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The formation of lithic assemblages

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ABSTRACT

Research into the processes that form the archaeological record is an important component of archaeological practice because formation processes are a key link between the materials that archaeologists study and prehistoric societies that they seek to understand. Computational modeling is a comparatively new technology with potential to provide new insights into the dynamics of human societies, but which has been minimally applied so far in the study of archaeological formation processes. We use computational modeling as an experimental environment to examine processes that form the archaeological record of lithic assemblages. This is especially important for lithics because it is a largely extinct technology and we cannot directly observe the accumulation of lithic assemblages over time frames comparable to those represented in the archaeological record. We systematically evaluate the individual and combined effects of the length of stay at sites, raw material distribution, differences in activities performed with lithics, and movement patterns on lithic assemblages that accumulate over different time intervals. Not surprisingly, increased access to raw material decreases the frequency of retouched artifacts in assemblages, while tasks that require more lithic use produce assemblages with higher retouch frequencies. While length of stay affects the density of lithic accumulations at sites, it has little effect on assemblages composition. Mobility patterns alone have limited impact on assemblage composition. However, mobility coupled with place provisioning or individual provisioning, associated with logistical and residential mobility strategies respectively, have significant impacts on assemblage composition consistent with prior empirical studies. Counterintuitively, the artifact palimpsests of multiple occupations that characterize most archaeological deposits may provide better information about human ecology and changing adaptations than assemblages that represent snapshots of a single or a few occupations. This work provides valuable new, quantitative insights into the information about past human social, ecological, and technological practices embedded in lithic assemblages.

1. Introduction

Whether to apply ‘lessons from the past’ to present and future issues, understand the drivers of social change, better appreciate our cultural heritage, or satisfy intellectual curiosity, archaeologists learn about the past by studying the archaeological record—those residues of past human behavior that persist to the present day. To do this, they often postulate largely intuitive relationships between the observable archaeological record and invisible past behaviors and societies, as does the lay public interested in the past. Since the mid-20th Century, however, there have been increasingly frequent calls for more rigorous, scientific study of the linkages between the archaeological record and past human systems (Smith et al., 2012). This trend has been especially encouraged by the work of scholars like Michael Schiffer (Schiffer, 1987, 1983, 1975), who used the term “formation processes” to describe the interacting social, behavioral, and natural processes that create the archaeological record (see also Butzer, 1982; Shott, 1998). Research on formation processes has grown steadily to encompass replication and other experimental archaeology, ethnographic observations, and materials analysis (c.f., Binford, 1977). In fact, much “archaeological science”, focuses systematically on the processes that form the archaeological record. Here, we present several examples of how a relatively new tool – computational modeling – can contribute to the study of archaeological formation processes.

Various forms of quantitative modeling have enjoyed a long history in archaeology, even though not widely used even today

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(e.g., Ammerman and Cavalli-Sforza, 1984; Gaines and Gaines, 1997; Martin, 1984; Metcalf and Barlow, 1992; Mills et al., 2013; Nolan and Cook, 2010). Computational modeling represents a relatively new direction in formal representation of the dynamics of human societies (but see Wobst, 1974 for a very early example of computational modeling in archaeology). By computational modeling, we are not signifying any use of a computer to solve or execute a model. Rather, computational modeling refers to the use of computational algorithms to represent the decisions and behaviors of individual agents interacting in a (often spatially explicit) virtual world, making it especially useful for social and ecological sciences (Bankes, 2002; Miller and Page, 2007). Because it aims to ’build’ social systems from the perspective of individual actors rather than from the aggregate perspective of the system as a whole, computational modeling is often referred to as ’bottom up’ modeling (Miller and Page, 2007; Mitchell, 2009; Van der Leeuw, 2004). To date, it has most commonly been used in archaeology to explore the dynamics of individual and social behaviors that are not readily evident from the static archaeological record (Barton et al., 2012; Christiansen and Altaweel, 2006; Costopoulos, 2008; Janssen et al., 2007; Kohler and van der Leeuw, 2007; Powell et al., 2009; Premo, 2005; Thomas, 1973). While other modeling approaches have been used to represent formation processes and their consequences for the archaeological record (Aldenderfer, 1981; Ammerman and Feldman, 1974; Bettinger, 1977; David, 1972; Kintigh, 1984; Kohler, 1978; Mills, 1989; Schlanger, 1990; Varien and Mills, 1997), computational modeling has been used only rarely so far to clarify how the archaeological record is created from a bottom up perspective. One early application of computational modeling to the study of formation processes examined how archaeological landscapes were created cumulatively over time in response to environmental and social parameters that attract or prevent settlement at particular places (Wandsnider, 1992). More recently, Brantingham (2006, 2003) has modeled processes that account for variation in raw material diversity in stone artifact assemblages. A strength of studies using modeling to study formation processes is that they shed light on phenomena at archaeological time scales in ways short-term actualistic studies cannot. This study follows in the tradition of this approach and employs an agent-based simulation model to study how the technological behaviors of mobile foragers shapes the formation of the archaeological lithic record.

1.1. Modeling lithic technology

Stone artifacts are the most durable and ancient manifestation of human technology, with examples dating to about 2.6my (Semaw et al., 1997). For most of the human past, they have been a key technology both for resource procurement and for creating other tools. But lithic technology has become all but extinct over the last several millennia, making it difficult to directly observe and measure how lithic assemblages were accumulated by societies that used stone artifacts in daily life. Even ethnoarchaeological studies of site formation among the few groups who still used stone technology in the 20th century have not been able to observe the long-term accumulation processes that produce the archaeological record (Hiscock, 2004; Holdaway and Douglass, 2011; Yellen, 1977). However, computational modeling of lithic technological behaviors that are not readily visible archaeologically and could not be observed over long time spans ethnographically can help quantify the long-term influence of social and environmental factors on the composition of the archaeological record. They can thus be an important complement to more traditional formation process studies.

As a fundamental component of prehistoric human techno-ecological systems, the accumulation of lithic assemblages at residential localities can be affected, among other things, by the spatial/temporal distribution of stone used for implement manufacture; the qualities of different stone for implement manufacture and use; human mobility patterns related to the procurement and transport of stone; implement manufacturing techniques; the activities in which stone artifacts are used; and the behaviors responsible for the discard of stone implements—the last resulting in the creation of archaeological assemblages (Andrefsky, 2009; McCall, 2012). Much has been written about the effects of different behaviors and environmental factors on lithic assemblages, and some actualistic studies have replicated particular aspects of lithic technology (e.g., biface manufacture) and collected information on the resulting lithic materials (Machin et al., 2007; Newcomer, 1971). However, comprehensive, quantitative models for the formation of lithic assemblages have not been developed previously—in a large part because the tools to do so did not exist until recently.

We stress that our goal in modeling lithic technological behaviors is not a digital ‘reconstruction’ of the past nor a detailed representation of forager lives. Rather, computational modeling provides an environment in which to design experiments (sensu Bankes et al., 2002) on the dynamics of human behavior and society in which we can systematically control important parameters and examine long-term change in ways not possible from actualistic observations. Such computational, controlled experiments are especially important because they provide a quantitative and replicable approach to study extinct human systems whose material remains are further largely missing or highly altered.

Any experiment must carefully specify and control the input parameters in order to understand the relationships between causes and effects. Simplicity is also desirable, especially when multiple parameters are allowed to interact. For this study, we have selected a limited suite of technological behaviors and assemblages characteristics to examine, ones that we and many others consider of importance. In addition to shedding light on aspects of the formation of lithic assemblages, we hope that this work will stimulate additional computational experiments that address dimensions of lithic technology we do not consider here.

This study uses a computational agent-based model to systematically assess the impacts of four sets of contextual and behavioral parameters on the accumulation and composition of lithic assemblages at a landscape scale: 1) variability in the occupation length of residential localities, 2) the distribution of lithic raw material sources, 3) the activities in which stone is used, and 4) forager land-use strategies. Even this limited suite of factors interacts in complex ways (Brantingham, 2003); agent-based modeling serves as an experimental environment in which we can systematically vary these parameters and quantitatively measure their effects on the formation of lithic assemblages.

An important consideration that often is misunderstood by those not familiar with agent-based modeling is that its ’bottom-up’ modeling approach means that the experiments described below were not designed to produce particular assemblage characteristics. Rather, we designed the model to represent forager behavior and then report the assemblages that are created. As discussed below, we have tried to represent in semi-abstract form a suite of forager technological and ecological behaviors, and assign those behaviors to forager agents. To the extent possible, we have been guided by ethnographic studies of recent foragers and stone artifact users, and theoretical concepts of human behavioral ecology in choosing how to model agent behavior. We should not treat modern foragers as simplistic analogs for prehistoric ones, of course (McCall, 2012). Rather, we abstract certain aspects of ethnographically observed behaviors that are theoretically grounded and particularly relevant to lithic technology.

Modeled lithic assemblages are the result of modeled behaviors and their interactions performed over varying lengths of time and in different ecological contexts. While we designed the experiments and chose the suite of behaviors to model, and while these choices imposed boundary conditions (e.g., because we chose to use a single quality of lithic material, variation in raw material does not affect resulting assemblages characteristics) as is the case in any experiment, the assemblages produced were in no way predetermined by the model. In fact, some of the modeling results were surprising initially, but these surprises led us to new insights. Moreover, we try below to be as explicit as possible about the experimental design so that others can replicate and modify that design to investigate the possible effects of other factors on the formation of lithic assemblages.

2. Model description

Our model was developed in the open-source NetLogo simulation environment (Wilensky, 1999). Full details of the model and the model code itself can be found in the CoMSES Net Computational Model Library (http://www.openabm.org/model/3949). The model environment has one kind of mobile agent: forager bands. These agents operate in a gridded landscape of square cells termed *patches* in NetLogo. Some patches can be defined as camps, others as lithic raw material sources, and the rest as the landscape through which the foragers move. As described in more detail below, forager agents move from camp to camp, engaging in tasks at each camp. They carry lithic artifacts with them to use in these tasks. Lithics used in tasks can be resharpened (i.e., retouched) to maintain their usability, but eventually they are exhausted and discarded. New lithic artifacts can be made when lithic raw materials are available. This can be when agents encounter a raw material source as they move across the landscape or if they have carried raw material from a source to a camp.

We do not model births or deaths of forager agents, nor do we model the acquisition and consumption of resources other than stone (i.e., our agents do not eat, procreate, or die in the model). We assume that foragers do these things, but since we are concerned about the formation processes most directly responsible for producing lithic assemblages in the archaeological record, we focus on these processes alone. Future experiments could add foraging for food and its consequences on fertility and mortality to the base model we have created here.

Our modeling environment can simulate multiple forager band agents in different territories. However, for greater clarity of results, we report here on experiments using only a single foraging group agent in a single, circular territory with a radius of 30 patches (Fig. 1). Except for the tests of occupation duration (see below), each model involved 50 trips—from one camp to another—averaging a little over 200 individual model steps in which the agent moved from one patch to another within the 2827 patch territory. Because of stochasticity in parameters like the location of camps, raw material sources, and use intensity at each camp, we repeated each experiment 100 times for each combination of parameter settings (except for experiment on the formation of archaeological palimpsests discussed below), aggregating the resulting information on the lithic assemblages created. Previous work (Barton et al., 2011) and preliminary sensitivity tests suggest that this number of repetitions sufficiently captures the variability for the simulation experiments reported here.

2.1. Modeling forager mobility

Residential and logistical mobility are concepts that have been widely applied to forager movement patterns since they were initially proposed by Binford (1980). We have previously suggested that these may represent conceptual extremes of a continuum of movement patterns (Riel-Salvatore and Barton, 2004), and there is in fact considerable variation in measures of mobility among recent forager societies (Bettinger, 1991; Kelly, 1995). Nevertheless, there are some important differences in the organization of activities in time and space, technology, resource use, group size, and social institutions among foragers who primarily engage in logistical as

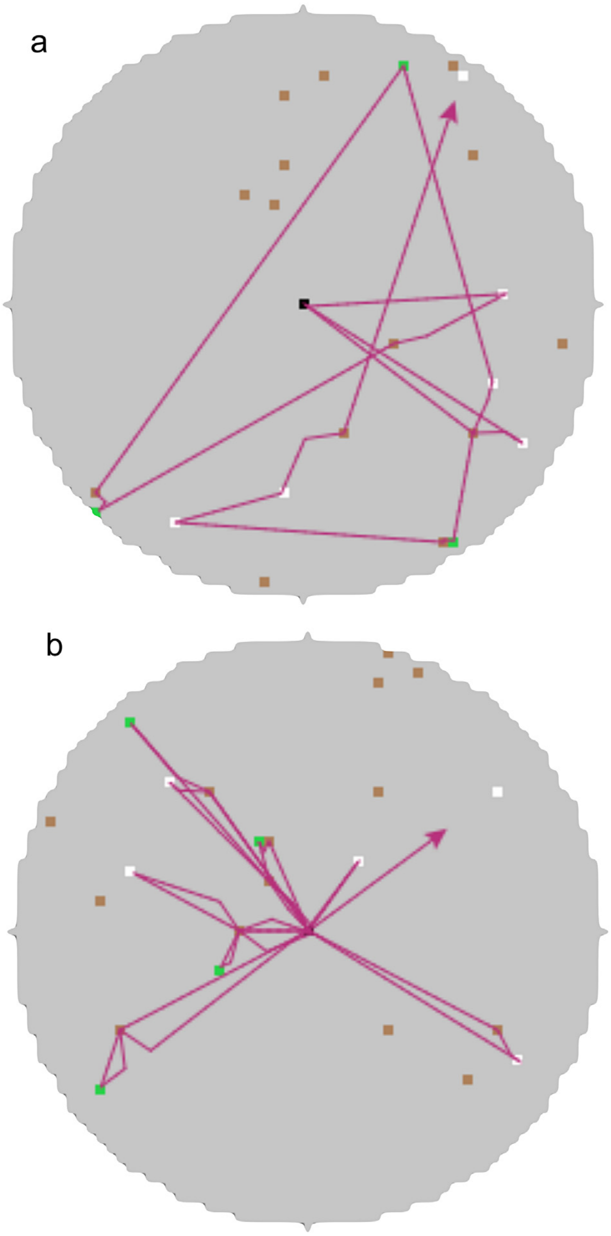


Fig. 1. Display from modeling environment showing movement patterns of forager agents, and distribution of camps and lithic sources within a territory with a radius of 30 patches (grid cells) and 2827 total patches. The red line tracks the movement of a forager agent (red triangle) from camp to camp. Camps are patches colored black, white, and green. Figure 1a represents a residential mobility pattern; black, white, and green patches are all residential camps. Figure 1b illustrates a logistical mobility pattern. Black patches are base camps; white and green patches are resource extraction camps. Lithic sources are brown patches with density set to 0.5 sources per 100 patches. Note how the agent paths from camp to camp can deviate to visit a raw material source within the radius of agent perception. (To better see the colors referred to in this figure legend, the reader is referred to the web version of this article.)

opposed to residential mobility (Binford, 1980; Grove, 2010, 2009; Kelly, 1995, 1992, 1983). Given these differences, it may be more realistic to consider an apparent continuum from residential to logistical mobility where some groups are mostly residentially mobile but occasionally use a logistical mobility pattern, and vice versa, rather than combined continuous variation in length of time a camp is occupied and the distance from the camp that individuals search for food (e.g., Premo, 2012).

Hence, in our experiments, as a forager band agent moves throughout its territory, it can choose a *residential mobility* pattern in which it moves from camp to camp (for simplicity, we term these *residential camps* throughout the paper). Alternatively, it can engage in central place foraging, or *logistical mobility*, in which it moves from a central *base camp* to a *resource extraction camp* and returns to the base camp. A forager agent can shift between these two mobility patterns or follow only one mobility pattern during a simulation run. But it is not possible for an agent to shift through a continuous spectrum of mobility between residential to logistical (e.g., Premo, 2012). Modeling mobility in dichotomous fashion makes it more straightforward to test the effects of mobility on lithic assemblages, as well as possibly representing real-world forager behavior more accurately. Simulation runs can be initialized so that a forager agent has a probability of using either residential or logistical foraging (expressed in the model interface as a percentage between 0 and 100%). For example, a forager agent may have a 20% probability ($p = 0.2$) of using a logistical strategy and an 80% probability ($p = 0.8$) of using a residential strategy during a simulation. This allowed us to analyze the cumulative contribution of different amounts of residential or logistical mobility on palimpsest assemblages, as discussed above, as well as compare the effects of produced only under residential mobility with those produced only under logistical mobility.

For either residential or logistical mobility, an experiment begins with the agent at a camp in the center of the territory. In any experiment, if an agent chooses residential mobility for a modeling cycle (e.g., 50 trips with particular parameter settings), a random location within the territory is chosen for the next camp. The agent moves to this new camp, where it performs a set of tasks, using lithic artifacts, after which it may resharpen and/or discard the artifacts it uses. A new camp is then selected randomly within the territory and the forager continues to move from camp to camp in this way (Fig. 1a). There is a 20% probability that the next camp selected will be the initial central patch. This simulates landscape features that attract settlement, even with residential mobility (e.g., Wandsnider, 1992). It also makes it possible to simulate locales that can be occupied sometimes as a residential camp and at other times as a base camp (see below). Also, without this feature, the chance that any residential camp would be occupied more than once is close to 0. We wanted to be able to better compare our digital assemblage palimpsests with real world archaeological sites where repeated use as a residential camp has made a locale archaeologically visible. The model thus allows for patches to be used as three 'classes' of occupation sites: base camps, residential camps, and resource extraction camps, sometimes in alternating fashion.

If an agent chooses a logistical mobility pattern, the initial central locality is defined as a base camp. A random location in the territory is selected as a resource extraction camp, to which the agent moves and performs tasks. The forager agent then returns to the base camp where it again performs tasks. A new random location is chosen for the next resource extraction camp and the sequence repeats. That is, rather than moving from camp to camp within the territory, forager agents travel out to a resource camp and back to the base camp (Fig. 1b). Note that for these experiments, a base camp is situated at the center of the territory and does not move during the course of a simulation run. Of course, real-world base camps are moved to different locales over time, but they are still occupied for longer time spans than residential camps or resource extraction camps, which is what this modeling protocol simulates.

A forager band agent moves one patch at a time in the direction of its next destination. As discussed in detail below, the forager agent may encounter a raw material source en route to a camp, where it can collect new lithic materials if needed. All forager agents move at the same speed (one patch at a time), but are tireless and can reach both nearby and distant camps with equal ease. The only effects of distance between camps are 1) the amount of time to reach a camp (longer for distant camps) and 2) the chance of encountering a raw material source (which increases with the distance moved between destinations). Forager mobility can be tracked in terms of each *move* made by a forager agent (i.e., from one patch to the next) or in terms of *trips* from one camp to the next.

2.2. Modeling lithic use and discard

Agents can carry a fixed, maximum quantity of lithic artifacts during their trips. This quantity is set by the researcher at the beginning of a modeling experiment. Each of these 'artifacts' embodies a fixed amount of potential useability that is tracked as *lithic utility units* (LUU). The concept of lithic utility (Kuhn, 1994; Shott, 1996) refers to some quantity of useful work that can be accomplished with a stone artifact. Real world foragers can carry LUU in the form of cores, from which flakes or blades can be struck and then used, in the form of flakes/blades removed from cores prior to transport, or in the form of shaped 'tools' like bifaces (Kelly, 1988). While some piece sizes and morphologies can optimize the utility to weight ratio of stone for a given lithic technological system (Kuhn, 1996), overall, the amount of utility available to a forager band remains largely a function of the total amount of stone it can carry, regardless of whether it is in the form of fewer large pieces or many small pieces. Hence, our model employs generic stone artifacts carried and used by forager agents, each having the same initial amount of LUU, rather than as classifying them as cores, flakes, blades, etc., that might have different utility parameters. From this perspective, different technological systems that can provide varying amount of useable edge per kg of stone (but cf. Eren et al., 2008) simply alter the amount of LUU that a forager band can carry for the same effort of transporting a given weight of stone. In order to focus on the effects of the four parameters selected for investigation in the experiments reported here, however, technological system was held constant—though future experiments could investigate the potential impacts on the results reported here.

While some lithic artifacts can have forms specially designed for specific uses, the greatest majority of ethnographic and archaeological lithics are characterized by a life cycle of production as an unmodified flake or blade, use, possible rejuvenation through retouch, and eventual discard (Bleed, 2001; Clarkson, 2005; Dibble, 1995; Holdaway and Douglass, 2011; Jelinek, 1976). Our model captures the continuum of lithic use, rejuvenation, and discard in a simple way: lithic artifacts can have four potential states—unused, utilized, resharpened, exhausted—corresponding to LUU integer values 3-2-1-0 respectively. Tasks at any kind of 'camp' use up some amount of lithic utility, moving artifacts through the use-life process, from unused to exhausted.

The *maximum use intensity* is the maximum possible amount of lithic utility that can be consumed by a set of tasks at any camp, and is set at the beginning of each modeling cycle. The actual use intensity at any particular camp is a value randomly distributed between 1 and the maximum use intensity. This simulates stochasticity in task intensity between camps, and the consequent variability in the rate of reduction of lithic artifacts carried by forager agents. The model assumes that forager agents prefer to use the least used artifacts for tasks initially, a tendency documented ethnographically (Holdaway and Douglass, 2011). For example, an agent carrying four artifacts and engaging in a task with a use intensity of 10 will initially use 4 LUU, transforming all four artifacts from unused to utilized. It will then use 4 more LUU, transforming all artifacts to resharpened. Finally, it will use 2 more LUU (for a total of 4 + 4 + 2 = 10) transforming 2 of the artifacts to an exhausted state with no remaining LLU, while the other 2 artifacts remain in a resharpened state with 1 remaining LLU each.

While there is a fixed maximum number of artifacts that each forager band agent can normally carry, it is also possible to allow agents to *provision* residential and base camps (sensu Kuhn, 1992). When provisioning is enabled, an agent that encounters a raw material source can carry unused artifacts to the camp that is the next destination.

As they move, agents preferentially carry artifacts with maximal remaining LUU to be best prepared for any task they might encounter at the next camp in order to maximize their utility:-transport cost ratio. In contrast, exhausted artifacts (i.e., those with 0 LUU) are always discarded prior to a move, since it is pointless to carry stone with no remaining utility. When preparing for a move, if a forager agent has available more artifacts than the maximum number it can normally carry (e.g., due to provisioning the camp in the current or a previous visit), it will select those with the most remaining LUU to carry to the next camp. In this way, depending on the amount of place provisioning and the intensity of the tasks at a particular site, "resharpened," "utilized," and even "unused" artifacts potentially can be discarded in addition to exhausted ones. Unused artifacts are discarded when a combination of place provisioning and a low intensity of use leaves the agent with more unused artifacts than it can normally carry when it travels to the next camp.

During each modeling experiment, the number of unused, utilized, resharpened, and exhausted artifacts discarded at each camp and raw material source are tracked, as is the number of artifacts in each state carried by all agents at any time during the simulation. These data are then exported in a standard data format ("csv") and subsequently analyzed statistically.

2.3. Modeling lithic raw material resources

Lithic raw material sources are distributed randomly within each territory (Fig. 1). In real-world terrains, the geographic distribution of accessible raw materials is a function of surface bedrock geology and surface geomorphic processes like stream flow that can expose raw material deposits or accumulate cobbles of flakable stone. However, the distribution of raw materials can be considered randomly distributed with respect to other resources that foragers need, like animal herds or stands of nut-bearing trees. Forager camps may be situated to take advantage of lithic raw material exposures or they may be situated to optimally access other resources. Abstracting key parameters of raw material access, sources may vary from near to far from a particular camp, they may range from common to rare within a forager's home range, and they may be visited in the course of other activities (embedded procurement) or foragers may make special trips to raw material sources (direct procurement) (Andrefsky, 1994; Bamforth, 1986; Gould and Saggers, 1985; Nelson, 1991).

Since our forager agents are tireless, the distance to a raw material source is irrelevant for the experiments reported here. This could be examined in another experiment with forager agents that expend energy and must also hunt or gather to replenish that energy. We model the ubiquity of raw material by setting the density of sources per hundred patches, so that accessibility of raw material sources is comparable across territories of variable size. Embedded vs. direct procurement is modeled by assigning a variable-sized radius of perception to forager agents at the beginning of a simulation experiment that allows them to recognize a raw material source. If a lithic raw material source comes within the radius of perception of an agent en route between camps, the agent will deviate from its path to visit the raw material source before continuing on to its destination (Fig. 1). If the radius of perception is very small, forager agents will only visit raw material sources they encounter as they move from camp to camp. If the radius is very large, foragers will perceive and visit sources whenever they need new raw materials, regardless of whether it is directly on the route to another camp. We kept the radius of perception to a single intermediate value for all experiments reported here so that agents could replenish raw materials frequently but would tend to visit those sources closest to their route between camps. Subsequent experiments could be designed to explicitly test the effects of different procurement strategies on assemblage composition.

In this model, raw materials from all sources have the same qualities. That is, all artifacts made from all raw materials have the same four potential states, and each artifact embodies exactly three LUU. Future experiments could examine the effects of different raw material qualities by varying the amount of LUU in artifacts made from different raw material sources, or could simply track the representation of different raw material sources in the assemblages that accumulate at each camp (e.g., Brantingham, 2003).

When forager agents visit a raw material source, they discard all used artifacts (i.e. LUU <3) and replace them with unused ones (i.e., LUU $= 3$). As noted above, additional unused artifacts can also be acquired to provision the next camp. If no raw material source is encountered, the forager will continue to its destination carrying only the artifacts it carried from the prior camp, regardless of their state. This happens more frequently when raw material sources are very rare in a territory than when they are common.

3. Results of experiments

The experimental design and modeling environment described above allowed us to carry out a set of experiments to examine the effects of different behaviors and environmental conditions on the formation of lithic assemblages. Because we are interested in the formation of lithic assemblages rather than the life histories of individual artifacts, we focus on measures like assemblage size (i.e., total number of artifacts accumulated) and the amount of residual utility in an assemblage. The latter is sometimes scaled as *expedient* to *curated* (e.g., Bamforth, 1986; Nelson, 1991), measured here as *retouched frequency* (= resharpened + exhausted/all artifacts), or the proportion of unused and utilized artifacts in an assemblage. This measure is recorded for individual assemblages and aggregated palimpsests of digital lithics deposited at each camp during model runs.

Varying the numbers of trips from a base camp to foraging camps in a model run affects how long an agent uses a base camp, allowing us to evaluate the impacts of occupation duration on assemblage formation. By changing the use intensity of tasks, we can assess the effects of different activities on the formation of lithic assemblages. We can examine the impacts of access to lithic raw material by varying the density of raw material sources within foraging territories, as well as the consequences of different mobility strategies and of decisions to provision places versus individuals. We are also able to assess the combined effects of these different parameters, and importantly, to study the effects of changing conditions over time on the accumulation of palimpsest

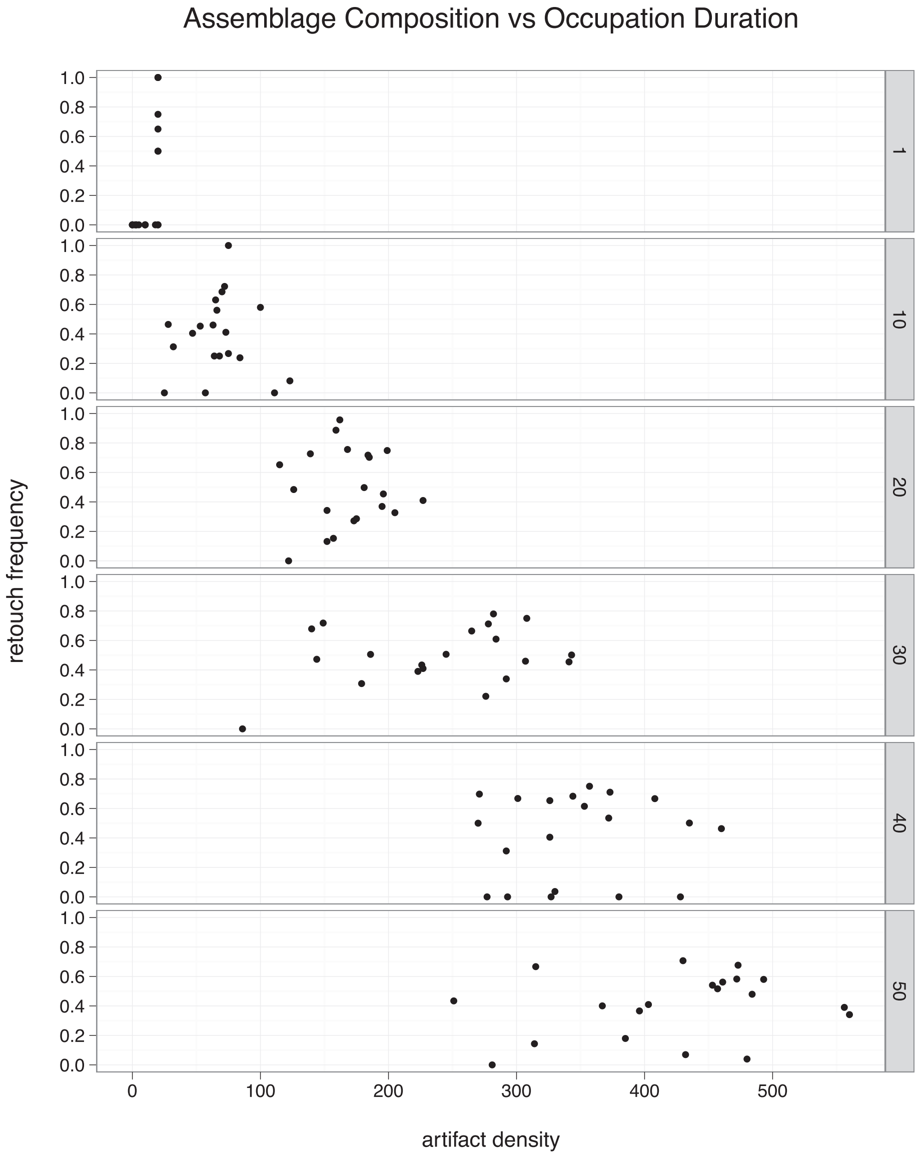


Fig. 2. Effects of varying occupation duration at a camp on composition of accumulated lithic assemblages. Assemblage composition is measured in terms of artifact density and retouched frequency. Numbers at the right of each graph indicate occupation duration as the number of foraging trips that took place while a camp was occupied. Each point represents the lithic assemblage that accumulated during an occupation of a given duration.

assemblages that characterize the vast majority of the archaeological record. In all our tests, we utilize a very wide relative range of parameter values in order to ensure that we can fully capture the consequences of modeled behaviors on assemblage composition. We discuss the results of these experiments in more detail below.

3.1. Occupation duration

Since most lithic artifacts have finite and usually very short use lives (Barton, 1997; Frison, 1968; Holdaway and Douglass, 2011; Jelinek, 1976), it can be expected that the longer an agent occupies a locale, the greater the number of pieces that will be discarded there, and the higher the density of the resulting accumulated lithic assemblage. However, since occupants also can reuse and resharpen previously discarded pieces, length of occupation could also affect assemblage composition, assemblage size, and artifact density at a site (Morrow, 1996; Shiner, 2006). To assess this, we set up an experiment in which we systematically varied the number of trips by agents using a central-place foraging movement pattern (i.e., out to a resource collection site and back to camp, with provisioning set to 50% as described below) in a modeling cycle to simulate differences in occupation length. For a short occupation, foragers only made a single logistical foraging trip; with a long occupation, the forager agent used the site as a base camp for many logistical foraging trips. Occupation duration was set to 1, 10, 20, 30, 40, and 50 trips (i.e., from very short to very long occupation), allowing us to assess the impact of the amount of time spent at a camp.

It is clear that the density of the accumulated lithic assemblage increases as occupation varies from 1 to 50 trips (Fig. 2), and lithic density and occupation duration are highly correlated with $R = 0.94$ ($p << 0.01$). However, and somewhat counter-intuitively (c.f., Grayson and Cole, 1998), occupation duration seems to have no clear effect on assemblage composition, measured by the retouched frequency within the total assemblage ($R = 0.12$, $p = 0.18$). This could help differentiate between assemblages that accumulated due to long occupations and those that represent a different kind of occupation such as a large, aggregate group. For the former, we might see changes in assemblage size with no change in retouch frequency. But for the latter, an increase in assemblage size might be accompanied by a change in retouch frequency (e.g., from a short-term camp of a small residential forager band to the base camp of a larger group of logistical foragers). It is also important to note here that we are referring to the effects of occupation duration alone, all else being held constant. When an assemblage is a palimpsest of multiple occupations by foragers who may shift their land-use or resource use patterns over time, assemblage composition can be affected (see below).

Since length of occupation had no significant impact on assemblage composition, we used 50 trips for model runs in other experiments, except as noted, to ensure that we obtained relatively large assemblages for statistical analysis.

3.2. *Differences in tasks*

Intuitively, variation in the nature of tasks conducted at a camp should affect lithic assemblages in several ways. In the context of this study, task variation could affect overall assemblage composition by changing the rate at which lithic utility is consumed and artifacts go from unused to exhausted. Fig. 3 shows the results of an experiment in which we varied the maximum use intensity of tasks from 20 to 60 LUU. As the range of possible LUU consumed in tasks at a particular camp increases from 0–20 to 0–60, there is a concomitant increase in the frequency of retouched pieces in assemblages, as well as a decline in the variance of retouched frequency. That is, when most tasks consume LUU at a relatively low rate, assemblages can vary from ones composed almost entirely of unused and lightly utilized pieces to ones composed almost entirely of resharpened and exhausted pieces. But when use intensity varies over a much greater range, most sites will be heavily dominated by retouched artifacts. Unsurprisingly, maximum use intensity and retouched frequency are strongly correlated ($R = 0.51$, $p << 0.01$). In other experiments (except as noted below), maximum use intensity was set at 30 LUU so that task effects did not overwhelm the potential impact of other parameters.

3.3. *Access to raw material*

Access to raw material is commonly cited as an important factor affecting assemblage composition (Andrefsky, 1994). Given the importance of lithic artifacts to prehistoric foragers and their short use lives, lack of ready access to toolstone to make new artifacts should strongly promote lithic conservation behaviors like resharpening used artifacts instead of discarding them. On the other hand, an abundance of raw material should allow foragers to discard dulled artifacts without resharpening them and make new ones. Hence, assemblages that accumulate under conditions of raw material scarcity should be dominated by retouched artifacts (including resharpened and exhausted pieces), while assemblages that accumulate under conditions of raw material abundance should be have much lower frequencies of resharpened and exhausted artifacts.

To test this, the density of raw material source localities within the foraging territory was systematically varied from 0.2 to 1.8 per 100 patches of territory. While the expected effect of raw material abundance on assemblage composition can be seen (i.e., a negative correlation – Fig. 4)), this relationship is not as clear-cut as the effects of tasks on retouched frequency and occupation duration on assemblage density ($R = -0.29$). Nevertheless this negative correlation is statistically significant ($p << 0.001$). For the following experiments, except as noted below, the density of raw material source localities was set to an intermediate value of 0.5 per 100 patches within a foraging territory.

3.4. *Mobility patterns*

Previously, we have proposed that land-use strategies have significant effects on the composition of lithic assemblages (Barton, 1998; Barton et al., 2011; Riel-Salvatore and Barton, 2004; Riel-

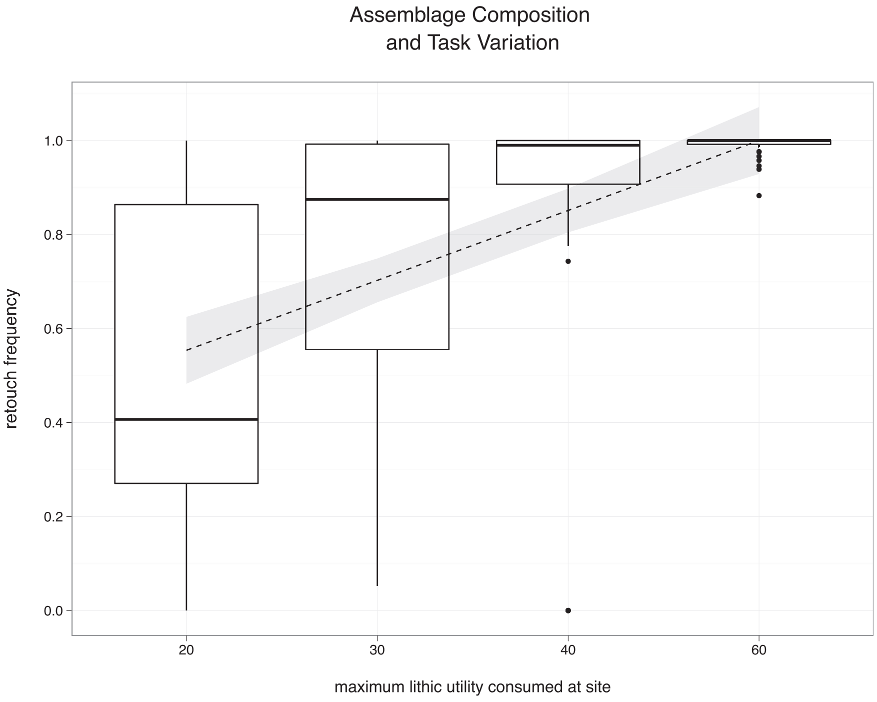


Fig. 3. Effects of task variation, in terms of intensity of lithic utility consumption, on assemblage composition as measured by retouched frequency. Each boxplot represents assemblages generated with a different range of task intensity, from 0–20 to 0–60, with the numbers on the x-axis indicating the maximum possible task intensity for a site. The intensity of tasks at any single site was randomly selected from within that range. Dashed line and gray shading represent regression and 95% confidence interval for retouched frequency vs. maximum task intensity.

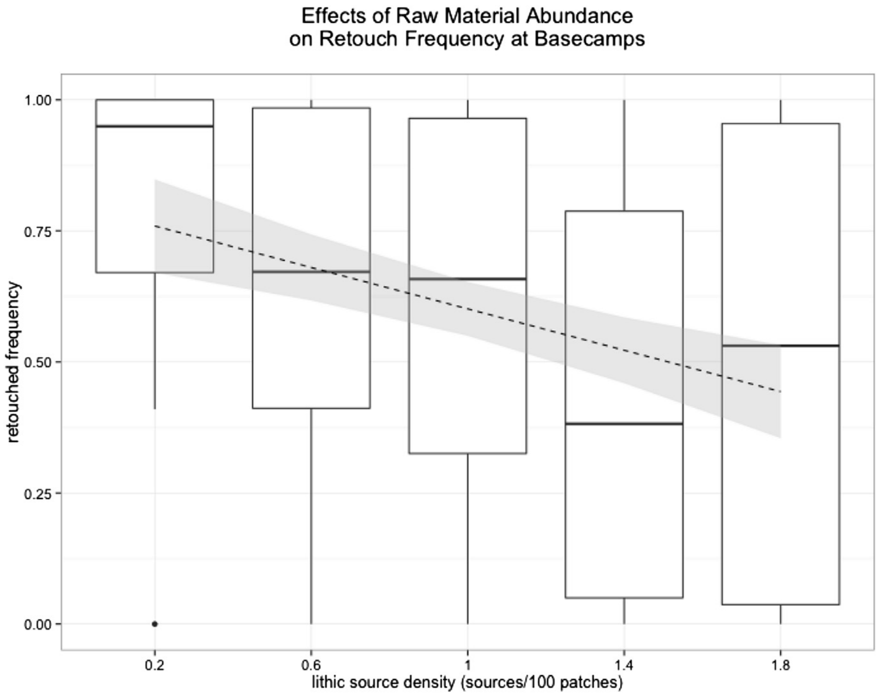


Fig. 4. Effects of raw material abundance on assemblage composition as measured by retouched frequency. Each boxplot represents a different density of raw material sources within the foraging territory of an agent. Values are given in patches designated as raw material sources per 100 patches of territory. Dashed line and gray shading represent regression and 95% confidence interval for retouched frequency vs. raw material source abundance.

Salvatore, 2010; Riel-Salvatore et al., 2008). An important aspect of land-use strategies among foragers is their pattern of movement across the landscape over time. In a set of experiments designed to test the effects of different mobility patterns, we varied the probability of using a logistical or a residential mobility pattern during each model run (i.e., a model run of 50 trips between camps). For example, setting the probability of using logistical mobility to 0.70 meant that each run had a 70% chance of starting with a base camp and a logistical pattern of movement and a 30% chance of starting with the forager band agent moving from camp to camp. The resulting assemblages were aggregated every five runs within a total of 100 repetitions, to represent palimpsest accumulations at archaeological sites. Because we treated mobility as a probabilistic setting, all runs of a five run set could be all logistical or all residential for the above example with a probability of using logistical mobility equal to 0.70, but would more likely be a mix of strategies, dominated by logistical mobility.

Relating mobility to lithic assemblage formation, Kuhn (1992) introduced a useful distinction between *provisioning individuals* and *provisioning places* with lithic artifacts. Provisioning individuals refers to the lithic artifacts (and equivalent LUU in our modeling environment) carried by individuals as they move from place to place. Provisioning places refers to stockpiling lithic material (and equivalent LUU) at locales for future use. While there is a limit to the amount of stone an individual on foot can carry—especially if s/he also must carry other objects of technological and/or symbolic value, food and/or water, infants, etc.—there is no such limit to the amount of lithic material that can stockpiled at a place. As we note below, individual and place provisioning have significant and distinct effects on assemblage composition. However, when examining mobility patterns alone, we held provisioning constant across different mobility patterns.

When only individual provisioning was permitted, retouched frequency approached 1.0 for both residential and logistical mobility patterns. In contrast, Fig. 5 shows the effects of mobility patterns on assemblage composition when 50% place provisioning is permitted. That is, allowing a forager agent to collect 50% more than it normally carries at a raw material source to provision the next destination camp. After completing the tasks at the destination camp and discarding all exhausted artifacts, the agent will provision the camp with any lithics in excess of what it normally carries—preferring to carry those artifacts with the highest LUU and provisioning the camp with the others. With equal provisioning for all camps and with both mobility patterns, there is a noticeable difference between a locale used as a logistical base camp and the same locale used as a residential camp (Fig. 5b). An ANOVA indicates this difference is statistically significant ($p = 0.006$). In sharp contrast, the camps of forager agents employing residential mobility (excluding the camp sometimes used as a base camp) and the resource extraction camps of a logistical pattern overlap completely with respect to retouched frequency (Fig. 5a), because both are very short term occupations; an ANOVA comparing residential camps and resource extraction camps returns a $p = 0.08$. Below, we look at the effects of individual and place provisioning in more detail.

3.5. Mobility and provisioning

We use the term land-use strategy to refer to an integrated suite of behaviors of which mobility is only one dimension, and in which foragers adjust the way they organize resource acquisition and processing, manufacture and use technology, group size in space and time, and even aspects of social organization. This follows Binford's original distinction between the logistical and residential mobility of collectors and foragers, respectively (1980) as well as subsequent usage (Barton et al., 2011; Grove, 2010, 2009; Kelly, 1983; Kuhn, 1995; Riel-Salvatore and Barton, 2004). From this perspective, logistical mobility strategies are not simply central-place foraging, but also involve a suite of other social, ecological, and technological behaviors including provisioning places for

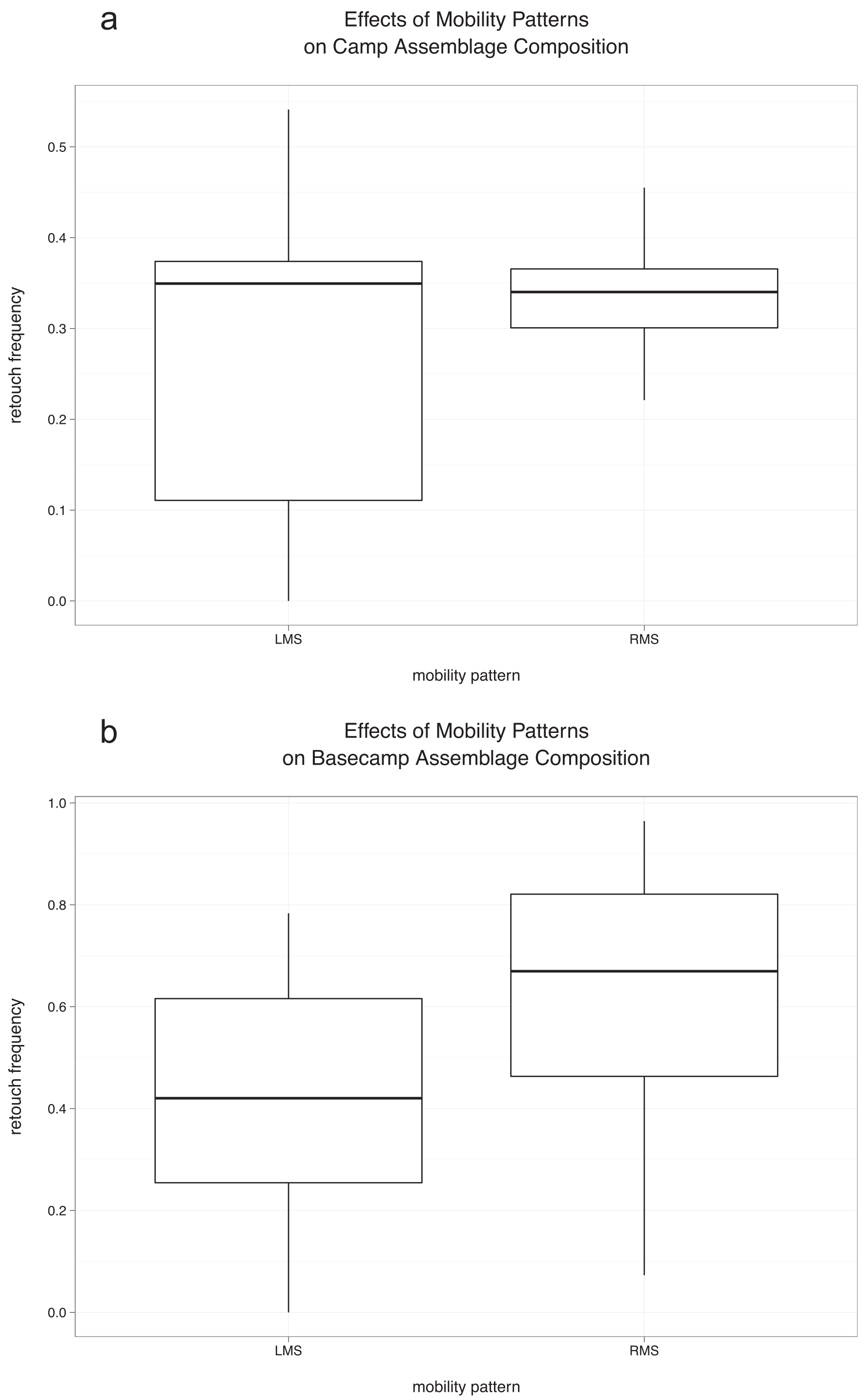


Fig. 5. Effects of mobility patterns on assemblage composition as measured by retouched frequency. Figure 5a shows retouched frequency for residential camps ("RMS") and resource extraction camps of a logistical mobility patter ("LMS"). Figure 5b shows retouched frequency for a single site which sometimes is occupied as a logistical base camp ("LMS") and other times as a residential camp ("RMS").

future use. Residential land-use strategies, on the other hand emphasize provisioning individuals rather than places as part of a different suite of behaviors (Kuhn, 1995, 1992). As such, keeping provisioning constant across mobility patterns does not match real-world forager land-use strategies, which requires another set of experiments.

To examine the effects of place provisioning we designed an experiment in which place provisioning was set to 50% above the amount normally carried by forager agents for base camps with logistical mobility to represent a logistical mobility strategy, or LMS. For resource extraction camps (with LMS) and residential camps (i.e., residential mobility strategy, or RMS) we varied place provisioning from 10% to 50% above what was normally carried—assuming that even with RMS foragers might try to carry at least a small amount of extra lithic material to their next camp if they had the opportunity to do so. The results can be seen in Fig. 6.

In all cases, increasing place provisioning significantly decreases retouched frequency. This is most apparent for base camps (Fig. 6b), but it is also a strong trend when a locale that is used as a base camp with logistical mobility is used as a short-term camp with residential mobility (Fig. 6a). The effects of mobility and provisioning are most clearly seen when combined as land-use strategies, however. Fig. 7 shows the results of an experiment in which place provisioning was set to 50% more than the amount normally carried for LMS base camps, and 10% more than normally carried for LMS resource extraction camps and for RMS residential camps. The probability of the forager agent employing an LMS strategy was then varied from 0 to 100 and lithic assemblage data was aggregated for sets of five model runs as described above. Because of the limited place provisioning associated with RMS residential camps and LMS resource extraction camps, shifts in land-use strategy has virtually no effect on lithic assemblage composition at these localities ($R = -0.13$, $p = 0.15$). On the other hand, shifting land-use strategy has a much more significant effect on assemblage composition at LMS base camps because of the importance of place provisioning at these locales ($R = -0.56$, $p << 0.01$). In other words, as we have observed empirically in the archaeological record, variation in land-use strategies has a very strong effect on the lithic assemblages that accumulate at locales that serve at least sometimes as logistical base camps.

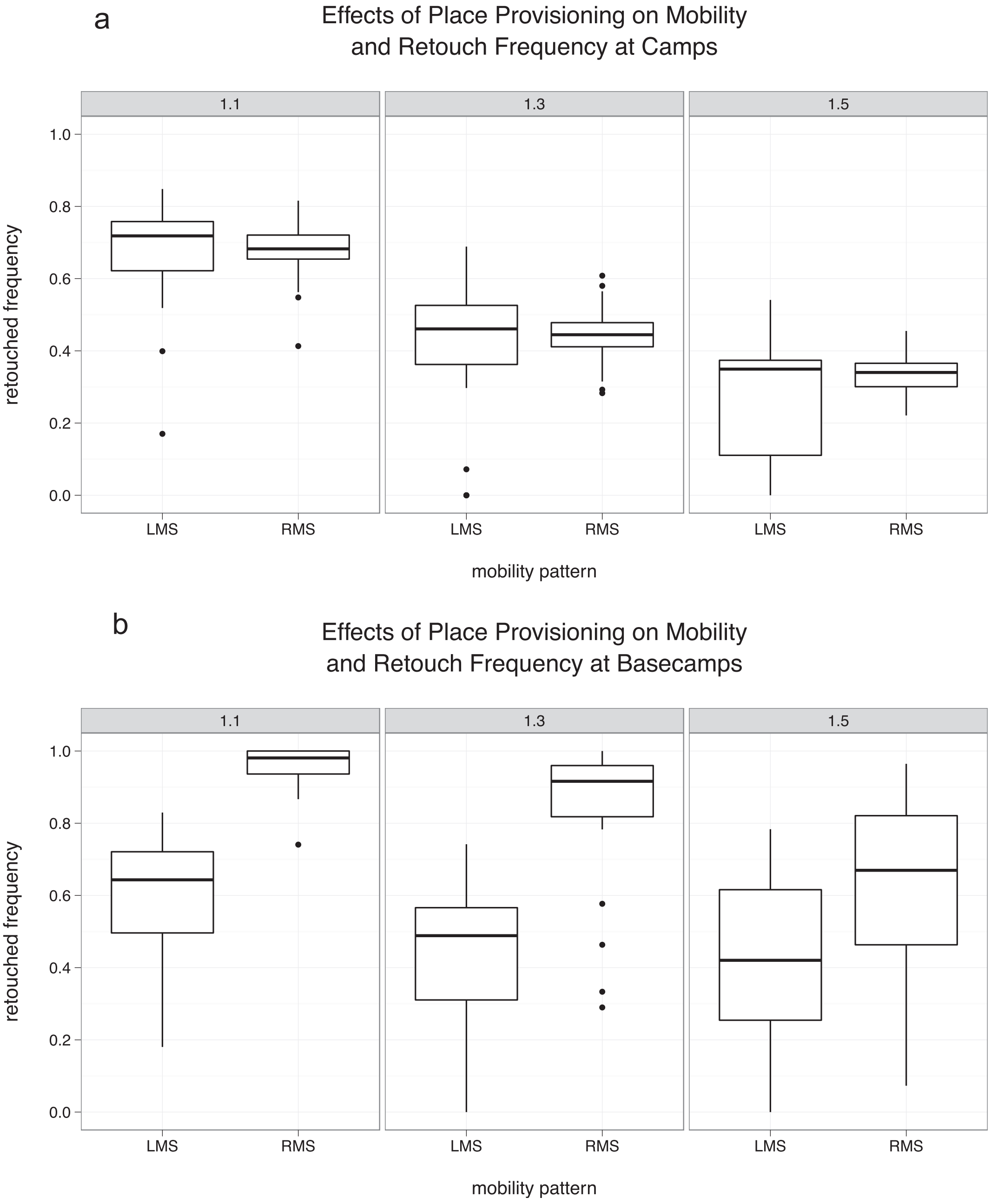


Fig. 6. Effects of place provisioning on assemblage composition as measured by retouched frequency, with different mobility patterns. Place provisioning is indicated as a multiplier of individual provisioning (the base amount of lithic artifacts that an individual forager agent will carry from camp to camp, which is set to 30 artifacts for these experiments). A place provisioning value of 1.3 indicates that a forager agent will carry 30 × 1.3 = 39 artifacts from a raw material source to provision the next camp. Figure 6a shows the effects of varying place provisioning for residential camps ("RMS") and resource extraction camps of a logistical mobility pattern ("LMS"). Figure 6b shows the effects of varying place provisioning on a single site which sometimes is occupied as a logistical base camp ("LMS") and other times as a residential camp ("RMS").

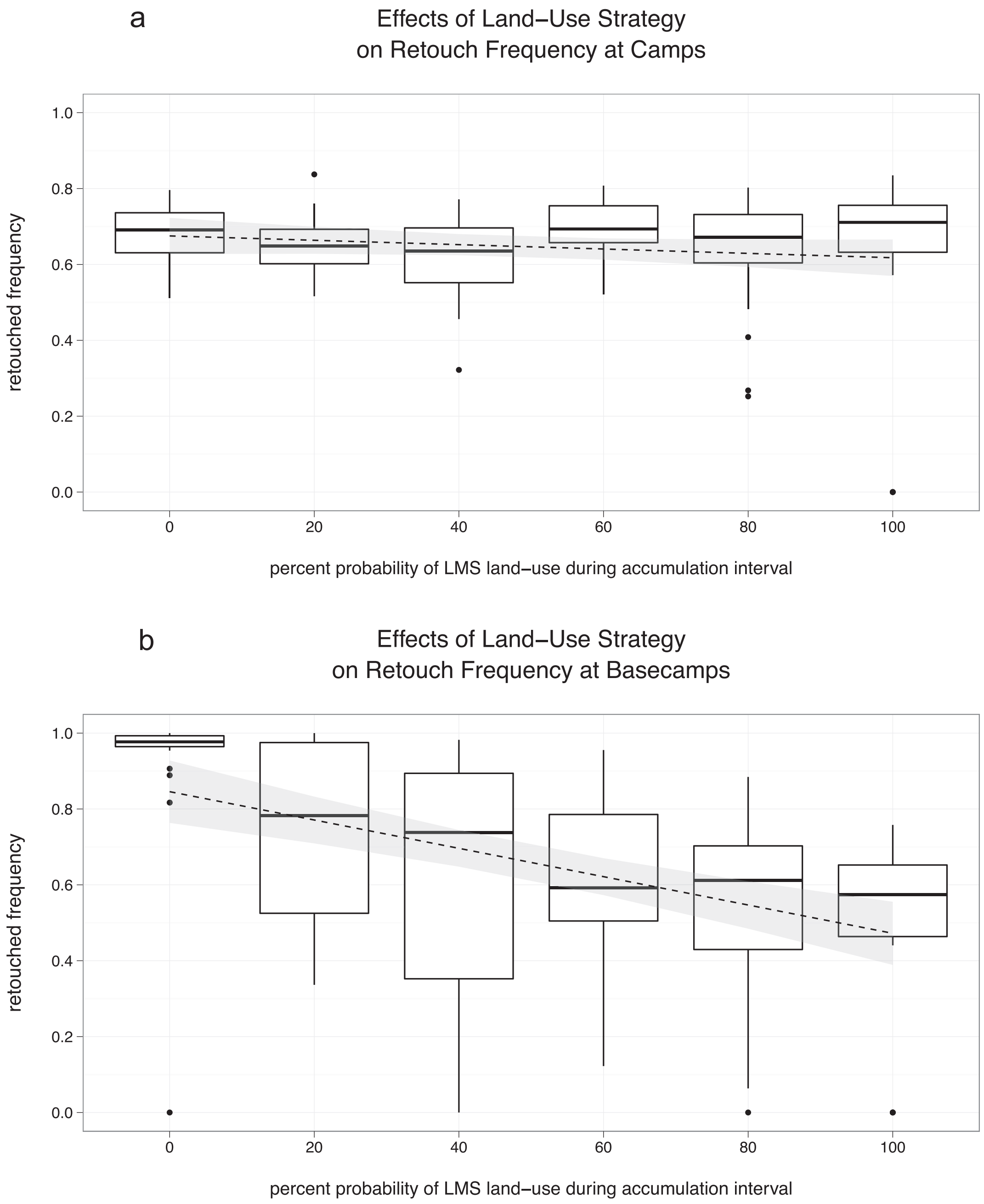
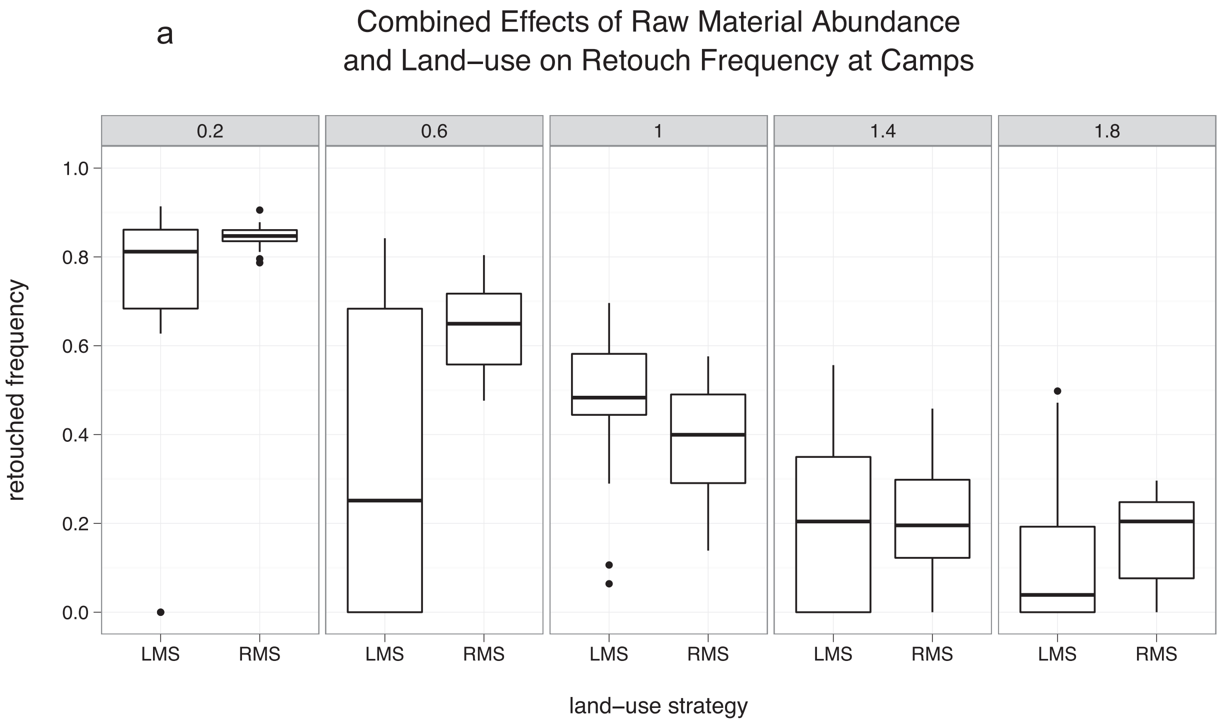


Fig. 7. Effects of varying land-use strategy on assemblage composition as measured by retouched frequency. Each boxplot represents assemblages that accumulated over five sequential modeling runs (each of which involved 50 trips between camps). The probability of employing a logistical mobility land-use strategy ("LMS"), as opposed to a residential mobility land-use strategy ("RMS"), is indicated by the value on the *x*-axis. Figure 7a shows retouched frequency for residential camps ("RMS") and resource extraction camps of a logistical mobility patter ("LMS"). Figure 7b shows retouched frequency for a single site which sometimes is occupied as a logistical base camp ("LMS") and other times as a residential camp ("RMS"). Dashed line and gray shading represent regression and 95% confidence interval for retouched frequency vs. probability of employing LMS land-use.

3.6. Multiple interacting effects

We repeated the experiments on task intensity and raw material abundance described above, modeling land-use strategies at 100% RMS and 100% LMS. Fig. 8 shows the combined effects of land-use strategy and raw material abundance. Increasing raw material abundance significantly decreases retouched frequency in all cases (with $p \leq 0.001$ for all five correlations between raw material abundance and retouched frequency), paralleling the results shown in Fig. 4. However, the effects on base camps differ in important ways from the effects on other camps. Variation in raw material abundance affects all camps equally, shifting their assemblages from being dominated by retouched (i.e., resharpened and exhausted) artifacts to being dominated by utilized and unmodified pieces (Fig. 8a). For locales that serve as LMS base camps, however, increasing raw material abundance also lowers retouched frequency, but not as dramatically as it does for other camps. Moreover, retouched frequency decreases much less for the same locales when they are occupied as RMS residential camps. In fact, overall, increasing raw material abundance amplifies differences in retouched frequency due to land-use, making it much easier to differentiate between LMS and RMS use of a locale (Fig. 8b).



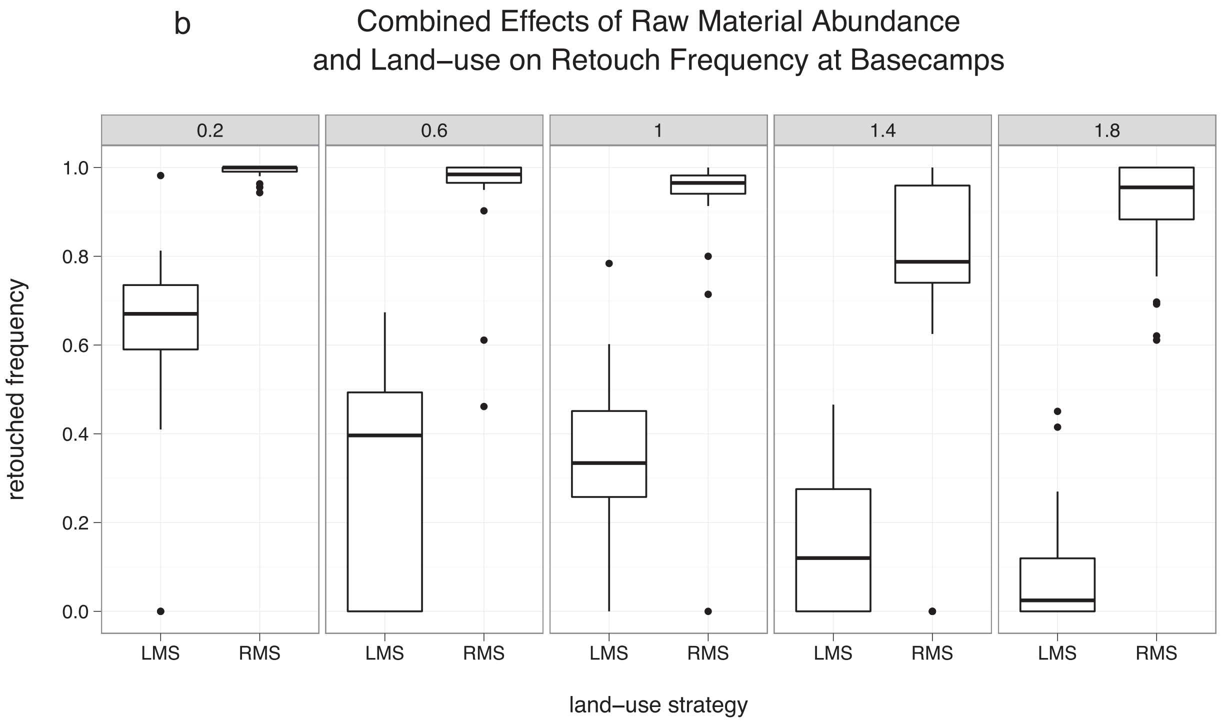


Fig. 8. Combined effects of land-use strategy and raw material abundance on assemblage composition as measured by retouched frequency. Each graph of Fig. 8a and b represent a different density of raw material sources within a foraging territory (the same range of values shown in Fig. 4). Each boxplot represents the assemblages that accumulated with a 100% probability of LMS land-use or a 100% probability of RMS land-use over 20 sequences of five model runs of 50 trips each. LMS land-use was simulated using logistical mobility and place provisioning set to 1.5× individual provisioning (1.5× 30 = 45 artifacts); RMS land-use was simulated using residential mobility and place provisioning set to 1.1× individual provisioning. Figure 8a shows the effects of varying land-use and raw material abundance for residential camps ("RMS") and resource extraction camps of a logistical mobility pattern ("LMS"). Figure 8b shows the effects of varying land-use and raw material abundance on a single site which sometimes is occupied as a logistical base camp ("LMS") and other times as a residential camp ("RMS").

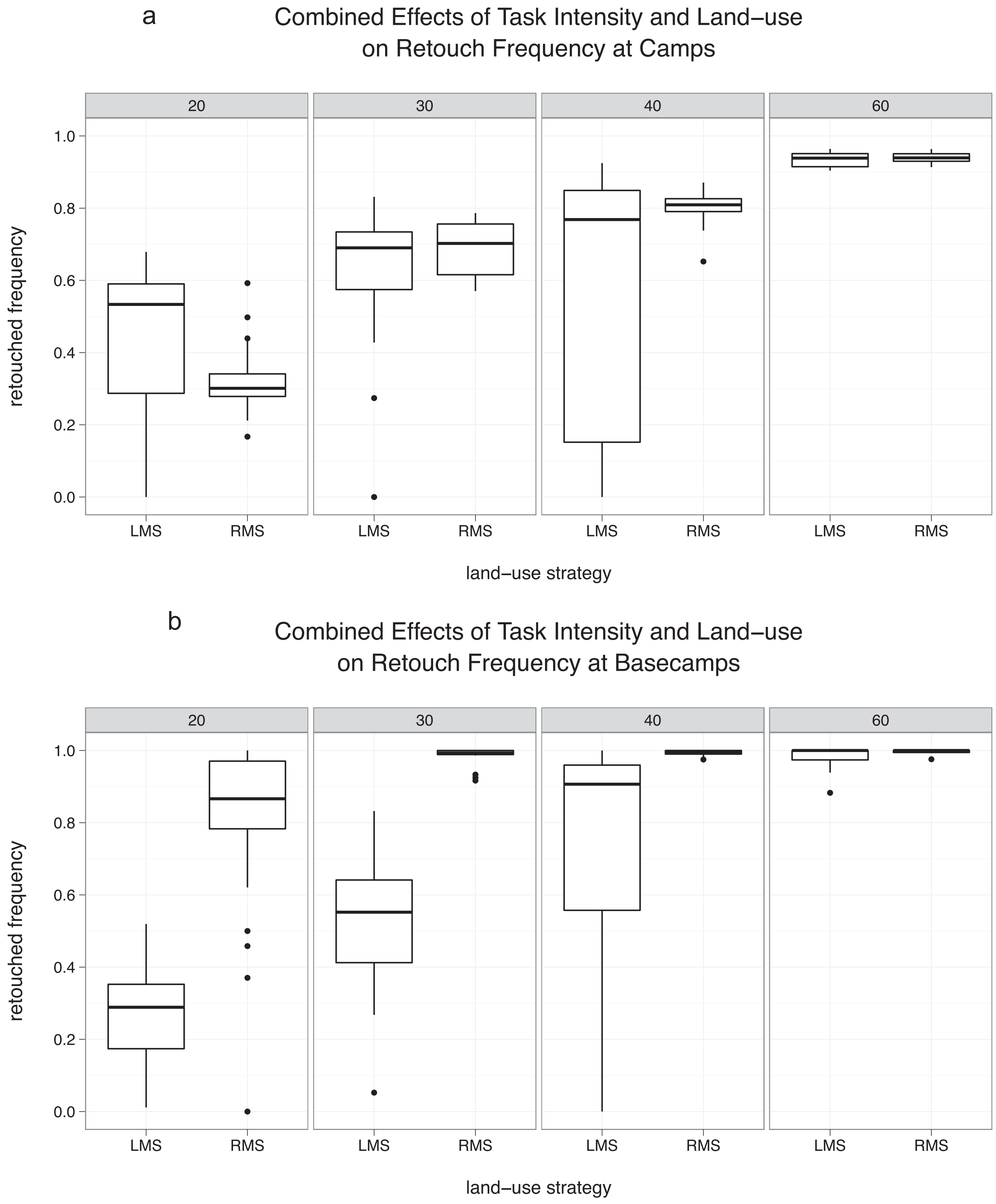


Fig. 9. Combined effects of land-use strategy and task intensity abundance on assemblage composition as measured by retouched frequency. Each graph of Fig. 9a and b represent a different range of task intensities (see Fig. 5). Each boxplot represents the assemblages that accumulated with a 100% probability of LMS land-use or a 100% probability of RMS land-use over 20 sequences of five model runs of 50 trips each. Figure 9a shows the effects of varying land-use and task intensity for residential camps ("RMS") and resource extraction camps of a logistical mobility pattern ("LMS"). Figure 9b shows the effects of varying land-use and task intensity on a single site which sometimes is occupied as a logistical base camp ("LMS") and other times as a residential camp ("RMS").

A similar pattern is seen for the combined effects of land-use strategy and variation in task intensity in (Fig. 9). In this context, very intensive tasks lead to high retouched frequencies in all cases, while declining task intensity causes a decline in retouched frequency for all camps, regardless of land-use strategy (Fig. 9a). However, even a slight decline in task intensity amplifies the differences between the assemblages found at locales that shift between base camps and residential camps when they are occupied under LMS and RMS (Fig. 9b).

A step-wise multiple regression allows us to assess the impact of all factors, across all tested ranges values combined (Table 1). The relative importance of each parameter's contribution to predicting retouched frequency is given by the t-value. Land-use strategy, measured by the percent probability of LMS, makes the greatest contribution by an order of magnitude or more. In other words, while raw material abundance and task intensity indeed affect assemblage composition, land-use strategy has a much greater effect on assemblage composition than these other two parameters.

4. Discussion

These modeling experiments highlight the usefulness of agent-based modeling for studying the formation of the archaeological record. Importantly, this methodological tool provides a means to quantitatively evaluate the long-term, cumulative effects of different behavioral and environmental factors in creating the kind of palimpsest assemblages that comprise much of the normal archaeological record. Given the practical impossibility of real-world replicative experiments in which a group of modern people are induced to spend years acting like ancient foragers, this kind of modeling is a valuable new way to systematically examine the interactions of behaviors and socio-environmental context that create the archaeological record over multiple occupations. It is important, however, to ground computational experiments like these in real-world data by comparing results against the empirical archaeological record.

In a series of prior empirical studies (Barton and Riel-Salvatore, 2012; Barton, 1998; Barton et al., 2011; Riel-Salvatore and Barton, 2007, 2004; Riel-Salvatore and Negrino, 2009; Riel-Salvatore, 2010, 2007; Riel-Salvatore et al., 2008), we identified a distinctive pattern in numerous Paleolithic lithic assemblages from stratified sites across western Eurasia, in which the frequency of retouched pieces is negatively correlated with artifact density (see also Clark, 2008; Kuhn, 2004, 2013; Sandgathe, 2006). These sites, we have suggested, sometimes served as LMS base camps and other times as RMS residential camps. Drawing from theoretical concepts grounded in human behavioral ecology, we argued that this pattern is a proxy for variation in land-use strategies, with palimpsest assemblages dominated by RMS at one end of the distribution and assemblages dominated by LMS at the other. This expectation is amenable to independent testing using our model. Fig. 10 shows modeled assemblages, plotted by retouched frequency and artifact density and colored by land-use strategy (i.e., the probability that LMS was used during a series of five runs, as described above). Fig. 10a shows assemblage composition and land-use strategy for RMS residential camps and LMS resource extraction camps. While the frequency of retouched pieces is strongly correlated with artifact density ($R = 0.55$, $p << 0.01$), the correlation is *positive*, not negative. Fig. 10b, in contrast, shows assemblage composition for locales that alternated between LMS base camps and RMS residential camps, analogous to real-world stratified cave and rockshelter sites whose assemblages we have analyzed. For these assemblages, retouched frequency is *negatively* correlated with artifact density ($R = -0.40$, $p << 0.01$), matching the empirical record of Paleolithic assemblages. Moreover, assemblages with high retouched frequencies and low artifact densities at the upper left extreme of the distribution are dominated by RMS land-use (blue), Those at the opposite extreme of low retouched frequencies and high artifact densities are dominated by LMS land-use (red), matching our predictions. We emphasize that while our modeling experiments proscribed different agent behaviors (e.g. intensity of tasks, occupational duration, provisioning, and mobility) and environmental conditions (e.g., density of raw material sources), assemblage characteristics like artifact density and retouched frequency are completely emergent results of the modeling.

These modeling experiments thus support our interpretation that the relationship between retouched frequency and artifact density is a robust proxy for ancient land-use strategies. Additionally, they show that this pattern is most apparent for sites whose occupation alternated between LMS base camps and RMS residential camps. The place provisioning that tends to go along with logistical mobility drives these distinctive patterns in the composition of lithic assemblages that accumulated at locales that served periodically as LMS base camps. Without place provisioning, logistical base camps look identical to any other camp, with a high frequency of retouched pieces. The evolution of diverse land-use strategies that combine mobility and foraging patterns, provisioning, technologies, and social organization may well be what characterizes human adaptations and lithic technology after the Lower Paleolithic (Hovers, 2012; Lycett and Norton, 2010). The kind of modeling we use here, combined with the empirical but static archaeological record, offers new avenues for testing such a proposition.

These experiments also predict a quantitative signature for locales that served exclusively as RMS residential camps and/or LMS resource extraction camps on the basis of assemblage composition. Often, these residential/resource camps are visited only a few times. Depending on the availability of raw materials, minimally used or unused artifacts may occasionally be discarded at these locales. But when residential/resource camps happen to be revisited often (e.g., because they are associated with a landscape feature like a lake or rock shelter), the emphasis on individual provisioning and lack of place provisioning results in occupants reusing, retouching, and exhausting any lithics with residual LUU found at the locale. These behaviors lead to a positive relationship between retouched frequency and artifact density—exactly the opposite of locales that alternated between LMS base camps and RMS residential camps, and the phenomenon documented in Fig. 10a.

The current empirical record suggests that many—and probably most—of the Upper Pleistocene stratified sites for which we and others have collected and analyzed assemblage data served as LMS base camps at least some of the time – at the very least they were the focus of semi-regular place provisioning. In contrast, residential/resource camps are largely missing from the record. This is not surprising given the very low artifact density that characterizes the lithic assemblages of most such localities. As can be seen in Fig. 11, base camp artifact densities are many orders of magnitude greater than those of residential/resource camps, even when a base camp locality was occupied periodically as an RMS residential camp. Such low-density occupational sites will be difficult to locate without non-site or patch-based survey methods (Barton et al., 2013, 1999; Peeples et al., 2006). Moreover, even when they are identified, it could be difficult to differentiate RMS residential camps from LMS resource extraction camps, at least on the basis of lithic data alone. They appear nearly identical with respect to artifact density (Fig. 11) and assemblage composition (Figs. 5 and 6), and the latter can be affected more strongly by tasks carried out at a camp and raw material accessibility than by land-use strategy (Figs. 8 and 9).

The difference in archaeological visibility between sites that served as LMS base camps and those that were RMS residential

Table 1
Stepwise multiple regression results, carried out in R, indicating the contribution of different behavioral factors to retouched frequency for all model runs.

	Estimate	Std. Error	*t* value	*p*
(Intercept)	0.5563650	0.0624470	8.909	<<0.01
Max use intensity	0.0113869	0.0012724	8.949	<<0.01
Raw material abundance	−0.1803553	0.0260853	−6.914	<<0.01
Occupation duration	0.0018799	0.0008889	2.115	0.03
Land-use strategy	−0.0044714	0.0002198	−20.342	<<0.01

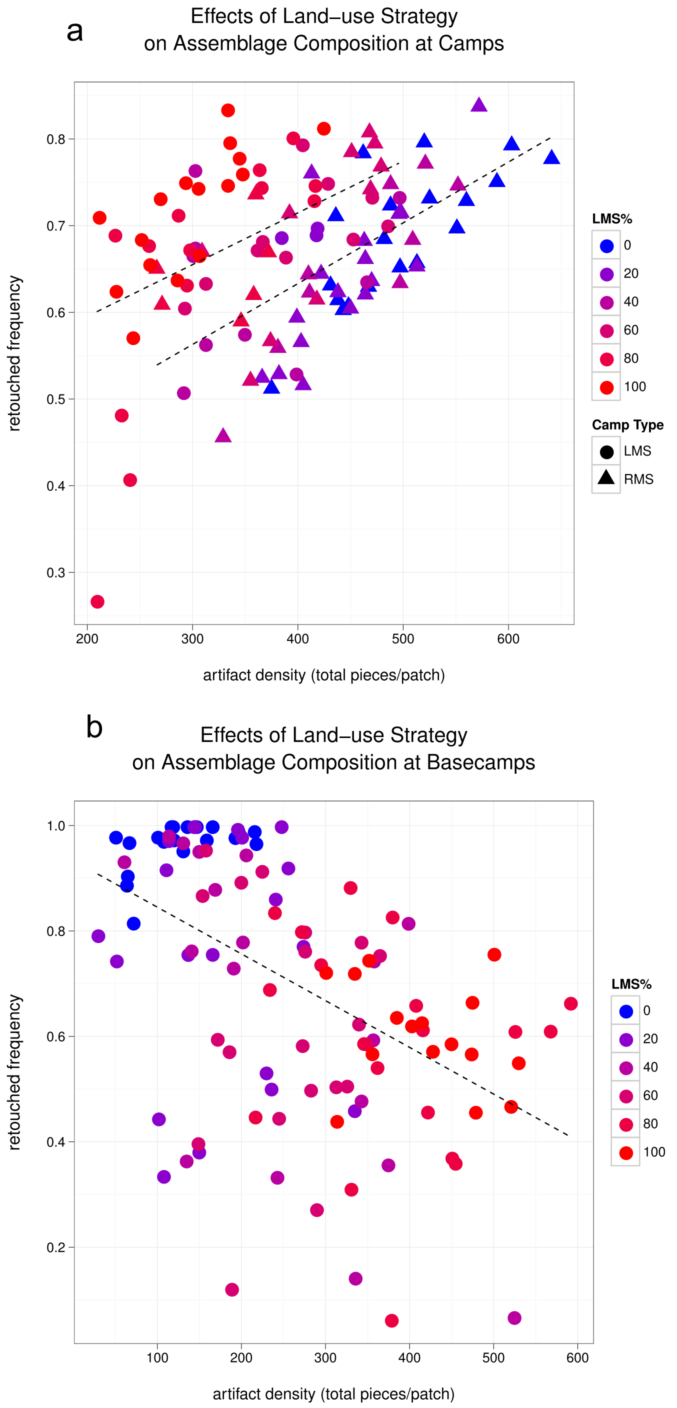


Fig. 10. Effects of land-use strategy on assemblage composition as measured by retouched frequency and artifact density. Each point represents the assemblages that accumulated with a probability of LMS land-use over 20 sequences of five model runs of 50 trips each. Probability of LMS land-use is indicated by color, ranging from blue for 0% (=100% RMS land-use) to red for 100% (=0% RMS). Figure 10a shows the effects of varying land-use for residential camps (triangles) and resource extraction camps of a logistical mobility patter (circles). Figure 10b shows the effects of varying land-use for a single site which sometimes is occupied as a logistical base camp and other times as a residential camp. Dashed lines indicate regression of retouched frequency vs. artifact density (separate lines for RMS residential camps and LMS resource extraction camps in Fig. 10a). (To better see the colors referred to in this figure legend, the reader is referred to the web version of this article.)

camps highlights another important lesson to be drawn from the results of these modeling experiments: the importance of palimpsests. Previously we have been careful to note that the Paleolithic assemblages we have used to study land-use dynamics in Pleistocene Europe are best understood as time-averaged palimpsests that mix debris from many discrete occupational episodes (Barton and Clark, 1993; Barton et al., 2011; Riel-Salvatore and Barton, 2004). Even though archaeologists have long been aware of the dangers of assuming that the archaeological record is one of 'snapshots' of past life (Binford, 1981), assemblages are often

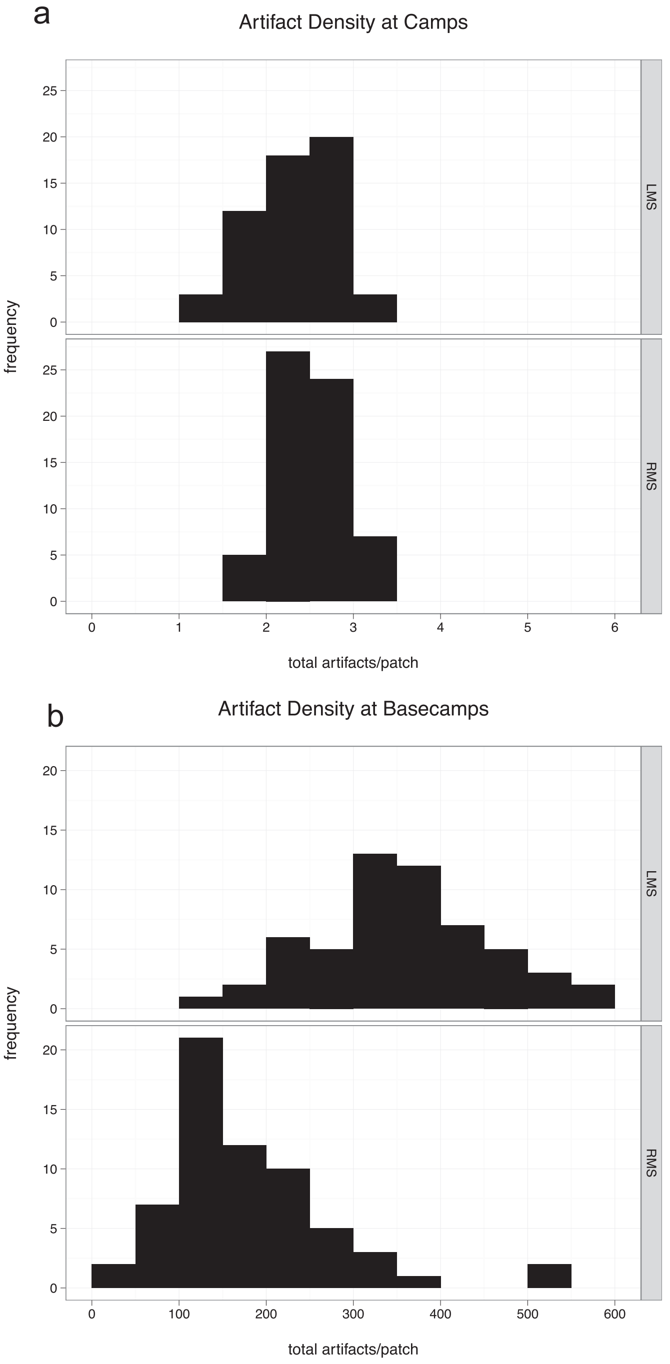


Fig. 11. Artifact density per camp of lithic assemblages that accumulated at RMS residential camps and LMS resource extraction camps (Fig. 11a), and at a single site that is sometimes occupied as a logistical base camp and other times as a residential camp (Fig. 11b). Note difference in *x*-axis scales for artifact density between 11a and 11b.

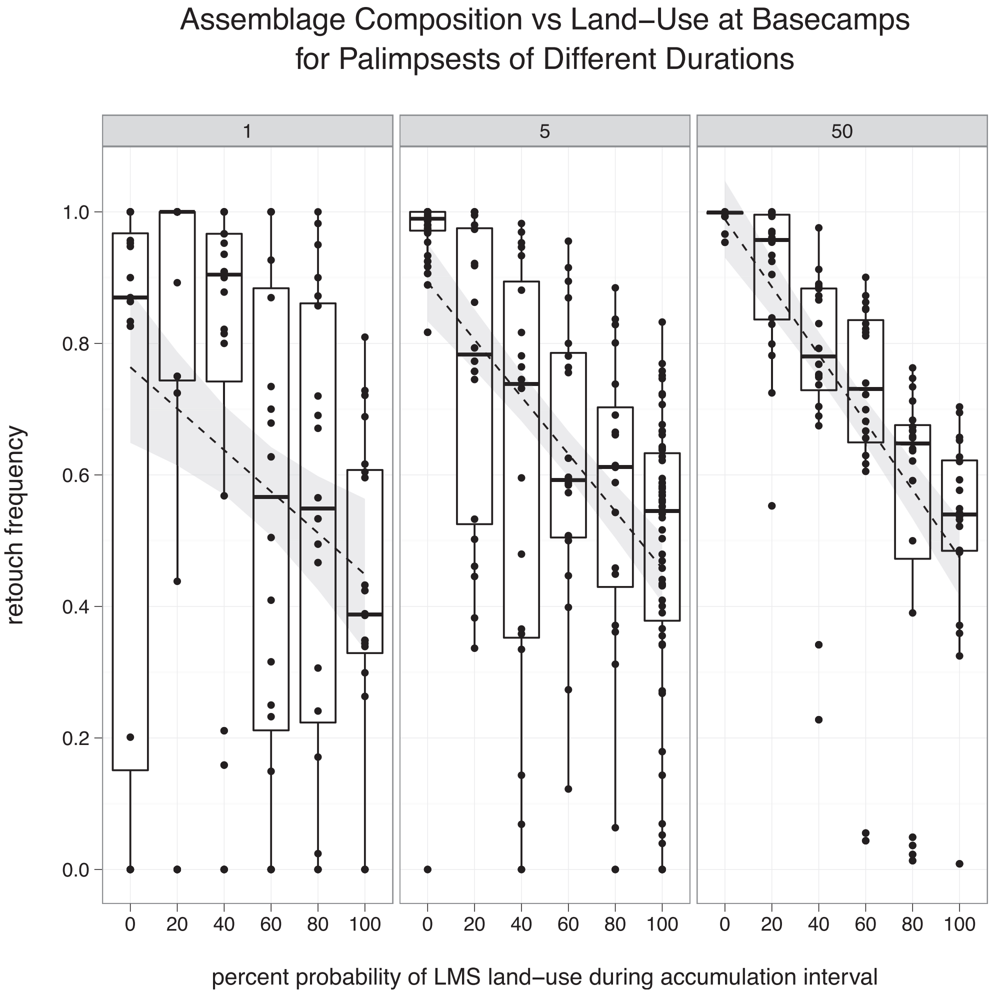


Fig. 12. Effects of lithic assemblages as palimpsests accumulated over different spans of multiple occupations on the relationship between retouched intensity and land-use strategy. Each dot represents a represents an assemblage that accumulated over a series of 1, 5, or 50 sequential model runs (i.e., occupational episodes) of 50 trips each. Dashed line and gray shading represent the regression and 95% confidence interval for retouched frequency vs. probability of employing LMS land-use.

treated in the literature as though they are single occupational episodes (see Dibble et al., 1997). Even when it is recognized that assemblages represent multiple occupations, there seems to be a general, if tacit, consensus that true 'snapshots' of the past are the ideal we strive for even if they are unattainable in many cases.

While the rare examples of single (or near-single) occupation sites clearly do provide unique glimpses into past lives (e.g., Cahen and Keeley, 1980), our experiments suggest that the occupational palimpsests that comprise the more normal archaeological record may in fact be better for studying the processes of social dynamics and culturally mediated behavioral response to changing social and biophysical environments than a collection of single-occupation snapshots. Climate change, for example, is a long term trend that cannot be seen in the many short-term fluctuations of temperature and precipitation. If human foraging behavior is tracking aspects of the environment sensitive to long-term climate change (rather than short-term weather), a sample of single-occupation snapshots is unlikely to show human response to such longer-term trends—especially given the small number of such snapshots actually available and their chronological ambiguity. That is, a series of time-averaged palimpsests, each spanning decades or even centuries, may better show trends of social and behavioral change than an equivalent number of single-occupation snapshots. Our experimental design provides an opportunity to compare the information potential of assemblages from single occupations with time-averaged palimpsests.

As noted above, one of the ways that we repeated model runs in our experiments was to aggregate results for a number of individual model runs. In most cases, we aggregated sets of five model runs. This is analogous to collecting for analysis palimpsest assemblages that accumulated over periods of five sequential occupational episodes. By varying the aggregation interval, we were able to compare results from palimpsests covering different time-spans. To compare with the five-occupational-episode palimpsests, we also conducted identical experiments with aggregation intervals of 1 episode (a single 'occupation') and 50 episodes (a long-term palimpsest). The results can be seen in Fig. 12. From single occupation to short-term palimpsest to long-term palimpsest the relationship between land-use strategy and retouched frequency becomes increasingly well defined; the overall trend is clearer and the 'noise' decreases. Correlations between retouched frequency and land-use also become stronger: $R = -0.29$ ($p = 0.001$) for a series of single occupations, $R = -0.60$ ($p << 0.001$) for five-occupation palimpsest assemblages, and $R = -0.70$ ($p << 0.001$) for fifty-occupation palimpsests. This implies that the archaeological record that we actually have may be considerably better for studying long-term cultural and social change than the record we often wish for (Bailey, 1983; Holdaway and Wandsnider, 2008, 2006; Smith et al., 2012).

5. Concluding thoughts

As with many other components of the archaeological record, lithic assemblages form as a result of complex, long-term interactions between diverse human socioecologies, and various phenomena in the biophysical world in which human actions play out. Actualistic experiments and ethnoarchaeological studies have been invaluable in identifying the effects of particular cultural and natural formation processes (Ahler, 1989; Amick and Mauldin, 1989; Andrefsky, 2009; Holdaway and Douglass, 2011; McCall, 2012). However, the complex socioecological dynamics that underlie the formation of the archaeological record in real-world, living societies make it impossible for an archaeologist to intuit accurately the effects of these multidimensional intersecting processes over long timespans. Moreover, because the record was formed over variable amounts of time in the past, there is no way to directly observe its creation and modification. While the literature is replete with narratives of how the record is formed, these narratives are largely untested and often untestable in the form presented. This raises serious concerns about how (or even whether) we can 'reverse' this process to make statements about the past from the archaeological record, nominally one of the central concerns of Americanist archaeology over the past 50 years.

Computational modeling does not resolve these issues. However, its bottom-up protocol provides a powerful tool to begin to disentangle the complex, time–transgressive, interactions among social and natural phenomena that created the archaeological record in transparent and quantitative ways that hitherto have been impossible. The approach we have taken here allows us to systematically evaluate the interactions and outcomes of a set of behavioral and environmental phenomena that are key to understanding the nature of archaeological lithic assemblages and that have been topics of discussion and debate for many years—and to do so in a transparent, quantitative, and replicable way. Our study has also led to new insights about phenomena that are not intuitively obvious from examining archaeological assemblages, but which emerge as singularly important if we are to use lithics to inform us about the past. These include the identification of new criteria for differentiating assemblages that accumulated in short-term residential camps and resource extraction camps from those associated with logistical base camps, and the informational value of palimpsests versus short-duration snapshots to understand long-term trends in human adaptation. Perhaps most importantly, the approach presented here produces explicit expectations that are testable against the empirical archaeological record.

We hope that others will be inspired to test our results and expand on our models to explore other dimensions of lithic assemblage formation. There remain important dimensions of the processes that form the lithic archaeological record to study, including the effects of differential raw material quality and post-depositional geomorphic processes that operate differentially in cave and open-air sites. Publishing model code—as we have done here—as well as reporting on the results of modeling is necessary for others to build on and evaluate this work. As computation assumes increasingly more important roles in science (including social science), it is critical that scientific computing be as transparent as other protocols. This means that code must be accessible for peer review and for creating new applications. But publishing code also requires that those who create models for scientific computing must be credited for their work to the same degree enjoyed by other research—cited by others who use that code and recognized by their academic or research institution. While computational modeling offers the potential to transform the way we use the archaeological record, our field and the institutions in which it is embedded must also transform in order for this new scientific approach to flourish.

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