argument as to why the processing functions for certain resources will resemble diminishing returns curves, and their argument probably applies to vertebrate prey.

These authors first characterize some kinds of resources as “structured” and others as “unstructured.” A structured resource is one for which the morphology of the prey item determines the order in which processing steps must be undertaken: for example, a pinyon nut must first be removed from the cone before the hull can be removed from the nut (e.g., Barlow and Metcalfe, 1996). For an unstructured resource, on the other hand, a forager can choose the order in which to undertake processing steps. When processing a resource of this sort, Metcalfe and Barlow argue, a forager should first take whatever processing step results in the greatest increase in load utility per unit of processing time, then take the step that results in the next greatest increase in load utility per unit of processing time, and so on. This will be the strategy that produces the load of the highest utility for any given amount of processing time, and the processing function that results from such a strategy will exhibit diminishing marginal returns.

Vertebrate resources are partially structured—for example, the scapula and fore limbs of a large mammal must be removed before all of the ribs can easily be removed from the vertebrae—but they are also partially unstructured—a fore limb can be removed before a hind limb, for example, and vice versa. In fact, there is probably a nearly infinite number of combinations of body parts that a forager could remove from a vertebrate carcass and transport home (Rogers, 2000 calls such combinations “configurations”), and there are certainly many different ways in which the removal of various body parts might be ordered. Thus, there should be sufficient flexibility in the way in which a vertebrate carcass can be processed to allow processing functions for this kind of resource to approximate diminishing returns curves.

I assume here that this is the case. Regarding the handling time-processing time distinction that the central place forager model makes, I assume that the initial handling stages of vertebrate carcass preparation \( (h_i) \) will be carried out in such a way that a load of size \( L_{\text{max}} \) will be produced in the most efficient manner possible, meaning that whichever processing steps produce a load of the highest utility per unit of processing time will be carried out first during these initial stages. For many vertebrate resources, however, it should be possible to further increase the utility of a load with additional processing time \( (p_i) \). I assume that this additional processing will be performed in the manner in which Metcalfe and Barlow (1992) argue that it should be carried out when an unstructured resource is being processed. This will result in processing functions for vertebrate prey that take the shape of diminishing returns curves.

If the processing function for a large prey item does approximate a diminishing returns curve, then the highest delivery rate that is obtainable

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6 Presently available measures of vertebrate body part utility (e.g., Binford, 1978; Lyman et al., 1992; Metcalfe and Jones, 1988) include no information about the amount of time required to remove various parts, or various combinations of parts, from a carcass. Thus, though useful for some purposes, these measures cannot be used to determine processing functions for vertebrate resources (cf. Metcalfe and Jones, 1988).
from that prey item can be calculated as shown in Fig. 1. In solving for this highest delivery rate, the optimal amount of time to spend processing the item after handling is also necessarily determined. It can be seen graphically that the highest delivery rate that can be obtained for prey type 2 in Fig. 1 is defined by a line beginning at the origin that is tangential to the processing function, and I demonstrate this mathematically elsewhere (Cannon, 2001a, Appendix A). This line also gives the optimal amount of processing time, which I denote as $p^*_T$; for any amount of processing time greater than or less than $p^*_T$, the delivery rate will be lower than the delivery rate obtained when $p^*_T$ units of time are spent processing. The maximum delivery rate provided by a large resource can be described by the equation:

$$R^*_T = E_i(p^*_T)/T^*_T,$$

where

$$T^*_T = c_i + p^*_T.$$

To explore the effects that transport distance will have on optimal processing time and the overall delivery rate, consider Fig. 3. Two prey types with identical handling times and processing functions are depicted here, and the only way in which these prey types differ is in average search and transport time: $s_1$ is considerably lower than $s_2$. This would be the case, for example, if prey type 2 could only be found in areas more distant from the central place, so that more time were required to transport units of this prey type home. It is apparent that the highest delivery rate that prey type 1 can provide is much greater than the highest delivery rate that could be obtained from prey type 2. In addition, however, note that the optimal amount of time to spend processing prey type 1—that is, the amount of processing time that results in the highest delivery rate—is much lower than the optimal amount of processing time for prey type 2.

This latter result is consistent with the prediction that can be drawn from the model presented by Metcalfe and Barlow (1992) that more time should be spent processing a resource in the field (i.e., removing low utility parts from the load that is carried home) the greater the distance over which that resource must be transported. What the model presented here makes easier to see, however, is that, all else being equal, spending less time processing a resource acquired close to home will always result in higher overall foraging efficiency than can be obtained by spending more time processing that resource when it is acquired far from home, even if additional processing increases the utility of the load that is carried back (assuming that actual processing time approximates $p^*_T$).

In addition, since the variable $s_i$ is the sum of average transport time plus average search time, this model can also be used to predict that more time should be spent processing a resource in the field the greater the average amount of time it takes to encounter a unit of that resource. This prediction cannot be derived from the Metcalfe and Barlow model because that model does not take search time into account. This prediction can be understood intuitively by considering that, when search time is high, a little extra processing.
time will increase total foraging time by a proportion that is small relative to the proportion by which it will increase the utility of the load that is taken home. When search time is low, however, that same amount of extra processing time would increase total foraging time by a proportion that would be larger in relation to the increase in load utility that could be obtained.

It is now possible to address the issue of prey choice. Fig. 4 depicts three prey types that provide different average delivery rates. If the goal of a forager is to maximize the rate of energy delivery to the central place, then that forager should necessarily choose to harvest the prey type that provides the highest delivery rate. Of the prey types shown in Fig. 4, prey type 1 will do so on average, and it can thus be predicted that a delivery rate-maximizing forager will most often harvest this prey type.

I point out that this model does not predict that a forager will harvest only the resource with the highest average delivery rate during a given span of time. The variable $s_i$ represents short-term average search and transport time, and search and transport time will vary around this mean for most resources: on some foraging trips it will take less than the average amount of time to encounter a unit of prey type $i$ and carry it home, while on other trips an above-average amount of search and transport time will be required. In terms of Fig. 4, for example, a forager may occasionally encounter a unit of prey type 2 soon enough that it could provide a delivery rate higher than the average delivery rate provided by prey type 1, as represented by the open dot to the left of the solid dot for prey type 2. In this case the forager should, of course, take the unit of prey type 2. Because the average time-to-encounter for prey type 2 is much longer than this, however, occurrences of this sort will necessarily be rare. Likewise, it may sometimes take longer than usual for a forager to encounter a unit of prey type 1, or one might not be found at all. In such a case the forager’s best option may be to pursue a resource with a lower average delivery rate that is encountered late in the foraging trip, so that at least something is taken home.

In essence, then, this model assumes that a forager makes an encounter-contingent decision about whether or not to pursue a resource based on reasonably accurate knowledge of such factors as the distribution of search and transport times for each potential prey type and the post-encounter return rate of each prey type. In other words, the model assumes that a forager decides whether to pursue a resource upon encounter based on an evaluation of the probability that he or she will encounter an alternative resource on that same foraging trip that can provide a higher delivery rate.

Unlike the standard prey model, which assumes that a forager searches for all prey types simultaneously, the central place forager model is consistent with a variety of search strategies because it does not treat search time as being distributed equally among all prey types. For this reason, it is better suited to the range of search strategies used by human foragers. As Kaplan and Hill (1992, pp. 184–185) discuss, some ethnographically observed central place foragers do search for all potential resources simultaneously, but others set out on foraging trips with specific

![Fig. 4. Three prey types that provide different average delivery rates. Prey types 1 and 3 are “large” prey types, and prey type 2 is a “small” prey type.](image-url)
resources in mind, while yet others follow strategies that fall somewhere between the two extremes (also see Smith, 1991). The model that I present here should be applicable to all such strategies. Moreover, as Kaplan and Hill also note, central place foragers who have a specific resource in mind when they leave on foraging trips sometimes end up harvesting resources other than the one that they had initially targeted. The central place forager prey choice model may often be helpful for explaining why such “target-switching” occurs because it can be used to explore the consequences of encountering resources more quickly or more slowly than a forager might expect at the outset of a foraging trip.

Regarding the assumption made by this model that a forager knows the relevant characteristics of potential prey types, I point out that most foraging theory models assume that foragers possess accurate information about the environments in which they live (e.g. Stephens and Krebs, 1986). For human foragers, this assumption is justified since it has been well documented that people in small-scale societies usually possess a remarkable degree of ecological knowledge (e.g., Felger and Moser, 1985; Hill et al., 1997; Nelson, 1983; Rea, 1998).

Returning to Fig. 4, prey type 1, which provides the highest average delivery rate, is a “large” prey type \(m_1 > L_{\max}\), while prey type 2, which provides a lower average delivery rate, is a “small” prey type \(m_2 < L_{\max}\). As I mentioned above, previous archaeological resource depression studies that have employed the standard prey model have used vertebrate prey body size as a proxy measure of post-encounter return rate because there is a strong correlation between the two variables (e.g., Bayham, 1979; Broughton, 1994a,b, 1997, 1999; Szuter and Bayham, 1989). The concept of “the post-encounter return rate of a resource” takes on a slightly different meaning in the central place forager prey choice model because this model recognizes that post-encounter returns will vary with processing time, which should vary, in turn, with search and transport time. I show elsewhere, however, that it remains appropriate to use body size as a proxy for post-encounter return rate when applying this model to such vertebrate resources as artiodactyls and leporids that are encountered sequentially (Cannon, 2001a).

Since this is the case, if a small prey type and a large prey type have equivalent average search and transport times, then the large prey type will provide the higher average delivery rate, and this should be the resource that is most often pursued by a delivery-rate maximizing forager. In fact, the large prey type would provide the higher average delivery rate even if it took somewhat longer on average to encounter and/or transport this prey type; only when the average search and transport time of the large prey item is sufficiently higher than that of the small prey item will the small prey item provide the higher average delivery rate.\(^7\)

This brings us finally to the issue of long-term change over time. As I discussed above, the variable \(s_i\) is the average amount of search and transport time for a resource calculated over some relatively short period of time. Over longer periods, however, the average search and transport time for a resource might change. If this were to happen, then the resource would, in effect, become a new prey type from the point of view of the central place forager model.

If the average amount of time that it took to find a unit of a particular resource increased over the long term (as would occur if the resource became less abundant on the landscape) and/or if foragers had to travel further to harvest that resource (perhaps due to declines in its abundance in nearby areas), then the average delivery rate that the resource provided would decline. This is illustrated by prey type 3 in Fig. 4: this prey type has a processing function identical to that of prey type 1, and the difference between these two prey types can be accounted for entirely by an increase in average search and transport time. Search and transport time for prey type 3 is so much greater, in fact, that the average delivery rate that it provides is lower than the average delivery rate provided by prey type 2, a small prey type. In a case like this a delivery-rate-maximizing forager should pursue the small prey type (prey type 2) more often than the large one (prey type 3).

Given this, the same key predictions about the effects of resource depression can be derived from the central place forager model as have been derived from the separate models used in previous archaeofaunal resource depression studies. One set of these predictions involves the kinds of prey that foragers harvest and another involves the parts of prey that foragers transport home. For each of these issues, predictions can be made both

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\(^7\) Specifically, this will occur when \(R_2 > R_1\), which, if prey type 1 is a “large” resource and prey type 2 is a “small” resource, will occur when \(s_i > [(c_2/c_1)E_i (p_i)] - (h_1 + p_i^c)\); see Eqs. (1) and (2).
about the changes in foraging behavior that should occur due to long-term resource depression and about the patterns that should be observed in archaeological assemblages as a result of such changes in behavior.

Regarding the kinds of prey harvested, larger-bodied vertebrates will usually provide higher post-encounter caloric return rates than will smaller-bodied vertebrates. As a result, if a large-bodied prey type initially has a relatively low average search and transport time, it will likely provide a higher average delivery rate than would any smaller-bodied prey type, and it should be the resource that foragers pursue most often. If the average search and transport time for the larger-bodied resource increases, however, there will come a point at which some smaller prey type begins to provide the highest average delivery rate, and at this point foragers should begin to pursue the smaller resource more often. Since the average search and transport time of a prey type will be highly dependent on the abundance of that prey type on the landscape, at least in areas close to the central place, such a change in prey selection will often reflect a decline in the abundance of the large-bodied resource. It will also reflect a decline in foraging efficiency.

As I discussed above, variability around short-term mean search and transport times should lead foragers occasionally to take resources other than the one that provides the highest average delivery rate. In addition, for any given resource, one or more of the key factors $e_i$, $m_i$, $s_i$, $h_i$, and $E_i(p'/C_i)$ may well have changed in a non-directional manner during some span of time. These factors could have varied seasonally, for example, or yearly if climate fluctuated from year to year, and such variation would likely have led foragers to pursue different resources in different seasons or in different years.

However, if a long-term directional trend occurred in any factor such as the average search and transport time of a resource, then a long-term directional trend should also have occurred in the proportions of different resources that were harvested. This would cause, in turn, a directional trend in the relative abundances of various taxa in archaeological assemblages (see Broughton and Grayson, 1993 for a similar point in the context of diet breadth analysis). In the specific case of depression of a large-bodied vertebrate resource, we would see a decline over time in the archaeological abundance of the large-bodied taxon relative to smaller-bodied taxa.

As for the kinds of vertebrate prey body parts that hunters transport home, the central place forager model predicts that foragers should spend increasing amounts of time in the field removing low utility parts from the loads that they carry home as average search and transport time increases. Archaeologically, this leads to the expectation that increases in search time and transport distance, such as might occur due to resource depression, will result in the deposition of lower proportions of low utility body parts at residential sites. As noted above, the prediction that processing time should increase with transport distance can also be derived from the model presented by Metcalfe and Barlow (1992). However, by integrating field processing into a unified theoretical measure of the rate of energy delivery to a central place, the model presented here makes it easier to see that such increases in transport distance and field processing time will generally reflect declines in overall foraging efficiency.

Faunal assemblages from the Mimbres Valley

To show how the model that I have presented can be used archaeologically to test hypotheses about resource depression and reduced foraging efficiency, I apply it to faunal data from the Mimbres Valley of southwestern New Mexico. These data were collected as part of a larger study of the relation between hunting efficiency and the importance of agriculture during the Mimbres pithouse and pueblo periods (Cannon, 2001a), and they come from the Galaz, Mattocks, and McA­nally sites, which are located in the central portion of the valley (Fig. 5). Because these were all sizable residential settlements, and because people surely would have had to leave these settlements to capture the animals whose bones they deposited at them, a model designed specifically for central place foragers is preferable to the standard prey model in this case for reasons that I have discussed.

Background

Based primarily on apparent changes over time in the relative abundance of artiodactyl specimens in archaeofaunal assemblages from the Mimbres Valley, several researchers have suggested that Mimbres hunters experienced depression of large mammal resources as the human population of the valley grew. However, the data necessary to test this hypothesis fully have not previously been
collected (see overviews in Cannon, 2000, 2001a; also see Sanchez, 1996). In particular, factors that might interfere with the use of taxonomic relative abundance as a measure of resource depression—for example, taphonomic effects or climate change—have not been considered in any detail, nor has artiodactyl body part representation been analyzed with the subject of resource depression in mind. The results of my analysis of data pertaining to these issues, a portion of which is summarized here, are largely consistent with the hypothesis that Mimbres hunters reduced local abundances of artiodactyls, as I illustrate below.

Galaz (LA 635) was located on the west side of the Mimbres River on the first alluvial terrace above the river’s floodplain. The site effectively no longer exists, having been bulldozed by pothunters, but workers associated with the Mimbres Foundation research group were able to excavate pithouse deposits here during the 1970s while the site was in the process of being dismantled (Anyon and LeBlanc, 1984). Mattocks (LA 676) is located approximately 6 km north of Galaz, and it also sits on the first terrace above the floodplain on the west side of the Mimbres River; Mimbres Foundation researchers conducted excavations in and around four pueblo room blocks at this site (Gilman and LeBlanc, in preparation; LeBlanc, 1975, 1976a,b). McAnally (LA 12110) lies on top of a small hill directly across the Mimbres River from Mattocks; this site consists of several pithouse depressions, two of which were excavated by the Mimbres Foundation (Arthur, 1994; Diehl and LeBlanc, 2001; LeBlanc, 1975, 1976b). The faunal assemblages from all three of these sites have been analyzed previously (e.g., Diehl and LeBlanc, 2001; Powell, 1977), but the data that I present here come from my reanalysis of them. This reanalysis necessitates some modification of the conclusions that have been drawn from earlier
analyses, particularly regarding the timing of important changes.

Variability in the use of faunal resources by people living at settlements in the Mimbres region appears to have been strongly influenced by differences in the local biotic communities surrounding those settlements (e.g., Cannon, 2000, 2001a; Sanchez, 1996; Shaffer and Schick, 1995). I have shown elsewhere, however, that such habitat effects are unlikely to be a problem for the relative abundance analyses that I present in this paper, which is understandable because the sites that I consider here are located fairly close together within the same type of vegetational community (Cannon, 2001a).

The culture history sequence that has been developed for the Mimbres region is presented in Table 2; this sequence is divided into periods and phases, which are distinguished mainly on the basis of ceramic and architectural attributes (see Anyon et al., 1981; Diehl, 1994; Diehl and LeBlanc, 2001; Hegmon et al., 1999; Nelson and Anyon, 1996; Wills, 1996). The Early Pithouse period (ca. AD 400–600) apparently represents the earliest occupation of the Mimbres region by people who grew crops. McAnally is one of only a few sites with structures dating to the Early Pithouse period that have been excavated in the Mimbres Valley, and LeBlanc (1976a) argues that the ceramic assemblage from this site indicates that these structures were occupied only during this period (see also Diehl and LeBlanc, 2001).

For the purposes of this study I have assigned individual deposits from Galaz and Mattocks to time periods based primarily on analyses of ceramic content, the results of which are entirely consistent with the stratigraphic relationships that exist among these deposits and with the chronometric dates that are available for them (Cannon, 2001a). Deposits at Galaz with useful faunal samples contain material dating to the Georgetown (AD 600–700) and/or San Francisco (AD 700 to early 800s) phases, the Three Circle phase (early AD 800s to AD 1000), and the Classic Mimbres phase (AD 1000–1130), which appears to be the phase during which the human population of the Mimbres Valley was the largest (e.g., Blake et al., 1986). The majority of the useful deposits at Mattocks contain material dating to the Classic Mimbres phase, though some of the material at this site dates to the preceding Three Circle phase and some dates to the subsequent Terminal Classic (which lasts until the late AD 1100s).

Table 3 presents numbers of identified faunal specimens, aggregated by time period, for the combined assemblages from Galaz, Mattocks and McAnally.8 To ensure that the most accurate and precise information possible is obtained concerning changes over time in these assemblages, I include in this analysis only samples from undisturbed, well-dated deposits that were screened through 1/4 in. mesh during excavation (see Cannon, 2001a for further details about analytical procedures). I also include here only those taxa that are most useful for answering the research questions that I am addressing: deer (Odocoileus sp.), pronghorn (Antilocapra americana), jackrabbits (Lepus sp.), and cottontails (Sylvilagus sp.).

Deer and pronghorn are among the largest-bodied vertebrates that occur in the Mimbres Valley today, and the extreme rarity of such larger-bodied taxa as elk (Cervus elaphus) and bison (Bison bison) in archaeological assemblages from the valley suggests that people encountered these larger animals very infrequently during the span of time considered here. Deer and pronghorn thus certainly provided the highest post-encounter return rates of any of the wild resources that were common in the area, and for this reason any decline in the abundances of these taxa on the landscape would likely have caused a substantial reduction in overall wild resource foraging efficiency. To determine how search and transport times for these artiodactyls changed over time in the Mimbres Valley, I examine their abundance in faunal samples relative to the abundance of smaller-bodied leporids. Bones of jackrabbits and cottontails dominate most faunal assemblages from the valley, and these two taxa are the only small-bodied vertebrates that are common in the

8 The Georgetown/San Francisco sample comes from Galaz, and this material cannot be dated any more precisely than “Georgetown phase and/or San Francisco phase.” The Three Circle/Classic Mimbres and Classic Mimbres samples include material from both Galaz and Mattocks, and the former of these two samples contains material that likely dates to both the Three Circle and the Classic Mimbres phases. The Classic Mimbres/Terminal Classic sample comes from Mattocks and contains material that dates to both the Classic Mimbres phase and the Terminal Classic. There is also a faunal sample from Mattocks that contains material dating to perhaps as late as the AD 1300s or 1400s, but I do not include this sample here because it has apparently been subjected to a taphonomic history that is quite different from those experienced by the other faunal samples from this site (see Cannon, 2001a).
assemblages included in this study that are also likely to have been deposited by people after having been captured and eaten by them.

**Artiodactyl relative abundance**

The model that I outlined above can be used to predict that reductions over time in the archaeofaunal abundance of a large-bodied taxon relative to the abundances of smaller-bodied taxa will be observed in cases in which central place foragers experienced depression of the large-bodied taxon. Table 4 presents total numbers of identified artiodactyl and leporid specimens per time period from Galaz, Mattocks, and McAnally, and it also provides “Artiodactyl Index” values, calculated as the ratio of all artiodactyl specimens relative to all artiodactyl specimens plus all leporid specimens (e.g., Broughton, 1994a,b; Janetski, 1997; Szuter and Bayham, 1989): if Mimbres Valley hunters experienced long-term depression of artiodactyl resources, this measure of taxonomic relative abundance should decline over time.

This does occur here. A $\chi^2$ test indicates that there are highly significant differences in artiodactyl relative abundance among the samples in Table 4 ($\chi^2 = 53.23$, $p < 0.001$), and examination of the adjusted standardized residuals from this

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**Table 2**

Mimbres–Mogollon culture historical time periods (after Anyon et al., 1981; Diehl, 1994; Diehl and LeBlanc, 2001; Hegmon et al., 1999; Nelson and Anyon, 1996; Wills, 1996)

<table>
<thead>
<tr>
<th>Period</th>
<th>Phase</th>
<th>Abbr.</th>
<th>Dates (AD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Pueblo</td>
<td>Cliff (Salado)</td>
<td>–</td>
<td>1300–1450</td>
</tr>
<tr>
<td></td>
<td>Black Mountain (Animas, El Paso)</td>
<td>–</td>
<td>1200–1300</td>
</tr>
<tr>
<td>Early Pueblo</td>
<td>Terminal Classic</td>
<td>TCM</td>
<td>1130–1200</td>
</tr>
<tr>
<td></td>
<td>Classic Mimbres</td>
<td>CM</td>
<td>1000–1130</td>
</tr>
<tr>
<td>Late Pithouse</td>
<td>Three Circle</td>
<td>TC</td>
<td>825/850–1000</td>
</tr>
<tr>
<td></td>
<td>San Francisco</td>
<td>SF</td>
<td>700–825/850</td>
</tr>
<tr>
<td></td>
<td>Georgetown</td>
<td>GT</td>
<td>600–700</td>
</tr>
<tr>
<td>Early Pithouse</td>
<td>Cumbre</td>
<td>EP</td>
<td>400–600b</td>
</tr>
</tbody>
</table>

*a Abbreviations for time periods used in subsequent tables.

*b The beginning of the Early Pithouse period has traditionally been placed at AD 200. However, Wills (1996) notes that all of the pre-AD 450 dates that are available for early ceramic sites in the upland Mogollon region are radiocarbon dates that may be subject to the “old wood problem,” and he suggests that AD 400 is a more appropriate date to use for the start of the Early Pithouse period in the Mimbres Valley.

**Table 3**

Numbers of identified specimens of artiodactyl and leporid taxa in combined samples from the sites included in this analysis, aggregated by time period

<table>
<thead>
<tr>
<th>Phase</th>
<th>Artiodactylaa</th>
<th>Odocoileus sp. (Deer)</th>
<th>Antilocapra americana (Pronghorn)</th>
<th>Leporidaeb</th>
<th>Sylvilagus sp. (Cottontails)</th>
<th>Lepus sp. (Jackrabbits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM/TCM</td>
<td>11</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>CM</td>
<td>56</td>
<td>16</td>
<td>3</td>
<td>20</td>
<td>113</td>
<td>135</td>
</tr>
<tr>
<td>TC/CM</td>
<td>26</td>
<td>15</td>
<td>4</td>
<td>16</td>
<td>62</td>
<td>83</td>
</tr>
<tr>
<td>GT/SF</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>EP</td>
<td>10</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>106</td>
<td>43</td>
<td>9</td>
<td>43</td>
<td>202</td>
<td>242</td>
</tr>
</tbody>
</table>

*a These specimens are from deer- or pronghorn-sized artiodactyls but were not identifiable below the level of order.

*b Identification of leporid specimens to genus was based on size; these specimens are those that are too fragmentary to determine the size of the animal from which they came.
test (e.g., Everitt, 1977, pp. 46–48) shows that leporids are substantially under-represented in the two earliest samples. In addition, Cochran’s test of linear trend among proportions (see Cannon, 2000, 2001b; Zar, 1999, pp. 565–568) indicates that the temporal reduction in artiodactyl relative abundance that is apparent across these samples is highly significant ($\chi^2_{\text{trend}} = 19.28, p < 0.001$). The combined samples from these sites thus show a clear decline in the relative abundance of artiodactyls between the Early Pithouse period and the Three Circle phase.

As I describe elsewhere (Cannon, 2001a), the patterns that occur at other sites in the Mimbres region for which large faunal assemblages are available are consistent with the pattern that is evident among the sites that I consider here: artiodactyl relative abundance declines during the period of time leading up to the Three Circle phase, and there are no major changes in artiodactyl relative abundance at any site within the valley from the beginning of the Three Circle phase through the Terminal Classic.

An analysis of artiodactyl age profiles in Mimbres Valley faunal assemblages, which should be sensitive to changes in harvest rates (e.g., Broughton, 1997, 1999; Koike and Ohtaishi, 1985, 1987), is also consistent with this pattern (Cannon, 2001a).

Of course, a variety of factors other than predation by people might also affect the taxonomic relative abundance values observed in archaeofaunal assemblages, and efforts must be made to control for such factors before it can be concluded that a decline in artiodactyl relative abundance truly indicates that hunters experienced depression of these resources (e.g., Grayson and Cannon, 1999). I present detailed analyses of potential confounding factors elsewhere (Cannon, 2001a), and it does not appear that the changes in artiodactyl relative abundance that I have described can be explained by variability in the taphonomic processes to which these faunal samples have been subjected, by changes over time in the technologies or the tactics that people used to harvest prey, or by changes in climate or vegetation that might have affected the abundances of prey on the landscape independently of human hunting. The relative abundance data that I have discussed here thus seem to indicate that Mimbres hunters experienced depression of large mammal resources, and a decline in hunting efficiency, sometime during the period between about AD 400 and AD 800 or 850.

### Artiodactyl body part representation

The second set of predictions that can be derived from the model that I presented above concerns the effects of resource depression on the kinds of large mammal body parts that central place foragers transport back to their residential sites. As I described, if the average amount of search time required before an artiodactyl was encountered increased, and/or if the average distance over which such prey had to be transported increased, then people should have begun to spend more time processing these prey in the field, and this should be reflected by a decline in the proportion of low utility artiodactyl body parts that they carried home.

To determine whether this occurred at the Mimbres Valley sites that I consider here, I explore whether there are differences among time periods in the mean utility of the artiodactyl

---

Table 4

<table>
<thead>
<tr>
<th>Phase</th>
<th>Artiodactyls</th>
<th>Leporids</th>
<th>Total</th>
<th>Artiodactyl Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM/TCM</td>
<td>16 (+0.20)</td>
<td>52 (0.20)</td>
<td>68</td>
<td>0.235</td>
</tr>
<tr>
<td>CM</td>
<td>75 (-1.66)</td>
<td>268 (1.66)</td>
<td>343</td>
<td>0.219</td>
</tr>
<tr>
<td>TC/CM</td>
<td>45 (-1.07)</td>
<td>161 (1.07)</td>
<td>206</td>
<td>0.218</td>
</tr>
<tr>
<td>GT/SF</td>
<td>5 (1.89)</td>
<td>5 (-1.89)</td>
<td>10</td>
<td>0.500</td>
</tr>
<tr>
<td>EP</td>
<td>17 (7.00)</td>
<td>1 (-7.00)</td>
<td>18</td>
<td>0.944</td>
</tr>
<tr>
<td>Total</td>
<td>158</td>
<td>487</td>
<td>645</td>
<td>0.245</td>
</tr>
</tbody>
</table>

Values in parentheses are the adjusted standardized residuals from a $\chi^2$ test performed on the bone counts in this table ($\chi^2 = 53.23, p < 0.001$; $\chi^2_{\text{trend}} = 19.28, p < 0.001$).

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9 The statistical methods that I use here all take sample size into account; in other words, the differences in artiodactyl relative abundance among these samples are large enough to be statistically significant despite the small size of the two earliest samples.
elements that are present at these sites. I employ Metcalfe and Jones's (1988) standardized, whole-bone Food Utility Index (FUI), derived for caribou (Rangifer tarandus), which provides a measure of the amount of calories contained in each part of the body of an artiodactyl. A reduction in the proportion of low utility body parts transported to a residential site, such as might occur due to resource depression, should result in an increase in mean FUI.

To evaluate whether mean FUI changes across the samples that I use, I first assigned to each faunal specimen in these samples the FUI value of the element from which it comes. I then calculated mean FUI values for each phase, which can be compared statistically using analysis of variance. I present the results of such an analysis below.

This analysis can show whether there are significant differences in mean utility among a set of samples, but it does not show whether the mean utility of any individual sample is particularly high or low relative to a value that might occur if people were transporting large mammal body parts without any consideration for their utility. In other words, before it can be concluded that people selectively excluded low utility artiodactyl body parts from the loads that they transported home.

Of course, analyses of changes in body part transport practices of the sort that I present here are of little value unless it can be demonstrated that observed patterns are not simply the result of density-mediated taphonomic processes (e.g., Grayson, 1989; Lyman, 1985; Rogers, 2000). As Lyman (1985) has shown, there is a weak negative correlation between the caloric utility of artiodactyl body parts and the volume density of the bones within those body parts as measured by photon densitometry. It is thus possible that a pattern in mean utility among a set of faunal samples might be the result not of differences in the kinds of body parts that people transported, but rather of variability in the intensity of taphonomic processes that differentially affect bones of different densities. Specifically, because skeletal elements associated with higher utility parts tend to be lower in density, intense density-mediated attrition of bones within a sample might reduce the mean utility value observed for that sample.

To control for such effects, I recorded all of Lyman's (1984) densitometer "scan sites" that are present on each artiodactyl specimen in the assemblages that I use, which allows calculation of the mean of the volume density (VD) values for the scan sites present on the specimens within a given sample. If mean volume density is found to differ significantly among a set of samples, then

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10 An objection might be raised to my application of utility values derived for caribou to the remains of deer and pronghorn. However, because I do not use the absolute caloric content of caribou body parts, but instead use Metcalfe and Jones's (1988) standardized FUI values, in which the caloric content of a body part is expressed as a percentage of the caloric content of the highest utility body part, all that must be assumed is that the utility of various body parts is proportionately the same for all of the taxa involved. Such an assumption would be unwarranted if these taxa varied greatly in anatomical structure, as do deer and bison, for example (e.g., Kreutzer, 1992), but given the overall similarity in body form among caribou, deer, and pronghorn, this assumption is not likely to be problematic for my analysis.

11 I include in my analysis all of the scan sites that are present on each individual bone specimen, rather than simply a "typical" scan site for each portion of each element as has been done in previous studies (e.g., Grayson, 1989; Lyman, 1985), because this should provide a more accurate representation of the degree to which density-mediated taphonomic processes have affected these samples. For example, if both high- and low-density scan sites are present on specimens, and if only the highest-density scan sites on those specimens are included in a density analysis, then the effects of density-mediated attrition will be exaggerated. The density value that I use for each scan site is the mean of all of the volume density measurements for that scan site published in Lyman (1984) for both deer and pronghorn.
there is cause for concern that any pattern in mean utility values observed among those samples might be the result of taphonomic factors rather than the result of variability in body part transport practices.

Just as with my analysis of differences in mean utility, though, such an analysis of differences in mean density does not show whether the mean density value observed in any individual sample is particularly high or low. In other words, before it can be concluded that density-mediated attrition has appreciably affected the bones within a given sample, it must be shown that the mean density of the scan sites present in that sample is significantly higher than might be observed in a sample of bones that was selected randomly. To determine whether this is the case, I use $t$ tests to compare the distribution of density values present in each of my archaeological samples to a null distribution composed of all of the scan sites present in the body of a single artiodactyl. Such a null distribution consists of 316 scan sites, the mean volume density of which is 0.353 and the standard deviation of which is 0.146.

Artiodactyl body part utility data for the combined samples from the three sites that I consider here are presented in Table 5. An analysis of variance shows that the observed differences in mean utility among these samples are significant at the $p < 0.10$ level ($F = 2.20, p = 0.071$), which suggests that the proportion of low utility elements deposited at these sites did vary over time. It appears that this result is due primarily to the differences between the three intermediate samples, all of which have mean utility values between 38 and 41, and the Early Pithouse and Classic Mimbres/Terminal Classic samples, both of which have mean utility values greater than 50.

This conclusion is strengthened by an examination of the results of $t$ tests comparing the mean utility of each archaeological sample to the mean utility of the null distribution composed of all of the elements in the body of a single artiodactyl (Table 5). The observed mean utility values for the three intermediate archaeological samples all approximate the mean utility value of the null sample, and none of them are significantly different from it. However, both the Early Pithouse sample and the Classic Mimbres/Terminal Classic sample have mean utility values that are much higher than the mean of the null sample, and these differences are significant at the $p < 0.05$ level.

These results do not appear merely to be reflecting variability among samples in the degree to which they have been affected by density-mediated taphonomic processes, as shown in Table 6. All of these samples do seem to have experienced some degree of density-mediated attrition: they all have mean density values that are higher than that of the null distribution composed of all of the scan sites within the skeleton of an artiodactyl, and the differences for three of them are highly significant, while those for other two, which are smaller, are nearly significant at the $p < 0.10$ level. However, an analysis of variance gives an insignificant result for a test of the hypothesis that mean scan site density differs among these samples ($F = 0.60, p = 0.662$). Thus, although each sample has likely experienced some density-mediated attrition, the effects of such attrition have evidently not varied among them in a manner that could have produced the pattern observed among their mean utility values.

Table 5
Mean artiodactyl body part utility for the combined samples from Galaz, Mattocks, and McAnally, aggregated by time period (result of ANOVA, testing for differences in mean utility among phases: $F = 2.20, p = 0.071$)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Mean FUI</th>
<th>NISP</th>
<th>SD</th>
<th>Results of $t$ tests for difference from mean of null sample$^{ab}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM/TCM</td>
<td>56.5</td>
<td>13</td>
<td>30.7</td>
<td>$t = 2.10, p = 0.038$</td>
</tr>
<tr>
<td>CM</td>
<td>40.4</td>
<td>97</td>
<td>25.2</td>
<td>$t = 0.69, p = 0.488$</td>
</tr>
<tr>
<td>TC/CM</td>
<td>39.6</td>
<td>44</td>
<td>22.2</td>
<td>$t = 0.37, p = 0.715$</td>
</tr>
<tr>
<td>GT/SF</td>
<td>38.2</td>
<td>5</td>
<td>20.0</td>
<td>$t = 0.00, p = 1.000$</td>
</tr>
<tr>
<td>EP</td>
<td>53.7</td>
<td>15</td>
<td>22.2</td>
<td>$t = 2.57, p = 0.011$</td>
</tr>
</tbody>
</table>

$^{a}$ Number of identified adult and sub-adult specimens to which FUI values could be assigned. The Classic Mimbres phase sample is larger than the sample of artiodactyl specimens for this phase that is included in Table 4 because I include specimens from a larger number of depositional contexts in this analysis (see Cannon, 2001a for details).

$^{b}$ Mean = 38.2, $n = 118$, SD = 20.3. All $p$ values are for two-tailed tests.

12 I exclude specimens from very young individuals from my body part analyses; see Cannon (2001a) for further details about the procedures followed here.
Table 6
Mean artiodactyl scan site volume density for the combined samples from Galaz, Mattocks, and McAnally, aggregated by time period (result of ANOVA, testing for differences in mean density among phases: $F = 0.60, p = 0.662$)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Mean VD</th>
<th>$n^a$</th>
<th>SD</th>
<th>Results of $t$ tests for difference from mean of null sample$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM/TCM</td>
<td>0.421</td>
<td>14</td>
<td>0.170</td>
<td>$t = 1.47, p = 0.142$</td>
</tr>
<tr>
<td>CM</td>
<td>0.429</td>
<td>88</td>
<td>0.144</td>
<td>$t = 4.37, p &lt; 0.001$</td>
</tr>
<tr>
<td>TC/CM</td>
<td>0.459</td>
<td>50</td>
<td>0.140</td>
<td>$t = 4.95, p &lt; 0.001$</td>
</tr>
<tr>
<td>GT/SF</td>
<td>0.483</td>
<td>5</td>
<td>0.188</td>
<td>$t = 1.54, p = 0.125$</td>
</tr>
<tr>
<td>EP</td>
<td>0.464</td>
<td>21</td>
<td>0.174</td>
<td>$t = 2.86, p = 0.005$</td>
</tr>
</tbody>
</table>

$^a$Sum of the number of scan sites present on all of the specimens within each sample.
$^b$Mean = 0.353, $n$ = 316, SD = 0.146. All $p$ values are for two-tailed tests.

I also note that there is no significant correlation between the mean utility of the body parts represented in these samples and the mean density of the scan sites that are present in them ($r = -0.44$, one-tailed $p = 0.230$). If higher degrees of density-mediated attrition have systematically lowered mean utility values among a set of samples, then a negative correlation should be apparent between their mean utility values and their mean density values. The absence of a significant correlation between mean density and mean utility among the Mimbres Valley samples that I use here suggests that density-mediated taphonomic processes have not had a substantial systematic effect on the mean utility values observed in them.

It thus seems that the proportion of low food value artiodactyl body parts that hunters transported to sites in the central Mimbres Valley increased between the Early Pithouse period and the Georgetown or San Francisco phases and then declined again either late in the Classic Mimbres phase or during the Terminal Classic (Table 5). It can also be concluded that hunters in the valley selectively excluded low utility body parts from the loads that they carried home during the earliest and the latest time periods represented here, but there is no reason to think that they were particularly selective in this regard during the intervening time periods.

Considering the implications of the central place forager model that I presented above, the decline in mean utility that occurs between the Early Pithouse sample and the Georgetown/San Francisco sample would seem to indicate that search and transport times for artiodactyl prey declined in the central Mimbres Valley during this span of time. The taxonomic relative abundance data from these samples, on the other hand, suggest that artiodactyl search and transport times increased over this period. A possible reason for this apparent discrepancy between the results of my taxonomic relative abundance analysis and those of my body part analysis may be that this case violates a key assumption that I made in order to apply the model.

Specifically, I noted that archaeological application of the central place forager model requires assuming that the distribution of maximum load sizes across foraging trips remained constant over time. However, there is reason to think that effective load sizes may have increased in the Mimbres Valley during the period of time in question. Settlements in the valley appear to have grown substantially during the Early and Late Pithouse periods (e.g., Anyon et al., 1981), and it is possible that the average size of hunting parties grew as communities became larger. If this occurred, then the size of the total load of meat that could have been carried home by an average-sized hunting party would have increased, and if the number of animals captured per party increased by a lesser proportion, then the benefits that could be obtained from spending additional time removing low utility body parts prior to transport would have been reduced. The mean utility of the body parts that hunters carried home might therefore have declined over this period due to an increase in the average size of hunting parties.

I point out that if such an increase in average hunting party size did occur, and if the average number of animals captured per party did not increase by a proportionately equivalent amount, thereby lowering the benefits to be gained by removing low utility body parts from the loads that were carried home, then the energetic delivery rates obtained by individual hunters would necessarily have declined. In conjunction with the reduction in the abundance of large mammals on the Mimbres Valley landscape that is implied by the artiodactyl relative abundance data that I have presented, this suggests that foraging
efficiency declined substantially for Mimbres hunters between the Early Pithouse period and the beginning of the Three Circle phase.

The other major change in mean artiodactyl body part utility that occurs among these samples is an increase between the Classic Mimbres sample and the Classic Mimbres/Terminal Classic sample. Taking the logic of the central place forager prey choice model into account, the reduction in the transport of low utility body parts that is entailed by this increase in mean utility suggests that average search and transport times for artiodactyl prey increased over this span of time. Such an increase in artiodactyl search and transport times is not evident in the taxonomic relative abundance data from these samples, but when the possible cause of this increase in artiodactyl search and transport time is considered, an explanation also appears for the absence of a coincident decline in the taxonomic abundance of artiodactyls relative to leporids.

Droughts can reduce the population densities of artiodactyls such as deer and pronghorn by lowering fawn recruitment rates (e.g., Bradybaugh and Howard, 1982; Kitchen and O’Gara, 1982; Mackie et al., 1982). Thus, the drought of the AD 1130s may have reduced the density of artiodactyls on the Mimbres Valley landscape, thereby raising the average amount of time required to locate these prey and transport them home. The model that I have presented here predicts that such an increase in average search and transport times for artiodactyl prey will be reflected by a reduction in the proportion of low food value body parts transported to residential sites. However, such an increase in artiodactyl search and transport times would not result in a decline in the numbers of artiodactyls captured relative to the numbers of leporids captured if the density of leporids on the landscape were reduced to approximately the same degree as was the density of artiodactyls. Annual precipitation can affect the size of leporid populations in arid western North America (e.g., Davis et al., 1975), and it is thus possible that abundances of both leporids and artiodactyls declined in the Mimbres Valley at the beginning of the Terminal Classic. This would account for the patterns observed in archaeofaunal samples from the valley, and it would certainly also have resulted in a considerable decline in hunting efficiency.

Conclusions

My application of the central place forager prey choice model to faunal data from the Mimbres Valley has provided a more complete test than has yet been attempted of a longstanding hypothesis about the effects of human predation on populations of large mammals in the region. It has also led to a novel hypothesis about certain social aspects of hunting in the Mimbres area that would not have been generated had such a model not been employed.

By integrating several issues that have previously been approached through separate theoretical models, the model that I have presented allows easier determination of the effects that factors such as prey choice, transport distance, and field processing will combine to have on overall foraging efficiency. Using this model to track changes over time in foraging efficiency in the Mimbres Valley, some important substantive conclusions can be drawn. First, the dramatic early decline in artiodactyl relative abundance that occurs in faunal assemblages from the central part of the valley suggests that average search and transport times for artiodactyl prey increased here between the initial occupation of the Mimbres region by farmers and the beginning of the Three Circle phase. In other words, there is good reason to believe that deer and pronghorn were more abundant on the landscape of the Mimbres Valley during the few centuries before AD 800 or 850 than they were during the few centuries after this. This reduction in the abundance of artiodactyls in the valley, which is best explained as being the result of increases in absolute rates of harvest by human hunters (Cannon, 2001a), likely caused a substantial decline in the per capita efficiency with which those hunters were able to capture prey and transport them home.
From the beginning of the Three Circle phase through the Terminal Classic, however, there are no appreciable changes in the relative abundances of artiodactyls in faunal samples from Mimbres Valley sites. The absence of a continued decline in artiodactyl relative abundance during this span of time suggests that the density of these animals on the landscape remained steady, perhaps because they were now so rare that people set out to hunt them only at occasional times of the year when search and transport times for them were likely to be low. The increase in the mean utility of the artiodactyl body parts deposited at residential sites that occurred either late in the Classic Mimbres phase or during the Terminal Classic suggests that the situation changed at this time as people began to travel further from home to hunt large mammals. The model that I have presented shows that such an increase in travel and transport distance, which may have been necessitated by the drought of the AD 1130s, would have entailed further declines in hunting efficiency beyond those that occurred early in the Mimbres sequence.

These results are consistent with those of recent studies of other aspects of the Mimbres–Mogollon archaeological record, which suggest that important economic changes occurred much earlier in the region than has previously been thought. Archaeologists working here have traditionally devoted most of their attention to the Classic Mimbres phase, and they have usually argued that, aside from the changes that occurred at the end of this phase (i.e., ca. AD 1130), the most important changes—including the depression of large mammal resources and major increases in the importance of agriculture—occurred at the beginning of it (i.e., ca. AD 1000), coincident with the transition from pithouse to pueblo architecture (see, for example, the overviews in Anyon et al., 1981; Anyon and LeBlanc, 1984; LeBlanc, 1989; Minnis, 1985; Sanchez, 1996). However, Diehl (1996, 1997; see also Diehl and LeBlanc, 2001) has argued that residential mobility began to decline throughout the region, and that agriculture began to increase in importance, well before AD 1000, during the same span of time in which the archaearofaunal taxonomic relative abundance data that I discussed above suggest that people in the Mimbres Valley experienced depression of large mammal resources. I have argued elsewhere that the available evidence from the valley is consistent with the hypothesis that people began to devote more time to farming in response to the decline in foraging efficiency that would have resulted from this early occurrence of resource depression (Cannon, 2001a).

In addition to providing insights into changes in foraging efficiency in the Mimbres Valley, my application of the central place forager prey choice model illustrates how the use of explicit theoretical constructions provides benefits regardless of whether the specific predictions that can be derived from them are met (e.g., Stephens and Krebs, 1986). The central place forager model points out an aspect of the Mimbres Valley empirical record that cannot be explained straightforwardly in terms of the declining availability of high-return prey on the landscape: the reduction in mean artiodactyl body part utility that occurs between the Early Pithouse period and the Georgetown or San Francisco phase, which is the same period of time over which the taxonomic relative abundance of artiodactyls declines dramatically. Without a model that can be used to link both prey choice and body part transport practices to changes in the abundances of prey around a central place, it would be far more difficult to see that the taxonomic relative abundance data and the body part data from the Mimbres Valley may be telling us different things, and a potential avenue for future research would likely have gone unnoticed. Though the hypothesis that the average size of hunting parties increased over time requires further evaluation, if hunting parties in the Mimbres Valley did become larger, this would likely reflect an increase in the degree to which hunting was carried out communally that would have important implications in its own right (e.g., Giraldeau and Caraco, 2000).

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