Martu Ethnoarchaeology: Foraging Ecology and the Marginal Value of Site Structure

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Abstract

Archaeological investigations of hunter-gatherer site structure have remained largely descriptive, despite significant explanatory advancements by evolutionary approaches to foraging behavior and ecology. To date, calls to incorporate site structure studies within this behavioral ecological framework have largely been ignored. We suggest there is a clear explanation for this. At large spatial extents, human behavior is constrained by patterned ecological variability, as such, a general theory of behavior is likely to characterize key aspects of human decisions. At small spatial extents, human behavior is not constrained by patterned ecological variability, therefore, the human decisions that produce site structure should be driven by mechanical constraints or random variation. However, variation in site structure may be ecologically relevant inasmuch as it informs on landscape level variation in human-environment interactions. Drawing on ethnoarchaeological data collected in collaboration with Martu, Aboriginal foragers in Western Australia, here we test empirically-derived, mechanistic predictions on site size and material size sorting to show how these can inform theoretically-derived, adaptive predictions from the Marginal Value Theorem. Results show that site size increases with the number of occupants and hence, the amount of in-patch foraging competition, while size sorting increases with the duration of occupation and hence, in-patch residence time. Combined, these attributes of site structure can be used as proxies of foraging behavior to explain variability in overall foraging yields. With this approach, site structure can provide insights into foraging decisions that can be examined through a general theory of behavior.

Keywords: hunter-gatherers, site structure, marginal value theorem, behavioral ecology

1. Introduction

Ecological and evolutionary approaches in hunter-gatherer archaeology continue to make tremendous strides toward explaining variation in subsistence (e.g., Broughton et al., 2011; Speth, 2010), settlement (e.g., Byrd et al., 2015; Winterhalder et al., 2010), technology (e.g., Surovell, 2012; Stevens and McElreath, 2015), storage (e.g., Morgan, 2012; Whelan et al., 2013), and demography (e.g., Kelly et al., 2013; Williams et al., 2015). But despite this progress, studies of site structure remain largely descriptive (e.g., Hill et al., 2011; Speth et al., 2012).

O’Connell (1995) made this same observation twenty years ago, noting the disparity between ethnoarchaeological studies of faunal remains and those of site structure. While the former were advancing successful explanatory frameworks, the latter remained stagnant. O’Connell suggested a simple, yet under-appreciated reason for this difference: studies of faunal remains were building on the foundations of a general theory which provided predictions *a priori* about how individuals are expected to behave in particular circumstances, but studies of site structure were based only on observations *a posteriori* without any guiding theory. Because the former predictions come from a general theory, they produce *deductive* inferences that should be true in all cases and therefore do not need to rely on direct ethnographic analogy in order to link ethnographic findings to the archaeological record. Because the later predictions come from empirical observations, they produce *inductive* inferences that must be tested in every case and cannot escape the problems of direct ethnographic analogy. It stands to reason then, for studies of site structure to move forward, they must begin with a general theory. Yet despite this seemingly simple fix, archaeologists guided by a general theory, such as behavioral ecology, have failed to meet O’Connell’s challenge.

We argue that there is a clear and simple reason for this: because movement at small spatial extents should not significantly constrain behavior, patterning in site structure will either be explained by simple mechanical parameters (e.g., human body size; Binford 1983) or random variation. However, movement at larger spatial extents should be significantly constrained by dynamic ecological patterning, and as such, can be explained by a general theory such as evolution by natural selection (e.g., Bird and O’Connell, 2006; Coddington and Bird, 2015; O’Connell, 1995). If this is true, then site structure can only be informed by a general theory of behavior inasmuch as site-level patterning can provide insight into larger, landscape scale decisions (including subsistence strategies, settlement and mobility; e.g., Binford 1980; Kent 1991).

In an attempt to incorporate studies of site structure within a general theory of behavior, here we link two common empirically-derived, mechanistic predictions about site structure to two theoretically-derived, adaptive predictions from a simple behavioral ecological model known as the Marginal Value Theorem (MVT, Charnov, 1976; Charnov and Parker, 1995). Then we test these predictions with ethnoarchaeological data collected in collaboration with Martu, an Aboriginal population who reside in and have native title over their ancestral estates in Western Australia.

2. Predictions

Behavioral ecological archaeologists focus on developing *adaptive* explanations of past human decisions that can be tested with material remains (Bird and O’Connell, 2006; Coddington and Bird, 2015). As outlined by Tinbergen (1963), adaptive explanations examine the evolutionary function of behaviors in how they contribute to survival and reproductive success. But this is only one of four levels of explanations commonly employed to

explain behavior. The others include *mechanistic* explanations, which focus on proximate causal factors, *ontogenetic* explanations, which focus on understanding how behaviors develop through the life course, and *phylogenetic* explanations which focus on how a particular behavioral trait evolved within a lineage (Tinbergen, 1963). As discussed above, predictions about site structure typically fall within the mechanistic level. Here we attempt to link two of these mechanistic proposals to adaptive predictions derived from the MVT.

2.1. Mechanistic Predictions

Several mechanistic “rules” of site structure have been proposed and tested with ethnographic or ethnoarchaeological data over the last seventy-five years (reviews in David and Kramer, 2001). Two of these are of particular relevance to the Marginal Value Theorem. These involve site size and the degree of size sorting.

First, because multiple people cannot occupy the same space while completing domestic tasks, the size of a site should increase with the number of occupants, of course, with all else being equal (e.g., tasks undertaken, kin-based residential rules, need for defense, etc.). This pattern was first described and tested by Cook and Treganza (1950) and subsequently confirmed by prominent ethnoarchaeologists working across the world (e.g., Yellen, 1977).

Second, because small discarded materials are likely to be dropped *in situ* (e.g., Binford, 1978a) and because large discarded materials will hinder ongoing activities within a site, people are likely to move larger items away from central activity areas (Hayden and Cannon, 1983) while overlooking smaller items. This causes significant size sorting wherein larger materials will tend to be more dispersed and smaller materials will tend to remain near the point of primary deposition

(O’Connell, 1987). Importantly, the degree of size sorting should be contingent on the duration of occupation: as individuals stay longer at a site, it becomes worthwhile to remove obtrusive waste (O’Connell, 1987, 100); at least up to some threshold where it becomes less costly to move to a new camp and start over (O’Connell, 1977). The amount of small material remaining *in situ* should decrease proportionally with the efficiency of the cleaning technology (O’Connell, 1987, 92).

These predictions suggest that with hunter-gatherer camps, the size of a site should be a reliable indicator of the number of people (and number of active foragers if proportional to the number of people) who occupied it and the degree of size sorting should provide information on the duration of site occupation. Site size may also increase with the actual (Yellen, 1977) or anticipated (e.g., Kent, 1992; Kent and Vierich, 1989) duration of occupation, which may present a potential confound, but this is something that can be examined empirically.

2.2. Adaptive Predictions

Based on the premise that natural selection should favor optimal food acquisition strategies, the MVT provides a framework to understand how long a forager should search for resources within a discrete patch before leaving to travel to a neighboring patch (Charnov, 1976; Charnov and Parker, 1995). Because a forager depresses the abundance of resources by removing them (Charnov et al., 1976), the energy acquired within a patch diminishes as a function of the time spent in the patch (Figure 1). Following Charnov and Parker (1995), the cumulative energy gain (G_t) within a patch can be described as:

$$G_t = G_m[1 - \exp(-c \cdot t)] \quad (1)$$

where t is the in-patch (foraging) time, G_m is amount of energy originally in the patch

(i.e., pre-foraging) and c is the rate at which acquired energy reaches G_m . Because the cumulative gain diminishes over time, there should be an optimal threshold at which a forager should leave the patch and travel to another patch. Charnov and Parker (1995) approximate the optimal leave time (t^*) as:

$$t^* = \frac{\left(\frac{c\mu+2}{c\mu+1}\right) \log(c\mu+1)}{c} \quad (2)$$

where μ is the travel distance to the next nearest patch. The depletion rate (c) should be inversely proportional to the available energy in the patch (G_m) as a result of the increased time required to search the patch (if prey density remains constant; Charnov and Parker 1995). In other words, larger patches have more resources, but take longer to search.

This model provides a clear framework to predict how the number of foragers within a patch and patch residence time should interact to determine the amount of energy acquired per capita. Holding the available energy within a patch constant, when there are more people within a patch, per capita gains will be lower (divided between more people) and less time will be spent searching within the patch. Holding the number of foragers constant, when a patch has more energy, individuals will spend more time searching the patch, which will increase the optimal patch residence time. Figure 1 illustrates these predictions with hypothetical scenarios.

While this model is specific to environmental situations where resources are patchily distributed, it holds for humans even if patches are homogeneous because humans are central place foragers (Orians and Pearson, 1979) who return acquired food to a home base. As such, human foraging segments environments into catchments around central places.

Figure 1: Graphical representation of the Marginal Value Theorem after Charnov and Parker (1995). From a baseline (a; $G_m = 1000, c = 0.5$), doubling the number of foragers in the patch should halve the energy acquired per capita, halve the time required to search the patch and decrease the optimal patch residence time (b; $G_m = 500, c = 1.0$), while doubling the energy available in the patch should increase the time required to search the patch (if prey density is constant) and increase the optimal patch residence time (c; $G_m = 2000, c = 0.25$). Note, travel time to the next nearest patch is held constant ($\mu = 175$).

2.3. Summary of Predictions

If **(P1)** site size increases with the number of foragers and **(P2)** size sorting increases with the duration of site occupation, then these attributes of site structure may be used as proxies for the number of foragers within a patch and patch residence time, respectively. If so, then per capita foraging returns should **(P3)** decrease with site size and **(P4)** increase with size sorting. If these findings hold, these elements of site structure may be incorporated within this general theory of behavior to help explain variability in foraging behavior at larger spatial extents where decisions are constrained by patterned environmental variation.

Following the strategy outlined in Coddington and Bird (2015, 11–12), we test these four predictions using ethnographic and ethnoar-

chaeological data collected in collaboration with Martu.

3. Ethnographic Background

Martu, also known as Mardu or Mardujarra, are part-time foragers who live on and have native title over their traditional estates (*sensu* Stanner, 1965) in Western Australia. Within the climatologically-defined Arid Zone and the Western Desert cultural area, the Martu homeland is centered on the Karlamilyi River, expanding west to the Pilbara, northeast to the Percival Lakes and south to Lake Disappointment (Figure 2). The Native Title Determination Area includes many of the estates belonging to Kartujarra, Manyjilyjarra, Warnman dialect speakers, though the core Warnman estates around Karlamilyi were retained by the Australian Government as a National Park.

Prior to European contact in the mid-twentieth century, Martu were full-time foragers. Subsistence strategies varied by gender: men focused on larger hunted game, both men and women pursued smaller game, and women focused on key plant resources (Tonkinson, 1993; Veth and Walsh, 1988; Walsh, 1987, 2008). Group structure was centered on female kin who formed cooperative partnerships (Scelza and Bliege Bird, 2008) and provided the majority of foraged foods (Tonkinson, 1993, 43–45; see also Gould 1969). When successful, men’s hunting contributed significant proportions of meat to the the diet, but since success was rare, men’s production was highly variable (Tonkinson, 1993, 43–45). Children foraged as well, sometimes helping to gather fruits or hunt small game, with the proceeds of their labor often consumed on the spot (Tonkinson, 1993, 47).

Many of these patterns continue today within a hybrid economy (*sensu* Altman, 2001) wherein hunting and gathering for wild foods remains one of the best economic al-

ternatives (Coddling et al., 2016). Men tend to focus on larger prey which comes with a higher risk of acquisition failure, while women focus on smaller, more reliable resources (Bliege Bird and Bird, 2008; Bliege Bird et al., 2009; Coddling et al., 2011). Men’s hunting occasionally contributes significantly to daily calories (Bliege Bird et al., 2009; Coddling et al., 2011), but given the high risk of failure, some aspects of men’s hunting may be driven in part by traditional forms of social and ritual competition rather than food (Bird and Bliege Bird, 2010). Such competition may have real material outcomes, including lowering the age of marriage for offspring (Scelza, 2010). Women’s cooperative partnerships remain extremely important for both resource acquisition (Bliege Bird et al., 2012b) and childcare (Scelza, 2009). The reliability of women’s hunting is increased through the use of anthropogenic fire, which feeds back to structure broad and varied environmental patterns (Bird et al., 2005; Bliege Bird et al., 2008, 2012a, 2013; Coddling et al., 2014; Zeanah et al., 2015). Children also remain active foragers, sometimes contributing significant amounts of food to their daily diet (Bird and Bliege Bird, 2005) and overall, foraging remains an important source of provisioned foods for dependents (Coddling et al., 2016).

One major aspect of foraging that has changed centers on mobility. While traditionally characterized as high mobility foragers (*sensu* Binford, 1980) who needed to move once local resources were diminished (Tonkinson, 1993), today Martu use vehicles to operate logistically (*sensu* Binford, 1980) from a central community. This logistic mobility facilitates a specific type of temporary settlement called a *dinner-time camps* (see, e.g., Meehan, 1982).

Figure 2: Areas surrounding Parnngurr within Martu Native Title area (insert).

3.1. Dinner-Time Camp Foraging

A foraging party will leave the community and travel to a named hunt region where they will establish a dinner-time camp. As the central locus of contemporary foraging, these dinner-time camps are extremely important as a focal node of economic production and social formation. While some dinner-time camps may be occupied repeatedly, most are used only once and produce very ephemeral material signatures. Once foragers arrive at the camp, some may stay behind to collect wood and build a fire, while others travel out in search of wild resources. With most foraging activities, individuals travel out from the dinner-time camp on foot and begin searching for target prey. Two of the most common prey types are sand monitor lizards (also known as goanna, *Varanus gouldii*, or *paranajalpa*) and hill kangaroo (also known as euro, *Macropus robustus*, or *kirti-kirti*). The former are found throughout the vast sand plains that blanket the area while the latter

are home in rocky ranges that dot the landscape (see Figure 2). Often these habitats occur side-by-side, allowing individual hunters to walk out on foot from a centrally located dinner-time camp and pursue either resource. While there is overlap in women’s and men’s activities (see above), often men walk out in search of hill kangaroo while women walk out onto the sand plain in search of monitor lizards (Bliege Bird and Bird, 2008; Bliege Bird et al., 2009; Codding et al., 2011). Because monitor lizards are a much more reliable resource (Codding et al., 2011), they provide the bulk of acquired calories returned to dinner-time camps (Bliege Bird and Bird, 2008).

We refer to the total time an individual spends searching for and pursuing resources within a patch or foraging activity as a *foraging bout*. Individuals rarely engage in more than one foraging bout per day, making Martu dinner-time camp foraging not completely consistent with the original formula-

tion of the the MVT, which was designed to evaluate the optimal time a forager should spend in a patch before leaving to travel to another patch. However, the model is still applicable in this case. Since foragers only undertake one bout per day, and the decision to leave a patch is contingent on an individuals assessment of opportunity costs, the general MVT framework still holds. Once an individual decides their foraging bout is over, they return to the dinner-time camp where everyone will process, cook and share their foods based on traditional practices (e.g., Bird and Bliege Bird, 2010).

Unlike more permanent camps from pre-contact times (e.g., Gould, 1977), dinner-time camps rarely have any formal structures or features beyond the roasting hearth. Hearths are the focus of activities at dinner-time camps. With smaller prey, like monitor lizards, the individual hunter is generally responsible for processing and cooking their catch. This involves removing the intestines, singeing the skin in hot flames, digging an appropriate sized pit, lining the pit with hot coals, burying the prey in hot sand, and placing hot coals and burning wood on top of the roasting pit. With larger prey, like hill kangaroo, it is the responsibility of an available relative, preferably a mother's brother (e.g., Gould, 1967), to take over processing and cooking. The general procedure is the same as with small prey, though with the disemboweling effort and the size roasting pit scaled proportionately to the size of the animal (see also Bird and Bliege Bird, 2010; O'Connell and Marshall, 1989). Once in the ground, cooking is passive and time is generally passed with conversations about the hunt, the impending meal, and life in general. Because they are only used once, hearths themselves have relatively low fidelity: ethnoarchaeological investigations reveal that while they are still identifiable eight years after creation, they are more subtle

and diffuse (Coddington, 2012); we expect they would not be identifiable for more than one or two decades.

Once cooking is complete, prey are distributed among all who are present (see Bird and Bliege Bird, 2010; Bird and Power, 2015; Bliege Bird et al., 2012b; Coddington, 2012, also Gould 1967 for more details on food sharing). Smaller prey are generally distributed whole while larger prey are disarticulated according to traditional law (see Bird and Bliege Bird, 2010). As individuals finish consuming their share, some bones are dropped in place while others are gently tossed to the side. In some ways this should produce material patterning similar to Binford's (1978a) "drop and toss" zones, which may result in size sorting (O'Connell, 1987). Once everyone has had their fill, the foraging party packs up into the vehicles and returns to the community. Most often all wild foods are consumed at the dinner-time camp, but when harvests are abundant, remains may be taken back to the community for later consumption of further distribution.

4. Methods

4.1. Data Collection

This study is part of a long-term ethnographic collaboration with Martu that began in 2000. Intensive quantitative ethnographic data used here were collected from 2000–2010 and include 1806 focal-individual follows (*sensu* Altmann, 1974) across 344 discrete dinner-time camps. The main unit of analysis is the individual foraging bout: the total time spent on search and pursuit within an activity or patch and the total energy acquired during that time. Greater detail on data collection methods and on summary analyses of these data can be found elsewhere (e.g., Bird et al., 2009; Bliege Bird and Bird, 2008; Bliege Bird et al., 2009, 2012b; Coddington et al., 2010, 2011, 2014).

Ethnoarchaeological investigations focused on a representative sample of dinner-time camps where either sand monitor or hill kangaroo hunting took place. Of the 344 discrete dinner-time camps, individuals targeted either sand monitors or hill kangaroo at 196 camps and twelve of these were selected for ethnoarchaeological investigations. Quantitative foraging data from this ethnoarchaeological subset do not differ significantly from the main foraging dataset, indicating that it is a representative sample (Coddington, 2012). Ethnoarchaeological excavations were undertaken between 2009–2010. Researchers revisited the selected dinner-time camps and established a grid centered on the hearth dividing the entire site into 1-x-1-m units. Soils were excavated with shovel scrapes within each 1-x-1-m unit that continued until sterile sand (typically <5cm). Materials were screened through nested 6-mm (1/4-in) and 3-mm (1/8-in) mesh, providing a large and a small fraction that could be used to examine variation in size sorting across the site. Analyses focused on faunal material. Greater detail on these methods and additional analyses are reported in Coddington (2012).

From these combined datasets, we extract six variables to test the four main predictions listed above: site size, the number of site occupants (and how many of those are foragers), the degree of size sorting, the duration of site occupation and both the median and mean per capita monitor lizard harvest. Site size is calculated as the number of 1-x-1-m units from which bones were recovered. The number of site occupants and the number of foragers are tallied from quantitative observations. Size sorting is calculated as the standard distance deviation (see below) of the 6-mm fraction relative to the 3-mm fraction. The duration of active site occupation (or occupation time) is the total person minutes at the site excluding time spent foraging. This should measure the cumulative impact of hu-

man activity at the site, which we expect will lead to greater size sorting. Because the distribution of monitor harvest (kcal per bout) is skewed (see Coddington et al. 2010), mean and median values per camp may provide a significantly different result. As such, we run analyses using both mean and median per capita harvest size (kcal) per bout.

4.2. Data Analysis

All analyses are performed in the R environment (R Core Team, 2015). Here we review our approach to estimating size sorting and to hypothesis testing.

The dispersion of bone fragments was quantified for each site as the standard distance deviation (or standard distance). This was implemented in the `aspace` library (Bui et al., 2012) using the number of bones recovered from each 1-x-1-m unit for each recovery method (fine and coarse grained mesh). For visualization purposes, standard deviation ellipses were also calculated for each recovery method. Size sorting was then calculated as the difference in standard distance between the 3-mm and 6-mm fractions so that the more positive numbers equal greater dispersion of larger bone fragments relative to smaller fragments.

Tests of predictions rely on linear models. However, ordinary least squares regression models are inappropriate for this analysis because the independent (response) variables are either heavily skewed (i.e., not normally distributed) or not continuous (e.g., count data). Instead of turning to rank-ordered non-parametric statistics, which reduce variation by converting continuous or count data to ordinal numbers, we rely on generalized linear models (GLM) designed to extend Gaussian linear models by specifying a distribution and link function appropriate to the data (Faraway, 2006; R Core Team, 2015). Unless otherwise noted in the text,

we rely on models with a Poisson distribution, log link and quasi-likelihood estimation. Poisson-log GLMs with quasi-likelihood estimation are appropriate for our data which are either count (e.g., number of occupants) or count-like (e.g., number of calories), and non-normally distributed.¹ Through quasi-likelihood estimation, these models also avoid over-dispersion by relaxing the assumption that the mean and variance are equal. As with GLMs generally, quasi-likelihood Poisson models are common in ecology (e.g., Ohara and Kotze, 2010) and their application is growing in archaeology (e.g., Shennan et al., 2013). Model results report the Y-intercept, estimated change in the dependent (y) variable with a change in the independent (x) variable, α or p -value associated with the independent variable (Ind. p), log-likelihood r-square value (R_L^2) which is the proportion of deviance explained by the inclusion of the independent (predictor) variable, and the p -value from a likelihood ratio test (LRT p) which indicates whether or not the inclusion of the predictor variable significantly improves the model fit compared to the null model. Because these models incorporate a log-link, y-intercepts and estimates are reported as the exponent for interpretation.

¹Results of Shapiro-Wilk Normality Test reveal that the dependent (response) variables are not normally distributed: number of occupants ($W = 0.64, p < 0.0001$), the number of foragers ($W = 0.85, p = 0.0408$), occupation time ($W = 0.59, p < 0.0001$), foraging time ($W = 0.81, p = 0.0138$), median harvest ($W = 0.86, p = 0.0893$), and mean harvest ($W = 0.82, p = 0.0359$). While the median sand monitor harvest only departs from normal with marginal significance ($p < 0.1$), it is sampled from a larger distribution of sand monitor hunts that is highly skewed ($W = 0.84, p < 0.0001$).

5. Results

Before testing the specific predictions, analyses must confirm that monitor lizard foraging follows the general framework proposed by the marginal value theorem and confirm that size sorting is present at these sites.

As shown in Figure 3, across 166 camps at which at least one individual went sand monitor hunting, the mean per capita harvest (E, kcal) varies significantly as a function of the time spent in patch (T, min) when fit with a normal-log linear model ($R_L^2 = 0.23, p < 0.0001$). This can be approximated by a diminishing returns curve following the MVT ($G_m = 3000, c = 0.007$). This is also true for the median per capita harvest ($R_L^2 = 0.19, p < 0.0001; G_m = 2500, c = 0.009$). These findings suggest that monitor lizard hunting, and the representative sample of ethnoarchaeological camps, should provide a viable window into MVT dynamics.

Figure 3: Mean per capita monitor lizard harvest (E, kcal) as a function of the time spent in patch (T, min) across 166 sand monitor hunting camps shown with a normal-log GLM fit (black solid line with dashed 95% confidence intervals) and an approximate diminishing returns curve following the MVT (gray solid line). Ethnoarchaeological camps shown as solid black points.

Size sorting was calculated from bone

Figure 4: Distribution of recovered bones from 3-mm mesh (left) and 6-mm mesh (right) across 1-x-1-m units superimposed for all 11 excavated ethnoarchaeological camps. Relative density of recovered bones per unit illustrated in gray-scale from none in white to maximum (43 and 33 respectively) in black. Standard deviation ellipses (circles) indicate that larger bone fragments are more dispersed overall. The center of dispersion (points) for both recovery methods remains close to hearth locations (located at 5.5m North, 5.5m East), with the 3-mm fraction being slightly closer.

counts per unit, which ranged from zero to 33 in the 6-mm fraction and from zero to 43 in the 3-mm fraction. Data on bone dispersion is available for ten of the twelve sites and monitor lizard hunting occurred at nine of these. The two sites for which dispersion data is unavailable include one where only a failed kangaroo hunt occurred, producing no material signature other than a hearth, and one where only a single bone was recovered, from which it is impossible to calculate dispersion. Of the remaining ten sites, larger bone fragments recovered from the coarse grained (6-mm) fraction are generally more dispersed than smaller bone fragments recovered from the fine grained (3-mm) fraction. Including all ten sites, the difference in dispersion between ranges from -0.85 to 0.41, with non-negative value for the mass of the distribution (7 out of 10 sites; IQR=-0.12-0.22, median=0.032). Excluding the one site where monitor lizard hunting did not occur, dispersion across the nine remaining sites confirms that larger material tends to be more

dispersed than smaller material: the difference in standard distance ranges from -0.27 to 0.41 (IQR=0.00-0.26, median=0.06) with only two sites exhibiting negative size sorting. These findings illustrate that significant size sorting generally occurs even at these ephemeral, short-term dinner-time camps.

These results confirm that the foraging data examined here does conform to the MVT assumptions, and that size sorting is occurring at these sampled camps. This allows analyses to move forward with the examination of each of the mechanistic and adaptive predictions proposed above.

5.1. Prediction 1: the number of foragers should increase with site size

Based on the simple mechanics of how humans occupy space, the number of site occupants and (if proportional) the number of foragers should increase as a function of site size. Across the eleven excavated sites, the number of site occupants and the number of active foragers significantly increase with site size (Table 1, Figure 5a). This confirms the

Figure 5: Plots and model fits summarizing results from the four main predictions. (a, P1) Number of site occupants as a function of site size (m^2). (b, P2) Duration of active site occupation as a function of size sorting. (c, P3) Median monitor lizard harvest (kcal) as a function of site size and (d, P4) as a function of size sorting. Confidence intervals show the standard error (95%) of the model fit. See Table 1 for details.

first mechanistic prediction and suggests that site size may be a useful proxy of foraging yields.

5.2. Prediction 2: the duration of occupation should increase with size sorting

If material becomes more dispersed as a function of more time spent at the site, then the duration of occupation should increase with degree of size sorting. Across the ten sites for which size sorting data was available, the active occupation time and the sum time spent hunting monitor lizards increases as a function of the difference in dispersion between large and small bone fragments (Figure 5b). While overall the models are a significant improvement over a null model, the effect of each independent variable is not sta-

tistically significant (Table 1). These findings suggest that size sorting may be a rough proxy for the amount of time individuals spend at a site and the amount of time spent foraging, but that the effect may sometimes be due to chance.

5.3. Prediction 3: overall foraging yields should decrease with site size

Based on theoretical insights from the MVT, more people, occupying larger sites, should cause greater in-patch competition and result in lower per capita yields. The results show that this generally holds true: monitor lizard harvests decline as site size increases (Figure 5c). But the effect is only significant inasmuch as the inclusion of site size improves the prediction of monitor lizard re-

Table 1: Summary of bivariate model results testing each of the four predictions.

Pred.	Dep Var.	Ind. Var.	Y-intcp.	Est.	Ind. p	R_L^2	LRT p^*
1	# of Occupants	Site Size	7.05	1.02	0.0696	0.31	0.0314
1	# of Foragers	Site Size	2.71	1.03	0.0517	0.35	0.0111
2	Occupation Time	Size Sorting	2624.91	3.29	0.3310	0.16	<0.0001
2	Foraging Time	Size Sorting	384.87	3.88	0.3690	0.12	<0.0001
3	Median Harvest	Site Size	2744.10	-1.02	0.4180	0.10	<0.0001
3	Mean Harvest	Site Size	2419.22	-1.00	0.9090	<0.01	<0.0001
4	Median Harvest	Size Sorting	1563.53	6.83	0.1060	0.28	<0.0001
4	Mean Harvest	Size Sorting	1879.76	5.34	0.0768	0.38	<0.0001

*Note: LRT p -values report the results of a likelihood ratio test, which indicates if the inclusion of the independent variable significantly improves the model fit compared to a null model.

turns when compared to a null model ($p < 0.0001$), with any independent effects of site size likely due to chance (Table 1). Moreover, this is not a very robust association, with site size explaining only 10% of deviance in median returns and less than 1% in mean returns.

5.4. Prediction 4: overall foraging yields should increase with size sorting

Foragers should stay longer in higher quality patches, which should result in greater size sorting and higher per capita returns. The data support this prediction, showing that mean and median harvests increase with the degree of size sorting (Figure 5d). Size sorting explains 28% of the deviance in median monitor lizard harvest and 38% in mean harvest. Though while the inclusion of the independent variable improves each model significantly ($p \leq 0.0001$), the effect of each independent variable is only marginally significant ($p \leq 0.1$; Table 1).

Overall, these findings roughly support the predictions, showing that per capita foraging yields decrease with site size and increase with size sorting. However, while the results do move in the predicted directions, the effects are less robust than would be ideal. These limited effects may result from the interactions between the number of occupants and patch duration.

5.5. Interactive Effects

To deal with the potential interactive effects of the number of foragers and the duration of occupation (and their material correlates) on overall returns, we analyze these in a series of multivariate models. Combined, the number of foragers and the duration of occupation accurately predict median and mean monitor lizard harvest (Table 2, Figure 6). This is especially the case with median harvests, where each independent variable is marginally significant and the overall model is highly significant explaining 58% of the deviance. These patterns are consistent into the material record: site size and the degree of size sorting also accurately predict monitor lizard harvest (Table 2, Figure 6). Again, these patterns are more robust with median returns, of which site size and size sorting have a marginally significant and significant effect respectively, together explaining 50% of the deviance. In both cases, these findings are more robust with median than mean returns and indicate that size sorting might be a more significant predictor of overall returns than site size.

6. Discussion

At a descriptive level, these findings confirm previous results illustrating that site size

Figure 6: Plots summarizing two multivariate models: the first (top row) examining the combined effect of (1a) the number of foragers and (1b) the duration of site occupation (min) on median per capita monitor lizard harvest (E, kcals); the second (bottom row) examining the combined effect of (2a) site size (m^2) and (2b) size sorting on median per capita monitor lizard harvest (E, kcals). Model fits illustrate the effect of each independent variable while holding the other constant at its median value. Confidence intervals show the standard error (95%) of the model fit. See Table 2 for details.

tends to increase with the number of occupants (e.g., Yellen, 1977) and that smaller artifacts are more likely to remain in their primary context than are larger objects (e.g., O’Connell, 1987). The later finding is quite remarkable given that these are ephemeral, short-term camps but size sorting is still present in seven of the nine focal sites.

At an explanatory level, these findings illustrate that aspects of site structure may be useful proxies of larger-scale ecological interactions that lead to variation in foraging yields. Where foraging follows the assumptions of the MVT, the combined interaction of site size and size sorting should be indicative of overall wild food harvests. Although

we do not want to over-interpret our empirical findings. Our bivariate model results are less robust than would be ideal, with relatively high p-values suggesting that some of these results may be false positives (Type I errors). Nonetheless, all of the trends do move in the predicted direction, which is encouraging in itself given the relatively small size of the ethnoarchaeological dataset and all of the noise expected in these parameters.

The limitations of these bivariate models may also result from the interactive effects of site size (as a proxy of foraging competition) and size sorting (as a proxy of patch quality). When combined in a multivariate model to control for these interactions, the

Table 2: Summary of multivariate model results examining the combined effect of each independent variable on mean and median monitor lizard harvest size (kcal) per bout.

Dep. Var.	Ind. Var.	Y-intcp.	Est.	Ind. p	R_L^2	LRT p^*
Median Harvest	Whole Model	3418.65	-	-	0.58	<0.0001
	# Foragers	-	-0.80	0.0829	-	-
	Occupation Time	-	1.00	0.0930	-	-
Mean Harvest	Whole Model	2342.56	-	-	0.25	<0.0001
	# Foragers	-	-0.94	0.4950	-	-
	Occupation Time	-	1.00	0.2420	-	-
Median Harvest	Whole Model	2245.96	-	-	0.50	<0.0001
	Site Size	-	-1.04	0.1059	-	-
	Size Sorting	-	11.41	0.0399	-	-
Mean Harvest	Whole Model	2187.05	-	-	0.44	<0.0001
	Site Size	-	-1.01	0.4383	-	-
	Size Sorting	-	6.73	0.0715	-	-

*Note: LRT p -values report the results of a likelihood ratio test, which indicates if the inclusion of the independent variables significantly improves the model fit compared to a null model.

results show that site size and size sorting can predict up to 50% of the noise in median harvests, with less than a 10% chance that any one variable is producing a false positive. This result confirms the main predictions proposed in this paper and highlight how these two measures of site structure can be used to inform researchers on broader scale patterns in foraging ecology.

In addition to supporting the major predictions, the results from multivariate models suggest that these measures may be more indicative of median than mean returns. Since median values are more robust to skew, this should be true with any resource where returns are characterized by a skewed distribution biased by zeros resulting from failed bouts. These findings also suggest that size sorting may be a clearer indicator of overall foraging yields driven by patch quality than site size may be of in-patch competition driven by the number of foragers. This could result because site size is more a reflection of the number of occupants than the number of foragers, or it could be that the number of foragers within a patch increases cooperation rather than competition, which may lead to

greater per capita yields (e.g., Smith, 1991, *cf.* Bliege Bird et al. 2012b).

6.1. Applications in Archaeological Contexts

This framework should significantly expand the explanatory role of site structure in archaeological studies of hunter-gatherers. However, these findings will be applicable in archaeological contexts only where at least two conditions are met, one relating to site formation and the other to investigation. First, accurate patterns of material dispersion will only be preserved in rapid depositional environments that are impacted by limited post-depositional activity. While this may be rare (e.g., Fanning and Holdaway, 2001), it is not unknown (e.g., Enloe, 2006). Second, adequate reconstructions of site structure will require investigations that excavate large, contiguous exposures and carefully record material to capture intra-site variation in their distribution (O’Connell, 1987, 1995). While previous work has cautioned about the extraordinary costs associated with fine-grained analyses of microrefuse (Metcalf and Heath, 1990), here we show that these interpretations are possible even with relatively coarse-grained

excavation techniques relying on a 1-x-1-m grid and nested 6-mm and 3-mm mesh screens. One final condition to consider concerns whether the activities under investigation were centered around hearths. Hearths provide a focal area for site occupants to center activities (e.g., Binford, 1978b,a) and a durable indicator for archaeologists to center excavations (e.g., Metcalfe and Heath, 1990; Simms and Heath, 1990); as such, the applicability of these insights to archaeological contexts will likely be amplified when hearth-centered activities are under investigation.

Where these criteria are met, including in archaeological contexts in Africa (e.g., Parkinson et al., 2009), the Near East (e.g., Maher et al., 2012), Europe (e.g., Enloe, 2006), Asia (e.g., Sakaguchi, 2007), and the Americas (e.g., Bamforth et al., 2005; Burns, 2005; Simms, 1989; Tipps, 1993), examinations of the relative differences in site size and size sorting through time or across space may be used to inform on variation in foraging efficiency and its consequences for subsistence, settlement and mobility. For example, if the suite of resources represented at a site and its size remain constant, a diachronic shift toward greater size sorting may indicate higher environmental productivity, producing higher foraging yields and lower mobility. Or, if the suite of resources represented at a site widens to include lower profitability resources, shifts toward larger sites and/or greater size sorting could be used as supporting evidence of resource intensification (i.e., Boserup, 1965, see Morgan 2015), with more people spending more time in patch taking lower profitability resources. Of course, in any of these circumstances, multiple lines of evidence will be needed to support these findings. Additional elements of site structure, such as the presence or absence of storage features, can also help inform on the duration of occupation (Binford, 1980).

6.2. *Future Ethnoarchaeological Work*

While the findings presented here are encouraging, future ethnoarchaeological investigations are needed to confirm these results and examine how they vary in different contexts. Existing data from extensive studies in Africa (e.g., Yellen, 1977; O'Connell et al., 1991) and Australia (e.g., Hayden, 1979; O'Connell, 1987) could also be used to evaluate some or all of these hypotheses. Additional questions may also be approached within this general framework.

For example, variation in size sorting at longer-term camps may be a function of the ways in which technologies alter cleaning efficiency (Metcalfe and Heath, 1990; O'Connell, 1987). The costs and benefits of different cleaning methods and technologies may present a trade-off that can be modeled by the MVT: with increased duration of occupation, investments in better cleaning technology might be offset by increased cleaning efficiency, which should lead to exponential increases in size sorting. This could be tested by examining contexts where hunter-gatherer settlement patterns produce some sites occupied for short intervals and others occupied for long intervals, both with attendant differences in cleaning technology.

Future work could also use this framework to examine how patterns in site structure vary by gender to reveal differences in the division of foraging labor. Specifically, where women's and men's foraging strategies produce different sites that differ consistently in the number of foragers or in the time spent foraging, comparisons between sites may reveal patterns in site size and size sorting that can be used to differentiate women's and men's camps (e.g., O'Connell et al., 1991).

The true value of any of this work will be its ability to expand our understanding of site structure from the perspective of a general theory of behavior (O'Connell, 1995). Until additional ethnoarchaeological work is

undertaken to validate and expand theory-driven analyses of site structure, "...archaeologists interested in site structure are stuck with highly speculative predictions and interpretations grounded in some combination of local ethnography, exotic ethnoarchaeology, and their own intuition" (O'Connell, 1993, 24).

7. Conclusion

Studies of site structure have remained largely descriptive, even over the past twenty years since O'Connell (1995) illustrated the potential utility of approaching these problems with a general theory of behavior. Here we suggest this is the result of an inherent limitation of site structure given that the behaviors which produce it are not significantly structured by adaptive constraints at the site level. As an alternative, we propose and implement an approach that uses measures of sites structure as proxies for larger scale patterns which should be structured by environmental variability. This is not new in itself (e.g., Binford, 1980), but is novel in linking these proxies to a general theory of behavior that provides deductive, *a priori* predictions that avoid the problems associated with direct ethnographic analogy (O'Connell, 1993, 1995). This approach does not completely resolve all the issues of site structure—especially those resulting from formation or investigation bias—but we hope this application will inspire future studies of site structure to examine these and develop other avenues to link patterned spatial variation in deposited material to larger ecological patterns of human decisions that can be explained by a general theory of behavior.

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