interpreting lithic raw material variability in Middle Palaeolithic contexts: a modeling approach with applications to the Bau de l'Aubesier (Southeastern France)

Pop, C.M.

Chapter Five

Exploring home ranges and non-local procurement through a minimally realistic model of raw material management at the Bau de l'Aubesier

Lithic raw material resource management and group mobility at the French Middle Palaeolithic site of the Bau de l'Aubesier: Application of a minimally realistic agent-based model

Cornel M. Pop, Lucy Wilson, Constance L. Browne

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Authors: Cornel M. Pop, Lucy Wilson, Constance L. Browne

Abstract:

In this paper we explore the impact of residential mobility on archaeological raw material variability at the French Middle Palaeolithic site of the Bau de l'Aubesier. We do so in view of better understanding lithic resource selection and regional land use strategies employed by the hominins who discarded or abandoned lithics at the site between roughly 200ka and 100ka BP. To this end we develop a novel, minimally realistic agent-based model of lithic resource management and apply it to simulate processes resulting in raw material transfers at a regional scale (here, an area of ca. 100 x 100 km). We demonstrate that, in southeastern France at least, Neanderthals selectively targeted lithic resources based on an intimate knowledge of their availability over a large area, and excellent navigational skills. Our results also indicate that Neanderthals regularly exploited lithic raw materials from residential camps over areas that were at least as large as those seen with ethnographically documented hunter-gatherer populations, and that the combined territories frequented by individuals who at some point also resided at the Bau over their lifetimes likely cover an area that, although large, nevertheless encompasses only a portion of the study region. Finally, we show that, except perhaps in highly unusual circumstances, and contrary to what is often assumed, raw material provenance data is unlikely to be informative with regards to the extents of the home ranges used by discrete Neanderthal groups, or of the settlement strategies such groups may have employed within those territories.

Keywords: Minimally realistic model; lithic raw materials; Middle Palaeolithic; simulations; agent-based modeling; provisioning strategies; hominin land use

1. Introduction:

Neanderthals are the most extensively researched extinct hominin species, yet many questions remain about their lifeways and their strategies of landscape utilization. One avenue of inquiry into the latter that has long been considered important is provided by lithic provenance studies. Since the geographic origin of archaeologically exploited stone can often be pinpointed with reasonable accuracy and precision, through such studies we can, at a minimum, determine the areas over which Neanderthals transported lithic materials. The picture that has traditionally emerged from this type of investigation is one of relatively restricted procurement zones around sites (e.g., Féblot-Augustins, 1993; 2009) and a general willingness to exploit easily accessible stone resources even if of questionable quality (e.g., Eixea, 2018; Sykes, 2017; Doronicheva et al., 2016; Pop, 2013). Procurement over distances exceeding expected home range limits is often documented (e.g., Doronicheva et al. 2016; Adler et al. 2014; Slimak and Giraud 2007), but such distantly procured materials typically amount to a small portion of the overall assemblages in which they are found (but see, e.g., Spinapolice 2012), and the pathways through which they were incorporated into the archaeological record are seldom clear (e.g., Turq et al. 2013). Beyond this general pattern, however, to which there are in any case a relatively large number of exceptions, our understanding of how stone procurement fit within wider Neanderthal adaptive strategies at a regional level is in many instances quite limited. Provenance studies may inform us of which geological sources were actively exploited at a given time, but the subsequent task of determining why and under what conditions, or the degree to which their exploitation reflects broader patterns of landscape use, remains a substantial challenge.

The Middle Palaeolithic site of the Bau de l'Aubesier (hereinafter "the Bau"), located in the department of Vaucluse in southeastern France, presents one case where the drivers of lithic resource selection and procurement are exceptionally well understood. Yet even in this case many unknowns remain regarding the pathways through which lithics were incorporated into the archaeological layers as well as the broader regional strategies of landscape use that they reflect. In this paper we seek to clarify some of these aspects by incorporating regional group mobility into existing explanatory frameworks. We do so with the goal of better understanding one of the remarkable characteristics of this site, namely that it does not conform to the general pattern noted above for the European Middle Palaeolithic, as most stone resources were procured at greater than expected distances (likely 8-13km) from the Bau despite the availability, today at least, of high-quality flint nearby.

It is of course possible that such nearby flints were unavailable to the Neanderthals who inhabited the site, but this *unavailability hypothesis* is difficult to defend given the time span represented by the archaeological layers (ca. 100,000 years) and the fact that there is little evidence to suggest dramatic changes to the lithic landscape since the initial occupation of the site some 200,000 years ago. Additionally, many (ca. 120) seemingly unexploited raw material sources are found within the minimum procurement area represented by raw materials utilized at the site (Figure 2) so it is very likely that hominins would have at least occasionally stumbled across these seemingly unexploited sources over the course of a hundred millennia. An alternative to the *unavailability hypothesis* is that sources were not exploited simply because, from the perspective of a Neanderthal inhabiting the Bau, it would have made no sense to do so.

We explored this possibility in Chapter 4, where we proposed an explanatory framework that considered sources not only in terms of their intrinsic characteristics, such as the quality of the available materials and the extent over which they are exposed, but also in light of their relative placement within the network of sources accessible from the site. With this conceptually simple framework we were able to identify sources that should have been used (optimal procurement candidates) as well as sources that should not have been exploited by the site's inhabitants even if seemingly appealing when considered on their own. With this framework we were also able to account for most of the archaeological observations. A pending question, however, is whether this *optimal-candidate hypothesis* can hold - that is, whether it can still explain the complete avoidance of sources over a 100,000-year period - if we factor in residential mobility and the concomitant input of raw materials procured at other sites.

To answer this question, it is necessary to consider which sources should have been targeted under the proposed *optimal-candidate hypothesis* at *other* sites frequented by the inhabitants of the Bau. It is also necessary to consider the likelihood that raw materials procured at such other sites would be transported to, and discarded at, the Bau. Finally, we need to consider how many such materials we may expect to find at the site, not least because it will affect their likelihood of identification among the rest of the archaeological materials. Unfortunately, we do not know how Neanderthal groups actually moved within the region, nor do we have compatible raw material data for contemporaneous sites in the area to serve as a guide. However, previous work (Chapter 4) has indicated that we cannot reject the possibility that landscape utilization was relatively uniform, at least when considering the aggregated data for the entire sequence at the Bau, so we do have a useful starting point. This, coupled with the quality of the lithic provenance dataset available for the site and the available resource selection models, makes it possible to address these issues through a simulation approach.

In this paper we therefore aim to introduce, test, and apply a minimally realistic, behaviourally and spatially explicit model of regional mobility and lithic management for the region surrounding the Bau so as to thoroughly assess the viability of the *optimal-candidate hypothesis*. The model we propose tracks raw materials throughout their entire use lives and allows us to make *quantitative* predictions with regards to raw material variability (see Pop 2016) at hypothetical sites throughout the region, using simple yet rigorously defined behaviours and a minimalist set of assumptions. These predictions are based on a combination of two methods, namely: a) estimating probabilities of source exploitation for each hypothetical site location on the basis of local conditions (i.e., spatial configuration of sources) and selection criteria evidenced at the Bau, and b) simulations of post-procurement management and transport implemented through an agent-based approach. Using this combination of methods, which gives us the ability to trace potential pathways followed by materials likely to have *actually* been exploited in the past, we address the following basic questions:

1. What proportions of lithics procured while at other sites (hereinafter, LPOS) should we expect to find at the Bau given a reasonable range of behavioural parameters?
2. What proportion of materials transported from other sites (i.e., LPOS) can we expect to originate from sources that were also exploited from the Bau (i.e., seemingly local)?
3. To what degree is the simulated variability among the LPOS compatible with archaeologically observed raw material variability at the Bau?
4. Can incorporating group mobility help us better understand land-use strategies in the region?

Taken together, answers to these questions have the potential to not only clarify raw material utilization at the Bau and the Vaucluse more broadly, but also to address the more essential question of the degree to which lithic raw materials can be informative with regards to the scale and nature of human mobility within a region. As noted at the onset, lithic sourcing studies have generally been assumed to have high potential in this regard, but few systematic evaluations of this potential have been conducted to date (e.g., Brantingham, 2003; Pop, 2016). Moreover, the minimally realistic model introduced here can also serve as the basis for more complex future simulations for the region, and may of course be applied to other context as well – indeed, it should be applicable in any Middle Palaeolithic context where the distribution of lithic resources is well-known.

2. Background: The Middle Palaeolithic site of the Bau de l'Aubesier

The Bau de l'Aubesier is a large rockshelter located at the western border of the sub-alpine chain in the department of Vaucluse, southeastern France. Found in rugged terrain halfway down the gorge of the Nesque river (Figure 1), the Bau is strategically placed at the intersection of multiple types of ungulate home ranges (Fernandez 2001) and provides easy access to water as well as high-quality flint in an area where the former can be scarce. The region is rich in Middle Palaeolithic sites and widespread surface artifact scatters suggest a relatively continuous utilization, and plausibly habitation, of the landscape. Lithic raw material sources are also abundant and well-known, with 350 outcrops and secondary deposits systematically investigated and catalogued by Lucy Wilson over more than two decades of extensive research (Figure 2). Since the raw materials found at these are sometimes very similar, the sources have been grouped into 122 source areas, each consisting of 1 to 15 discrete sources and yielding distinct, archaeologically identifiable stone types. These sources constitute a lithic landscape that, although not identical to what would have been available at specific points in the past, is nevertheless representative of that exploited by the region's Neanderthal inhabitants. This is because the area was never glaciated and has remained relatively unchanged since the initial occupation of the Bau (see, for example, Wilson and Browne, 2014).

The site contains thick deposits – ca. 13 m towards the back of the rockshelter – which extend over more than 250m^2 (e.g., Lebel et al., 2001) and are very rich in both faunal remains and lithic materials. Indeed, although the Bau has only been partially excavated, at least 85,000 lithics (Texier, 2004; de Lumley-Woodyear, 1969) and over 2,700 ungulate remains, representing a minimum of 241 individuals (Fernandez, 2001; 2006), have been recovered from Middle Palaeolithic layers since the initial investigations by Franki Moulin in 1901-1903 (see Moulin, 1903; 1904). Several isolated deciduous and permanent Neanderthal teeth, two of which are carious, as well as a partial mandible with substantial pathologies (e.g., Lebel et al., 2001), have also been found at the site. With the exception of the topmost two layers, where some undiagnostic late Palaeolithic and Neolithic artifacts have been identified (e.g., Blackwell et al., 2000), the remainder of the sequence yielded Middle Palaeolithic materials. Most of the Middle Palaeolithic layers, deposited over some 100,000 years across the Middle and Upper Pleistocene (roughly 200 kya to 100 kya - e.g., Wilson and Browne, 2014 and references therein), are thought to represent palimpsests of coherent occupations amounting to more than incidental short-term stays (e.g., Wilson and Browne 2014). The faunal remains are the product of anthropic accumulation, with only a few traces of carnivore presence being noted (see, for example, Fernandez, 2006; 2001), and they point to strategic hunting and systematic butchering of several taxa at different times of the year. Although multiple species were targeted, and generally hunted when most vulnerable and abundant, horse and aurochs appear to have been favoured throughout the sequence (Fernandez, 2001).

Figure 1: View of the Bau de l'Aubesier rockshelter. The site as seen from the opposite side of the Nesque river gorge.

The lithic artifacts from the Bau, virtually all flint, have been classified as Typical Mousterian of Levallois facies (e.g., de Lumley-Woodyear, 1969; Wilson and Browne, 2014). The assemblages contain a large number of cores and manufacturing by-products pointing to substantial on-site reduction (see Texier, 2004; Carmignani et al., 2017; cf. de Lumley-Woodyear, 1969) as initially suggested by Moulin (1903). Cortical debitage is rare, however, and this has been interpreted as indicating partial processing at procurement locations (Texier 2004). There is also evidence for off-site discard, as Carmignani et al. (2017) report that, at least for the lower levels, refits are rare. In these same layers the authors report that raw materials, although procured from relatively distant sources (i.e., 8-13 km), are represented through all stages of lithic reduction (Carmignani et al., 2017).

While early analyses suggested techno-typological homogeneity across the upper deposits (e.g., Moulin, 1903; de Lumley-Woodyear, 1969), by the early 2000s it was already apparent that differences existed between the levels of the sequence. These are evidenced in the lithic components (e.g., Fernandez, 2001; see also Carmignani et al., 2017), possibly in hunting strategies (e.g., Fernandez and Legendre, 2003), and in raw material resource selection (Wilson and Browne, 2014). Notwithstanding what appear to be diachronic trends, however, recent work has shown that to evaluate macro-trends (e.g., resource avoidance) considering whole-sequence composition is useful (Chapter 4; Wilson and Browne, 2014; see also sections 4.1 and 4.3 below).

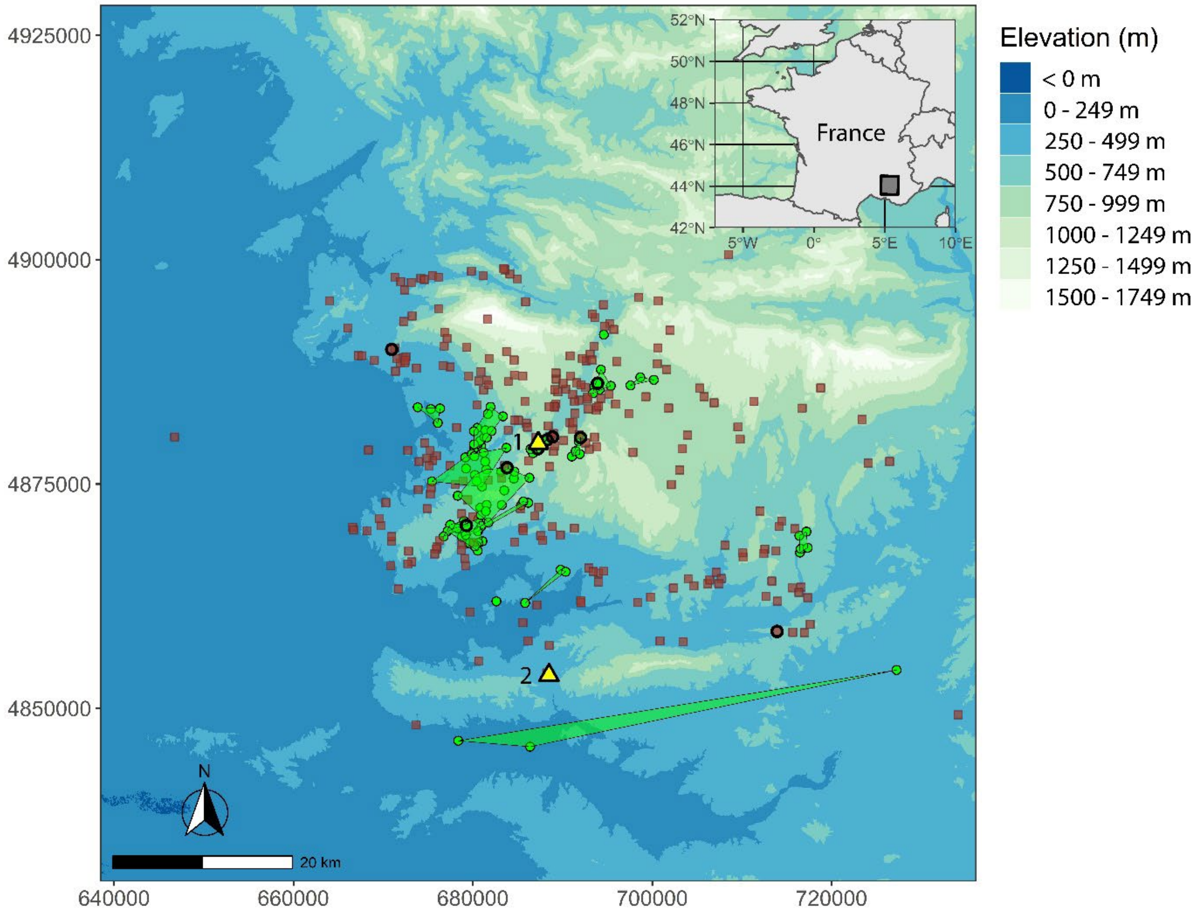

Figure 2: **The study region and the distribution of lithic resources.** The study region is defined on the basis of the 350 catalogued sources, shown here as green circles if they yield raw material types which are archaeologically represented at the Bau, and red squares if no evidence of archaeological exploitation is preserved at the site. Convex hulls enclosing sources belonging to specific, archaeologically represented source areas are shown as green polygons. The locations of the Bau (1) and of another Middle Palaeolithic site (2 – La Combette) for which relatively compatible raw material provenance data exist are indicated by yellow triangles. Hollow circles indicate sources considered optimal for exploitation from the perspective of hominins inhabiting the Bau, according to the method proposed in Chapter 4. Coordinates are given in UTM (zone 31N).

3. Towards a minimally realistic model (MRM) of Middle Palaeolithic lithic raw material management

3.1. *Why minimal realism?*

As the term is used here (c.f. Plagányi, 2007), a minimally realistic model (hereafter MRM) is one that seeks to bridge the gap between abstract neutral models (*sensu* Brantingham, 2003) and models which aim to emulate the past (*sensu* Premo, 2010). On the one hand, highly abstract models are not only difficult to interpret in terms of real-world relevance or applicability, even for the modeller (see Pop, 2016), but they also run the risk of unwittingly simulating impossible realities. On the other hand, attempts to re-create the past result in overly complex models that can be just as difficult to interpret, can lead to high scientific uncertainty (e.g., Wobst, 2010) and, as noted by Premo (2010), invariably have to contend with the problem of equifinality. To solve the problem of optimal complexity (see Lake, 2015 for a discussion), we follow Premo's (2010) general advice of including only the minimum required to address a given research question, with one simple but important caveat: we suggest that a minimally realistic model should *only* employ explicitly defined, real, and relevant units (e.g., grams of stone, actual coordinates or areas instead of abstract grid 'cells'). This additional rule, which helps ensure minimal consistency with reality, may require the inclusion of processes or parameters that, while not directly related to the research question (cf. Premo, 2010), are nevertheless necessary to develop a coherent model that accounts for the scale and nature of the chosen units.

In effect, then, an MRM seeks to be the simplest model (i.e., with the fewest variables or processes) that can generate patterns which are quantitatively comparable and compatible with archaeological observations (i.e., fit within basic observed constraints such as assemblage size) in the absence of a given mechanism (here selective land use and variable resource selection criteria), using real-world units (e.g., hours of travel), and postulating logically consistent behaviours and parameter settings that, based on our current state of knowledge, have a reasonable *a priori* probability of having been true in the target temporal and geographic context (cf. Brantingham, 2003; see Pop, 2016), and given the nature of the employed units as well as the chosen modelling scale. Therefore, as envisioned here, an MRM is necessarily both spatially and behaviourally explicit.

It should be stressed, however, that the goal of an MRM is *not* to replicate archaeological assemblages, but rather to produce output which is not fundamentally incompatible with archaeological observations (e.g., assemblages that are orders of magnitude smaller or bigger when using realistic parameters). In fact, we suggest an MRM should be employed to explore aspects of the record which are, today at least, unknowable (e.g., actual mobility at a regional scale), and advocate using more mainstream modeling approaches to understand aspects of the record which can, in fact, be known (e.g., variables influencing resource selection at a specific site – e.g., Browne and Wilson 2011; Wilson and Browne 2014; Wilson et al. 2018; see also Chapter 4).

3.2. *Model outline*

An outline of our model is shown in Figure 3, and a discussion of the chosen units, scales, and associated mechanics is presented in the next section. In essence, the model simulates a single autonomous agent, representing the residential group of an individual's descent line, which regularly moves camp within a region as resources are depleted. The agent's goal is to maintain a predictable raw material supply at camp and fully provisioned personal toolkits. The agent, aware at any time of its own position as well as the location and characteristics of nearby lithic resources, and able to efficiently navigate the landscape, achieves these goals by first identifying raw material sources that are optimal for exploitation (given their spatial configuration relative to the camp and the local topography) and then acquiring materials from one of these optimal sources at random according to empirically derived probabilities. Acquired materials are taken to camp and are used to replenish personal toolkits whenever needed, as materials are lost, discarded, or simply abandoned by agents in the course of daily activities both at camps and while engaged in off-site activities. For instance, some of the provisioned materials are abandoned during residential moves, which in effect results in the creation of small caches throughout the region that are likely to be available upon revisits.

The simulations start with the agent being placed at a random camp in the region, which is immediately provisioned with raw materials from a nearby source, and they end when the specified number of time steps is reached, since the model is discrete. The model does not specify foraging behaviours, nor the nature of processing activities performed at or while away from camp. It also assumes, as a baseline, both a uniform utilization of the landscape and resource selection criteria that remain constant at all locations. It further assumes that lithic sources, as well as the habitability of the given region, remained unchanged throughout the simulated period. Finally, the model does not specify any mechanism for learning – as a multi-generational group, the agent is assumed to have perfect (*collective*) knowledge of the topography and fixed resources in the region it inhabits, and to be capable of efficient allocentric navigation as indicated by previous work (Chapter 4; cf. Lake, 2015). It should be noted that, while the application presented here is context specific (i.e., it uses terrain, source, and assemblage data from a specific region), the model should be generally applicable to Middle Palaeolithic contexts.

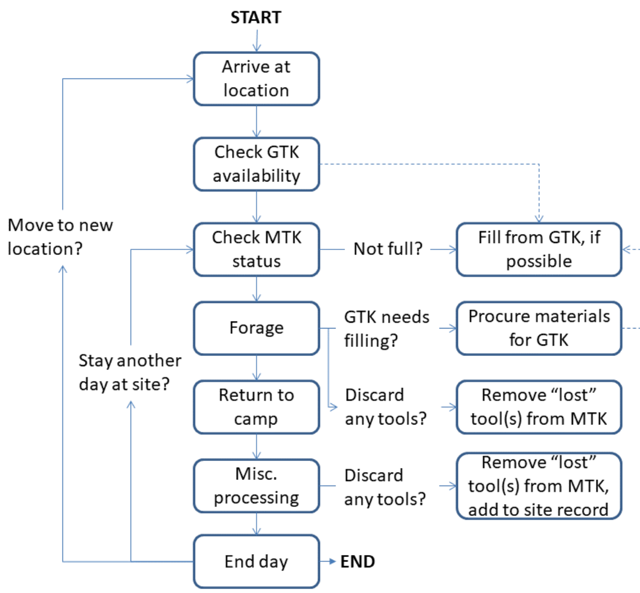

***Figure 3**: **Outline of the proposed minimally realistic model**. GTK refers to collective toolkits, that is materials available for group use at a given residential camp, while MTK refers to personal toolkits. In the context of the simulations discussed in this paper, only MTK items are carried between camps, and the number of days stayed at a camp is pre-determined upon arrival based on specified minima and maxima. Solid lines indicate steps taken by the agent, while dashed lines indicate steps that affect the refilling of personal toolkits from collective toolkits.*

3.3. *Elements of an MRM: Units and Scales*

3.3.1 Temporal scale

We propose simulating behaviours at a resolution or time-step equivalent to one day. Days, unlike other time units such as weeks or hours, represent full natural cycles at a scale at which human mobility, resource procurement, and lithic discard can be meaningfully studied from an individual or residential group perspective. Using larger cyclical periods (e.g., months, years), while useful for modelling larger scale phenomena (e.g., demographic changes), would result in what we would consider to be too much averaging of individual behaviours and would therefore be difficult to model in a behaviourally explicit way (i.e., how much is discarded, when, by whom, and procured where).

As with any scale of analysis, modelling daily behaviour under minimally realistic conditions does pose some challenges. Daylight, for example, varies throughout the year, placing constraints on foraging and travel, and so does the accessibility and distribution of resources. As Kelly (1995:

99) pointed out, “no environment is constant from season to season or from year to year”. On the other hand, daylight availability is unlikely to have been a problem throughout most of the Neanderthal range because the number of foraging hours, in recent hunter-gatherer populations at least (see Kelly, 1995), is limited and generally less than the minimum observable during the winter solstice (e.g., 8.9 hours observable today at the Bau – NRC Canada). With regards to seasonal or yearly changes in the availability of the only resource incorporated into our model, that is lithic raw materials, we suggest that making assumptions as to which resources would have been available, when, and in what quantities seems at least as problematic as assuming resources were generally accessible.

3.3.2 Agent

We envision a simple model which tracks the actions of a single agent which, conceptually, represents a small group of individuals. Modeling individuals is undesirable due to theoretical as well as practical considerations. First, humans as more or less fully individual agents, rather than relational entities which are part of kinship networks that strongly shape their decision-making processes, appears to be a recent construct (e.g., Henrich et al., 2010). Individuals are also unstable over time, in the sense that their mobility and the types of activity they engage in change throughout life. Furthermore, there are important differences between individuals (e.g., gender-specific activities) which may have an impact on factors such as mobility (e.g., Kelly, 1995), and modelling individuals would therefore require making a series of assumptions about the nature of such differences or, conversely, modeling the spatial behaviours of an ‘average’ individual who could never have existed. Second, the computational resources that would be required to model the effects of inter- and intra-individual variability (e.g., sex, age) over tens of thousands of years while simulating daily activities would be substantially higher.

On the other hand, we choose not to explicitly model “bands” (or other higher-level social units) because the concept is ill-defined in the first place (e.g., Binford, 2006; Kelly, 1995), and because “bands” are often fluid in group composition (e.g., Turnbull, 1987; Rai, 1982). Since resource utilization/processing generally occurs and is decided on at a family level (Kelly, 1995), and it is the spatial traces of these processes that we aim to simulate, we choose instead to define agents as simply groups serially linked through time by at least one common member. That is, we model the behaviours of the groups to which offspring of a common ancestor, along any branch of the descent line, belonged. We therefore make only minimal assumptions with regards to the nature of such groups (e.g., their range of sizes – see below), which may or may not correspond to bands, to individual families, or to other types of social units.

We argue that it is not unreasonable (i.e., it is minimally realistic) to model such groups over an extremely long timespan insofar it is acknowledged that their composition will vary and that they do not represent a coherent social unit across the entire modeled timeframe. Modeling such a “group” is justified because, unless the founding local population went extinct during the considered time frame, descent should always be traceable, in at least one case, through the entire period of interest. While our model assumes that the tracked lineage is always represented within a given study area, given the stochastic nature of the modeled processes (see below) exiting and then re-entering the area would only have a marginal effect, and this assumption should not, therefore, pose a problem. Moreover, whether multiple noninteractive or minimally interactive groups are considered or not, the resulting patterns are expected to be identical, so long as such groups are engaged in the same behaviours. Unless diachronic behavioural trends are sufficiently well understood for a target region so as to be reliably operationalized in the context of an MRM, we suggest assuming that baseline group behaviours were constant, and that agent choices can be adequately described as stochastic over the timescales involved.

3.3.3 Sites

We suggest defining agent mobility and procurement behaviours on the basis of randomly placed sites or camps, conceptualized as preferred (strictly in the sense of fulfilling basic needs) landscape locations used by the agents as places of residence for a variable number of days (see below). We acknowledge that camp locations were very likely strategically rather than randomly selected – this certainly appears to have been the case with the Bau (see Section 4) – but pending a better understanding of site chronology and placement in key regions we consider random distribution of suitable camping locations to be a useful starting point, so long as it is acknowledged as such. Placing sites randomly across the landscape in the context of each individual simulation has the advantage of accounting, at least partially, for the variability that may result from cyclical factors which are not explicitly considered in our model, such as seasonal fluctuations in resources or climatic variations over decades or millennia.

We make no formal distinction between functionally different site types, although various such types have been proposed to date for the Middle Palaeolithic (see, for example, Burke's, 2006 review; Daujeard et al., 2016). We do however account for a range of occupation types by allowing the agent (i.e., group) to select the length of habitation for every visit at every camp given simulation-specific minima and maxima. In reality, occupation length should reflect a complex mix of variables, such as availability of resources, return rates, and so on, but about these we make no assumptions, simply acknowledging that they will vary through time and from site to site. While the modeled behaviours remain the same regardless of the length of occupation, actions that would be expected to leave a clear "residential" signal, such as an abundance of locally procured materials and manufacturing waste, would occur much more rarely at sites inhabited by the agents for short periods than would be the case with long term occupations.

3.3.4 Mobility

Our model considers mobility at the group level in terms of "residential" moves between sites (see Turq et al., 2013), but we also factor in, albeit implicitly, the foraging activities of individual group members (see below – procurement). Since the frequency and length of residential moves may have depended on seasonal factors, we define the lengths of stay in terms of a range rather than a fixed value, as noted above. At the end of each stay at a site the agent (i.e., group) relocates to a new camp selected from the list of suitable locations available within a given simulation. This selection is limited to sites within a specified travel time interval from the agent's current position, and is random, with each site within the interval having an equal probability of being selected. The chosen time interval corresponds, minimally, to twice the maximum time individuals might have been willing to spend travelling, on a regular basis, to reach desirable resources from a given camp, a figure which, ethnographically at least, appears

to be rather constant (Kelly, 1995). The logic is simple and is based on Kelly's (1995) central place foraging model: once it becomes undesirable to keep exploiting resources available within the given foraging radius, camps are relocated, generally to a place where there will be no overlap with the previous site's exploitation territory, and which is not unnecessarily far.
The mobility condition defined here does allow agents to visit one location, and then immediately return to the previous camp, which is not something that would be expected if residential mobility is assumed to be primarily due to resource depletion. However, the probability of such occurrence is very low, given the relatively large number of viable candidates typically available with every relocation episode.

3.3.5 Toolkits

We define 'toolkits' at two levels: 1) a 'mobile toolkit' (hereinafter, MTK), which consists of personal gear (*sensu* Binford 1979), used both on and off-site, which is carried by tool users (a subset of the 'agent') whenever they are away from a camp (i.e., either during normal foraging activities, or during residential moves), and 2) a collective or group 'toolkit' (hereinafter, GTK), which consists of usable lithic materials available for the benefit of the group at residential sites. We make no assumptions about the technological or typological nature of the materials available in either the mobile or group toolkits, but we do assume that MTK elements represent coherent items (e.g., an actual flake rather than a group of unspecified artifacts), and that to a lesser extent the same is true of GTK items, which may be conceptualized as representing mainly individual cores or nodules.

3.3.6 Procurement

In the context of our model the tool users within the group are assumed to forage for unspecified resources around the sites, carrying with them raw material items of an unspecified techno-typological type that are occasionally discarded or lost while away from camp. Missing items are fully replaced on a daily basis with materials procured from the collective toolkit (GTK), individual MTK element sizes being determined prior to the transfer and drawn at random from an empirically derived distribution (see Methods), under the assumption that up to a specific percentage (see Discard/Waste below) of a GTK element may be collected as a single item (i.e., that the GTK element does not represent many small items). Each raw material type present in the GTK is given an equal chance of being selected provided that the needed quantities are present, under the assumption that any task-specific functional differences would be reflected in corresponding differences in the likelihood of the materials actually being collected and transported to the site. Moreover, in keeping with the goals of an MRM, we assume there were no biases in size selection by raw material type.

Agents also strive to maintain a predictable raw material supply at residential camps, collecting materials when needed (i.e., when the supply at camp is low). Unlike mobile toolkits, however, the collective toolkit is not always refilled, so as to reflect the substantial differences in required effort and to allow for the potential of alternative foraging priorities. When an adequate supply existed at a camp, for instance, time is likely to have been preferentially allocated to other tasks, while at times of very low GTK supply, procuring materials from sources in the area may well have been vital. Consequently, we set the likelihood of procurement within the course of any given day to be inversely proportional to the quantities available in the collective toolkit, whose maximum size is fixed in the context of individual simulations.

During procurement events materials required to fully replenish the collective toolkit, up to a set maximum (see section 4.3.1 below), are collected by an individual or foraging sub-group of the 'agent' from a single source. This source is selected from amongst those deemed viable for exploitation at a given camp according to the method proposed in Chapter 4. Our model does not define a hard distance or time-travel limit for lithic procurement around a camp, thus leaving open the possibility that some resources were procured through logistic trips *sensu* Binford (1979), during longer stays. However, given the abundance of lithic sources in the study area (see Figure 2), our baseline assumption is that, as has been suggested for similar contexts (e.g., Duke and Steele, 2010) such logistic trips would have been rare. We chose to model procurement from a single source at a time because such a strategy would have required only minimal coordination abilities (i.e., selecting an individual or sub-group responsible for procurement, when needed).

The overall provisioning strategy stipulated by our model is similar to Kuhn's (1995) and is based on similar assumptions (e.g., that most manufacturing and processing occurred at residential sites – see also Kelly 1995), but differs from the latter in some important aspects. First, we make no assumptions regarding the depth of planning reflected in provisioning of places versus provisioning of individuals. For example, our model does not assume that "[t]he strategy of provisioning of places […] requires some knowledge of both the timing and the probable location of future needs" (Kuhn, 1995: 23); rather, in our model the provisioning of residential camps (i.e., replenishment of the GTK) is simply a question of estimating how much material is more than enough. Second, our model makes no assumptions about the technological character of the transported materials. Finally, we do not assume that either the frequency of residential moves, or the duration of stays, is in any way strategically related to the provisioning of places or individuals (cf. Kuhn, 1995).

Our model of procurement does, however, make several important assumptions, including:

1) We assume replenishing toolkits in the course of daily foraging activities, upon chance encounters with good-enough sources for instance, would have been at best a minor component of the overall provisioning strategy. Violations of this assumption are incompatible with our identification of viable sources at the simulated camps.
2) We assume that the distribution of artifact sizes at a benchmark site, and consequently the distribution parameters employed here to estimate MTK element sizes (see Methods), is representative not only of the sizes of mobile toolkits carried by hominins while passing through said site, but also of their mobile toolkits at other sites. This assumption may be problematic (see Pop, 2016), but we suggest it still represents the best and most realistic way of estimating MTK element sizes given our current state of knowledge, and its reliability can in any case be assessed by examining discarded element counts.
3) We assume that the lithic resource selection criteria identified at the Bau are very similar to those at other camps. Differences would be expected to strongly affect the identification of viable sources across the landscape. We note that preliminary results of

a blind application of the resource selection model developed at the Bau to another site, La Combette, strongly suggest that this assumption is valid, since a moderate-to-strong and statistically significant correlation between predicted selection probabilities and observed raw material frequencies can be observed (see SOM 1).

4) An important assumption core to our identification of viable raw material sources at simulated camps (see Methods), which is nevertheless based on previous archaeological (Chapter 4) as well as ethnographic (e.g., Kelly, 1995) insight, is that of complete *group*-level knowledge of the lithic resources around camps.

3.3.7 Transport

Our model can accommodate two mechanisms for raw material transfers between camps, namely as regular elements of mobile toolkits (MTK) or as relocated collective toolkits (GTK) carried from one camp to the next. In the former case, from the perspective of raw material management, residential moves would be no different from other daily activities. On the other hand, collective toolkits may be expected to be at least partially transferred in the course of residential moves if the availability of materials at the target camp is unpredictable, and/or if the cost of resupplying said camp with suitable materials is expected to be high. In the context of an MRM, modelling relative risk (e.g., given position in the landscape), with concomitant assumptions regarding planning depth, seems undesirable, and we argue two simple scenarios should be favoured instead: agents should either transplant a fixed portion of the collective toolkits (<100% to provide a mechanism for the abandonment of non-exhausted items), assuming no information about the target camp, or carry nothing and make do with what is available in mobile toolkits. In this paper only this second mechanism is considered.

3.3.8 Discard

In our model there are multiple pathways for artifacts to enter the archaeological record. First, each element of the agent's personal gear (MTK) has an equal daily probability of being discarded and an associated likelihood of the discard event occurring either off-site (e.g., while foraging) or on-site. Personal gear elements discarded while at a camp, perhaps as part of regular maintenance tasks, enter the archaeological record directly, and are assumed to have never again been used as part of an MTK. This does not pre-empt the possibility that such discarded elements may have been recycled for on-site tasks, but we do assume no further reduction took place.

A second pathway consists of waste. Unspecified by-products of material transfer from collective to mobile toolkits (i.e., personal gear) thus enter the archaeological record directly during each MTK resupply event, amounting to a fixed percentage of the procured MTK element's mass. This is taken here to represent an average, and need not correspond to what is generated during a single event – in other words, this figure may include, conceptually, waste generated after a tool has been produced in the course of maintaining it while on-site. We make no further assumptions regarding this waste, and as such we make no attempt to specify the number of pieces it represents, or their characteristics.

A third and final pathway consists of sedimentation, which applies to the collective toolkits (GTK). We consider sedimentation in the context of an MRM because it is clear that in many contexts materials entered the archaeological record before being fully exhausted, and the size of many assemblages relative to the depositional time they represent suggests lengthy periods between revisits (see Methods below), enough for at least some 'abandoned' GTK items to have been covered by sediments. The inclusion of such a 'sedimentation' process is particularly relevant to instances where only mobile toolkit elements are transferred between camps (see above), since they provide a realistic (and here only) mechanism for the incorporation of non-exhausted elements into the archaeological record. In line with an MRM's goal of simplicity, each GTK item is considered to have had an equal daily chance of sedimentation through some process that would render parts of it, or all of it, invisible or inaccessible (e.g., a roof fall). To simplify the model, and since a GTK item may technically represent one or more rocks collected together (i.e., at a specific time) from a given source, the actual mass of the material that enters the simulated record is selected at random (uniform) from a GTK item's total mass. We acknowledge that this model of discard does not explicitly account for tools meant exclusively for on-site processing.

4. Methods and Data

We implemented our minimally realistic model using the Anaconda distribution of the Python language (v3.6.4) and ran a total of 320 simulations, or 10 per parameter combination (see Table 1), as detailed below. All GIS operations were scripted in Microsoft R Open (v3.5.1, R Core Team, 2018) and conducted in GRASS (v7.4.0, GRASS Development Team, 2018) using open-source R packages that included raster (Hijmans, 2017) and rgdal (Bivand et al., 2018). R was also used to process and analyze the simulation outputs. In order to ensure the reproducibility of our results, the random number generator was seeded with CMP's birthday or a variant thereof in all scripts that used it.

4.1. *GIS data and processing*

Our simulations used 3 arc-second (~90 m), void-filled SRTM (v4.1) digital elevation models (DEMs) provided by CIAT (Jarvis et al., 2008), which we processed and clipped to the region of interest (43°N to 45°N and 4°E to 6°E) as described elsewhere (Chapter 4). Over this area we placed 144,400 (380 x 380) uniformly distributed point features, ca. 257 m apart along a N/S or E/W axis and representing potential camping locations, and projected the known coordinates of two archaeological sites (the Bau and La Combette) as well as previously documented (e.g., Wilson and Browne, 2014) raw material sources. We did not consider any other landscape features (e.g., rivers, vegetation cover) except slope, as we filtered out inaccessible areas with slope values greater than 60% (see Chapter 4 for details).

We computed travel times (to and from) between all camps and raw material sources using DEM-derived anisotropic least-cost maps generated in GRASS with the r.walk module, employing a maximum cost value of six hours and default slope and cost parameters (see Chapter 4 for further details). We then filtered out potential camps located at more than three hours from the nearest raw material source, so as to simplify calculations, and computed travel times between each of the remaining 86,371 (i.e., $86{,}371^2$ minimum-cost paths) using the same method. This enabled us to filter out neighbours suitable for residential moves in the context of individual simulations (see below and section 3.3.4).

Source exploitation probabilities were pre-computed from the perspective of each potential camp location using a method first applied at the Bau in Chapter 4. In essence, the approach involves performing a cost-benefit analysis for each source in light of available alternatives and filtering out raw material sources that are identified as sub-optimal for exploitation. This requires evaluating the cost (here, time) of travelling between sources on the way to a given camp and considering this effort in light of the relative benefits (e.g., raw material quality) afforded by the alternative. With a small subset of optimal alternatives thus identified, we calculated their individual probabilities of exploitation by applying the logistic model derived from the Bau assemblage (see Chapter 4), under the assumption that resource selection remained stable across the region. With regards to this assumption it should be noted that the selection signal at the Bau represents the average observed over some 100,000 years, so it should capture fundamental aspects that may reasonably be expected to apply to other sites as well. As already noted above (section 3.3.6), we tested whether this is indeed the case by comparing source selection probabilities predicted for a different site, La Combette, against archaeological observations (see SOM 1).

To minimize model complexity and improve efficiency, we pre-selected a fixed number (see section 4.3.1) of potential camp locations for each simulation, drawing these at random (uniform) from the total of ca. 86,000 available overall, and always adding the target archaeological site – the Bau. For each we created a list of other included camps that were viable neighbours for the next residential move (see 4.3.1) and of exploitation probabilities for sources worth exploiting, and these data were pre-allocated for individual simulations.

4.2. *Archaeological data:*

We use previously published provenance data on 15,674 lithics from the Bau (e.g., Wilson and Browne, 2014), procured from a minimum of 17 and a probable maximum of 101 sources in the region (i.e., 17 source areas – see section 2). These lithics come from more than 11 layers at the site spanning approximately 100,000 years of deposition (see section 2) and represent all elements with an identifiable raw material type from a total of 40,770 examined pieces, the rest of which were too altered by patination or burning to allow for a reliable characterization. We also use currently unpublished data on the mass of 5,338 individually measured lithics from the Bau, amounting to ca. 86 kg, to empirically estimate the mass distribution of simulated mobile toolkit (MTK) elements. We achieve this by fitting a continuous Weibull distribution, shown to successfully model artifact size distributions of the kind considered here (see Lin et al. 2016 and references therein), and employing the resulting shape and scale parameters to draw MTK element sizes at random during procurement episodes.

4.3. *Operationalizing the MRM*

The MRM proposed above was implemented according to the flowchart described in section 3.2 and with the help of a custom simulation scheduler available at http://github.com/cornelmpop/sim_dispatcher. To capture the range of variability that may be expected given the random nature of the modelled processes and the uncertainties inherent in estimating past behaviours, we used extreme but realistic ranges instead of fixed values for many of our parameter settings, running 10 simulations of all possible minima/maxima combinations. As noted above, each simulation used a pre-allocated subset of the uniformly placed hypothetical camps, and each used a random seed based on CMP's birthday and the simulation's unique ID. Taken together, and given the stochastic nature of the modelled processes, the combined results of individual fixed-parameter simulations should also cover temporal fluctuations in said parameters (i.e., actual variations in group size through time), provided that these remained at all times within the defined ranges. This is true even if strong directional changes are archaeologically documented (see section 2), although of course in such cases the measure of centrality in the simulated distributions would be misleading. It must also be noted that the raw material provisioning strategy implemented and tested here is based on exclusively direct (i.e., from the camp) procurement of collective toolkit (GTK) elements (see 3.6).

As implemented here, the model individually tracks multiple sources of archaeological accumulation at specified camps (e.g., the Bau), namely: a) mobile elements discarded on site, b) waste associated with the transfer of material from the collective toolkit to mobile toolkits, and c) collective toolkit materials buried while the agent is away from a camp (see section 3.3). For each of these we record the geographic source of the raw materials, their original place and time of procurement, and their mass (in grams). Items discarded by the agent off-site are not tracked, and elements in the waste or sedimentation data represent events rather than individual pieces – in other words, only the association between mass and raw material type can be explored in these records.

4.3.1. Setting parameters

The model parameter ranges were set based on published literature and fine-tuned through a model calibration procedure described below. Within individual simulations these parameters are either set to a constant value (e.g., group sizes, or the probability of daily discard), or they are randomly selected when needed based on a set of circumstance-specific rules.

4.3.1.1. Baseline parameter ranges:

The length of the simulations was set to 100,000 years, so as to cover the depositional history of the Middle Palaeolithic layers at the Bau. Over this time span we modelled the daily behaviours of groups ranging in size from 5 to 28 individuals. The lower limit of this range corresponds to perhaps two adults and three children, assuming an interbirth interval of ca. 3 years as suggested by the evidence from El Sidrón (Lalueza-Fox et al. 2011; see also Nava et al. 2020). We consider this to be a highly extreme but nevertheless minimally realistic estimate for the size of the residential groups which a Neanderthal may have, at any one time, been a part of. The higher limit is also more extreme than commonly suggested (e.g. Lalueza-Fox et al., 2011; Vallverdu et al., 2010; Burke, 2006; Daujeard and Moncel, 2010; Churchill, 2014) and is based on Hayden's (2012) calculations. For the sake of reducing the number of simulations needed, we set the number of 'productive' individuals as a fixed percentage of these groups, namely 30%, rounding to the nearest integer value. The percentage was chosen to represent a situation with few adults and a large number of children, as suggested by the recent findings at Le Rozele (Duveau et al., 2019), and the resulting figure corresponds to the number of individuals envisioned to carry mobile toolkits.

The number of consecutive days the agent spends at a camp is, unlike other parameters, defined using ranges (see 2.2.3), set here to 1-6 and 15-90 days. On each relocation the agent selects the number of days to be spent at the new camp at random, with each value within the specified range having an equal probability of selection. The lower range reflects an extremely mobile groups, in line with Verpoorte's (2006) suggestion regarding the Neanderthal record, while the latter translates to an average of ca. 7 residential moves per year which falls more in line with ethnographically documented hunter-gatherer cases, for which Marlowe (2005) reports a median of 5. Both group sizes and residential moves are thus shifted with respect to modern hunter-gatherer populations, with the minima extending beyond their observed range and the maxima approaching the center of the documented distributions (see Marlowe, 2005).

We set the number of mobile toolkit elements carried by individuals to a minimum of 3 and a maximum of 9. Given a mean mass of 16 g (see section 4.2), and a turnover corresponding to an average of one item every 10 days, these figures would result in a consumption of ca. 111 to 333 tools per year, or a minimum of 1.8 to 5.3 kg per person. These are in line with, if not exactly equal to, estimates provided by Luedtke (1976) based on ethnographic cases, and the minimum would also cover the three different classes of personal gear elements documented by Binford (1979) with the Nunamiut. The maximum quantity of materials procured by foraging individuals or groups is set to between 5 and 15 kg per event, a range being used here mostly to estimate the impact of this variable on the overall output, while the actual amount procured is based on the availability of materials in the collective toolkit (see 2.2.5). These estimates are based loosely on: a) the assumption that special purpose procurement trips would probably have been rare (see 3.5), b) the observation that sources with large rocks (19-35 cm) were preferentially targeted at the Bau (e.g., Wilson and Browne, 2014) and that, at least in some cases, refits of nodules exceeding 9 kg are documented (e.g., at Maastrich-Belvedere, see Veerporte et al. 2016), and c) consideration of other parameters (e.g., raw material needed per individual) which would have made situations of inadequate supply requiring immediate procurement of larger packages unlikely.

Sedimentation rates were estimated from the characteristics of the Bau where, based on the available dates, approximately 6-7 m of sediments were deposited over the course of some 100 millennia, corresponding to an average rate of roughly one centimeter per 143–167 years. We acknowledge that this is a very rough estimate, and that sedimentation at other camps likely occurred at different rates, but currently we have no better basis for estimating sedimentation at random camp locations. At these rates we could reasonably expect that most if not all of a collective toolkit would be covered by sediment every 1500 years or so (i.e., 10 cm), but also that a substantial amount of the larger pieces (e.g., cores) would still be visible after ca. 800 years (i.e., ~5 cm of sediment). This suggests that, even envisioning extreme delays between site revisits, leaving collective toolkits behind during residential moves, as insurance or perhaps passive gear *sensu* Binford (1979), would have resulted in low-cost, predictable supplies throughout the region, with losses due to sedimentation being a minor concern. Under these conditions the size of the collective toolkit is not a major concern – after the initial cost of fully provisioning a camp, which in the context of 100,000 years of habitation is negligible, the cost of resupplying it based on need should remain constant. Consequently, we set the collective toolkit's size to an arbitrarily chosen value of 20 kg, and sedimentation probabilities to 1 per 1,000 years for every GTK item.

4.3.1.2. <u>Calibration of model parameters</u>*:*

As the model is defined here, the average quantity of personal gear produced and discarded at a site, which ultimately governs the overall size of the assemblage, can be estimated as the product of the length of habitation, in days (D), the number of productive group members (P) who carry mobile toolkits, the quantity of items carried by each of these (MU_p), and the probability each item of personal gear has of being discarded on a given day (M_d). Multiplying the resulting value by the probability of items being discarded on site (M_r) provides an estimate of the average number of mobile toolkit items to be found in a simulated assemblage (S_s). In short, the expected number of discarded personal gear items is given by the following formula:

$$S_s = D * P * MU_p * M_d * M_r$$

Thus, over a period of 400 years of habitation an average of 2 individuals carrying mobile toolkits consisting of 3 items each, would produce an assemblage of 29,000 items of personal gear (i.e., not including manufacturing waste) if each item had a probability of 1 in 10 of being discarded or lost on a given day, and a 1 in 3 probability of that discard occurring on site, with each tool user requiring approximately 2 kg of stone per year, not including waste and unused collective toolkit items. Even these very conservative parameter estimates thus result in simulated assemblages that, while realistic, are somewhat large given archaeological observations at the Bau, both in terms of mass and counts. Since it is very unlikely that there were fewer than two tool users per residential group, or that these carried less than three items of personal gear, either the total length of habitation is too high, or the probabilities of discard are too low, or both. In other words, assuming materials were not removed by post-depositional processes, the Bau was either inhabited for less than 0.5% of the depositional history thought to be represented by its Middle Palaeolithic layers, or its inhabitants discarded fewer items in total or more items off-site.

While no direct assessment of discard rate estimates is possible, we can probe habitation lengths further. Assuming a continuous habitation of the *region*, and the modelled approach to selecting the next residential site (see 3.3.4 above), the total number of days stayed (*D*) at a given location over the course of the simulated period is a straightforward function of the total number of camps considered per simulation (*N*). To derive a formula specific to our modeled conditions we ran a total of 4,000 simplified and shortened simulations (10,000 years each) where the agent took no actions while at a camp. These considered 10 different values for the number of sites (from 1,000 to 28,000 in 3,000 increments) and two different values for the lengths of stay and move radii respectively, with each configuration being replicated 100 times. The resulting formula is given below for the average cumulative total number of days stayed at any given camp over 10,000 years ($D_{10,000}$), but to obtain the number of revisits the result can simply be divided by the average lengths of stays:

$$D_{10,000} \approx 3.5 * \; e^{(13.84 - 0.9915 * \log N)}$$

Thus, we can expect that, on average, a single agent will spend a total of 963 days at each camp over the course of 10,000 years in a simulation where 4,000 viable camps are considered, and 1,913 days if 2,000 camps are considered. If the agent stayed at a camp for 1-6 days, the average number of revisits would be 275 and 547 respectively, while if the agent camped for 5-30 days the average number of revisits would be 55 and 109. With 4,000 and 2,000 camps, then, we would expect cumulative habitation of individual sites of ca. 26 and 52 years respectively over the course of the entire 100,000-year period considered here, with revisits occurring on average every 182 and 92 years. Given the sedimentation rates discussed above, it may well be that such discrete occupations, though separated by very long time spans, would be very difficult to distinguish archaeologically. Consequently, from a simulation perspective**,** it is impossible to reject the possibility that the Bau may, indeed, have been inhabited for a tiny fraction of the time represented by its Middle Palaeolithic layers.

Since the number of sites is expected to primarily affect assemblage size, we decided to set their number to 2,000 and to vary the probabilities of discard instead, since these are much more difficult to estimate. Moreover, to keep the number of simulations manageable we vary only the probabilities of the discard occurring on-site, from values of 0.2 (i.e., most personal gear will be discarded off-site) to a value of 0.8 (i.e., most personal gear will be discarded on-site, as suggested by Binford, 1979). These and other final parameters of the simulations are listed in Table 1 below, and the resulting simulated assemblages are expected to contain from a minimum of ca. 2,300 to a maximum of ca. 124,000 items of personal gear, which we deem to be sufficiently close to archaeological observations at the Bau to suggest the parameters used are minimally realistic.

Table 1: Simulation parameters. *10 simulations were carried out for each parameter combination. Using these parameters, the simulated assemblages are expected to contain a minimum of 2,300 and a maximum of 124,000 items of personal gear.*

Parameter	Setting 1 (min)	Setting 2 (max)
Simulation length	100,000 years	
Time resolution	1 day	
Group size (people)	5	28
Tool users	30%	
Days at camp	1-6	15-90
Items of personal gear per tool user	3	9
Personal gear item mass (g) – Weibull shape	1.177	
Personal gear item mass (g) – Weibull scale	53.06	
Probability of daily discard from personal gear	0.1	
Probability of on-site discard	0.2	0.8
Maximum procurement mass (kg)	5	15
Maximum collective toolkit size (kg)	20	
Yearly sedimentation probability	1/1000	
Number of viable camp locations	2000	
Travel time to locations considered for residential moves (hours)	4-5	

5. Results:

5.1. *General characteristics of the simulated Bau assemblages:*

The simulated Bau assemblages vary in size from 724 kg to 2,953 kg, with a mean mass of discarded or abandoned lithics of 1,377 kg (SD = 573 kg) and a median of 1,178 kg (IQR = 518 kg). However, these figures include outliers produced by one extreme parameter combination, namely group sizes of 28 individuals, personal toolkits consisting of 9 elements, and probabilities of on-site discard of 80%. With such outliers excluded, the total mass of the simulated assemblages attains a maximum of only 1,735 kg, with a mean and median of 1,181 kg (SD = 255 kg) and 1,097 kg (IQR = 436 kg) respectively.

Items discarded from personal gears (i.e., MTK) account for 3.3 to 60.2 percent of the simulated assemblages by mass, with a mean of 23.7% (SD = 16.6%) and a median of 19.9% (IQR = 22.1%), or up to 39.2% if the outliers noted above, and which only have a major effect on this component of the simulated record, are excluded. In that case the mean is 18.8% (SD = 11.1%) and the median 13.6% (IQR = 19.6%). Waste materials resulting from the creation of mobile toolkit elements from locally procured collective toolkits (i.e., GTK) account for 4% to 27.1% of the simulated assemblage mass, with or without outliers, having a mean of 11% (SD = 6%) and a median of 10% (IQR = 6%). Sedimented materials, on the other hand, account for 24.6% to 91.6% of the mass, with a mean of 64.9% (SD = 19.36%) and a median of 68.4.6% (IQR = 27.9%). The large proportion of sedimented materials *suggest* that either the sedimentation probabilities were set too high (likely, given that the estimated sedimentation rate at the

Bau is positively skewed due to episodes of roof fall which would have added a lot of material very quickly), that the maximum size of the collective toolkit is larger than would have been reasonable given the probability of site revisits, or a combination thereof. Regardless, the result is a likely inflated signal for locally procured materials. The overall raw material composition of the simulated assemblages is shown in Figure 4, aggregated by source area.

Only 91 of the known 122 source areas contributed materials to the virtual Bau assemblage across the entire set of 320 simulations. These included 16 of the 17 (missing ID = 76) with evidence of archaeological exploitation at the actual site, which account for 99.95% of the archaeological materials with known provenance. With 11 of these 16 source areas the range of the mass abandoned at the virtual Bau by the agent encompasses the mass of the actual archaeological materials, estimated on the basis of the number of pieces and the available weight distribution data; an additional source area (ID 13) falls outside the range only by a small margin (it contributed 1 archaeological piece to the Bau assemblage, and a few pieces - minimum of 55 grams - to the virtual Bau). 75 source areas are represented at the virtual Bau, but not at the actual site, so technically archaeological observations fall outside the simulated range. However, these source areas typically contribute very small amounts of material within the simulations (75% of these contribute as little as 7 grams or less), so this should not be interpreted as a poor fit; indeed, it is conceivable that some of these source areas are represented by the occasional small flake at the site, which may be among the many patinated or burned lithics whose provenance could not be established (see section 4.2).

Nevertheless, as evidenced in Figure 4, there are five cases where archaeological estimates fall well outside the range observed in the simulations. Of these, two consist of source areas (ID 36 and ID 57) that were exploited by the inhabitants of the site to a larger extent than expected under modelled conditions; their apparent overexploitation *may* indicate preferential habitation of areas where sources belonging to these appear as optimal procurement candidates, since neither the quality of the materials (maximum of 3 on a scale that reaches 10), nor their location relative to the Bau (1-2 hours) can explain their degree of archaeological representation. Of the three source areas that, under modelled conditions, should have been exploited to a substantially larger degree than is archaeologically observed, one (ID = 52) is represented by a low-quality source (ID 7) that was likely misidentified as an optimal local procurement candidate. If materials collected by the agent from that source while residing at the Bau are ignored, the simulated raw material frequencies fall in line with archaeological observations. The lower-than-expected exploitation of the remaining two source areas (53 and 58) remains currently unexplained and warrants further investigation in the future. Aside from this, however, archaeological observations are overall consistent with the results of our simulations, suggesting that the optimal candidate hypothesis can hold when factoring in the effects of residential mobility and inter-site raw material transport.

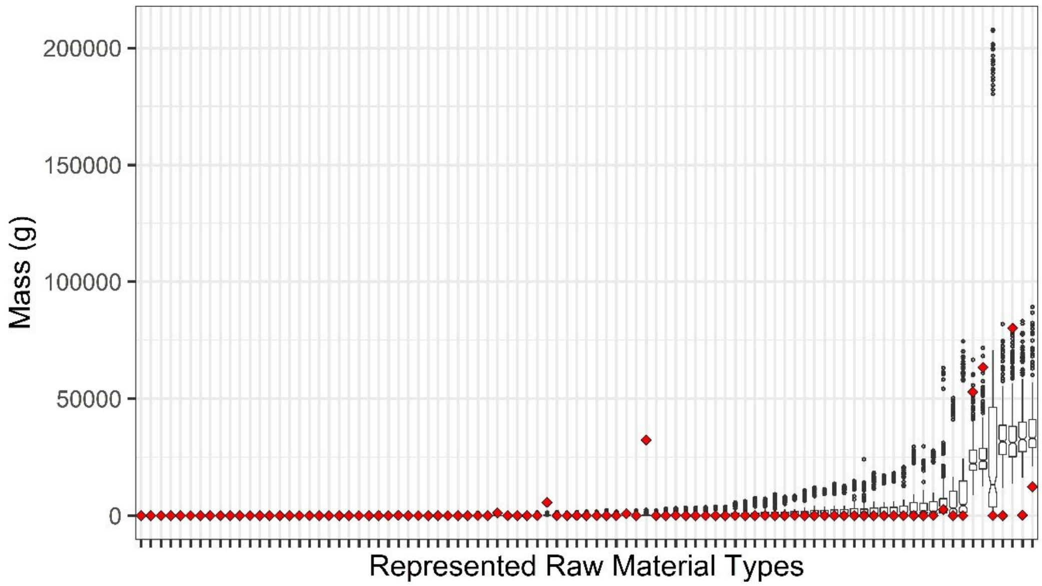

Figure 4: **Simulated raw material variability at the Bau de l'Aubesier.** Boxplots represent the range of variation in the mass of lithics made from raw material types found at source areas exploited by the agent (n = 90) and discarded or abandoned at the simulated Bau across the full set of simulations (n = 320), which covered all parameter combinations. Red diamonds indicate the estimated mass of actual archaeological materials recovered from the site, calculated by multiplying published counts by the median of the mass data to which the Weibull distribution was fitted (see section 4.4).

5.2. *Expected LPOS incidence:*

If lithics materials procured at other sites (i.e., LPOS), –which, as modelled here (see section 3.3.6) consist exclusively of personal gear items (i.e., MTK) - are considered in terms of their mass contribution to the overall simulated Bau assemblages, they account for a minimum of 0.6 and a maximum of 47.1 percent of the latter, with a mean of 11.6 (SD = 12) and a median of 7.1 (IQR = 10.7) percent. If sedimented materials are excluded, as they may be overestimated in our simulations (see above), the LPOS contribution varies between 6.8 and 64.4 percent, with a mean of 30.7 (SD = 21.3) and a median of 23.6 (IQR = 33.6) percent. With or without sedimentation, the variability is driven by the number of days stayed at camps, with shorter stays resulting in much higher representation of non-local materials (a mean of 50 [SD = 12.4] with stays of 1-6 days versus a mean of 11.5 [SD = 3.1] percent with stays of 15-90 days), and by the probabilities of on-site discard (on average 23.2 [SD = 14.9] percent of the mass if using probabilities of 20%, and 38.3 [SD = 23.9] percent if using probabilities of 80%). Other considered variables have no direct effect on these proportions, although they do influence the mass contribution of sedimented materials.

The proportion of LPOS among personal gear items (i.e., MTK) discarded at the virtual Bau was found to vary between a mean of 78.9 (SD = 0.5, n = 160) percent with short simulated occupations (1 to 6 days) and 18.7 (SD = 0.5, n = 160) percent if simulating longer stays (15 to 90 days). This suggests a straightforward relationship between the average length of stays and the average percentage of non-locally procured personal gear items discarded at a site. Comparisons in terms of mass revealed an almost identical picture, with virtually identical means but slightly larger standard deviations (0.64 and 0.68 percent with shorter and longer stays respectively). Other than the length of stay, no simulated variable played a noticeable role in the relative incidence of locally and non-locally procured personal gear items, not even the number of such items that are carried by the agent.

In short, these simulations reveal that, no matter how we look at an assemblage, we can generally expect a relatively substantial proportion of the discarded materials to have been procured while residing elsewhere, even if personal toolkits are considered as the only means of inter-camp transport (i.e., no trade, no general-purpose material transport between sites). They also reveal that, under modelled conditions and depending primarily on the lengths of residential stays, these non-local materials are brought in from a large number of camps, with individual ones seldom contributing more than a small number of artifacts (ca. 12 per camp per simulation, but the distribution is strongly and positively skewed, having a maximum observed value of 109 artifacts per camp across all 320 simulations).

5.3. *LPOS from sources also exploited at the Bau:*

Under modeled conditions, materials procured by the agent while residing at other camps from sources it also exploits when staying at the virtual Bau account for between 0.29 and 30.15 percent of the total mass of lithics discarded or abandoned at the simulated site (median = 3.5, mean = 6.4 percent), and for roughly half of the LPOS total. Indeed, as shown in Figure 5, there is a very strong correlation between the mass of such LPOS and those acquired from sources which are not exploited by the agent from the virtual Bau. The specific details of this correlation are not important, of course, since they are specific to the modelled conditions used here, which are only meant to be minimally realistic. The correlation does suggest, however, that the percentage of lithics which may appear to have been locally procured by hominins residing at the Bau, but which were in fact procured at other camps and transported to the site as elements of personal gear, could be estimated from the incidence of clearly non-local (i.e., unexploitable from the Bau) materials – as modelled here, at least, they occur in roughly equal amounts. These results also suggests that evidence for local lithic resource selection and management at sites where a large proportion of lithics are likely to have been imported from other camps should not be taken at face value.

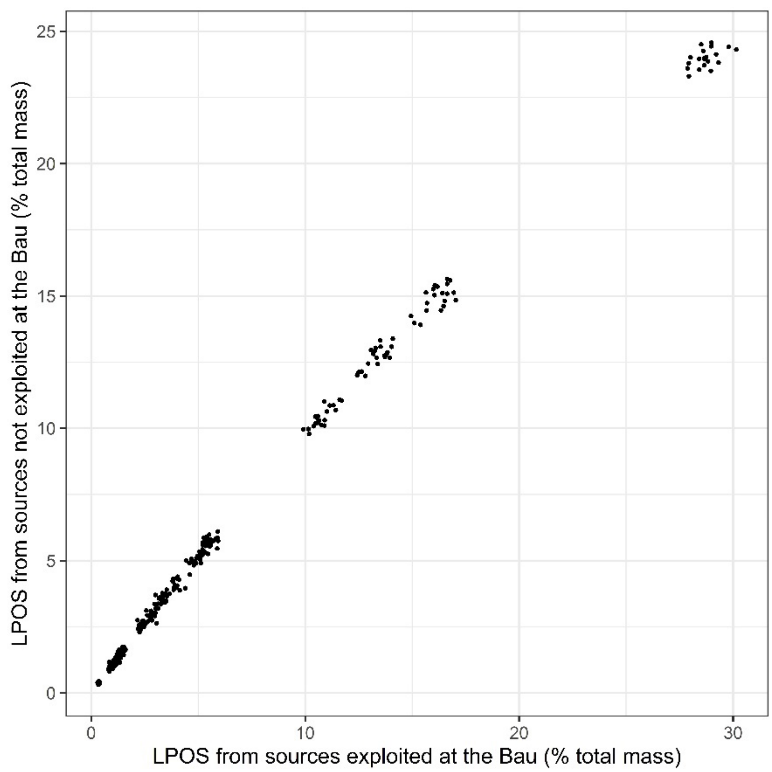

Figure 5: **Relationship between LPOS from sources exploited and unexploited at the Bau.** Lithics procured at other sites (LPOS) by the agent from sources that were also exploited from the virtual Bau account for a substantial proportion of the total simulated assemblage mass and show a very strong and predictable relationship with the incidence of LPOS procured by the agent from sources that are not exploitable from the site.

It is worth noting that our simulations indicate the likelihood of LPOS from locally exploited sources being discarded at a site may depend to some extent on the distance between the site and the material's source. With conditions specific to the study region, for instance, lithics procured by the agent from sources found within one hour of the Bau account for roughly one third of the total simulated Bau assemblage by mass (mean = 35.1, SD = 4.7 percent), and only a tiny fraction of these were indirectly procured by the agent while residing at other camps (min = 0, max = 1.26, mean = 0.18 percent). However, if sources found within 3.5 hours of the site are considered, and which contributed between 48.2 and 91.1 (mean = 77.6, SD = 9.7) percent of the total simulated assemblage mass, 0.2 to 24.1 percent of these (median = 2.67, mean = 4.95) were procured while at other camps.

5.4. *LPOS and observed raw material variability:*

As can be seen in Figure 6, the number of MTK (i.e., personal gear) elements made from specific raw material types and discarded by the agent into the simulated Bau assemblages exhibits a largely predictable relationship with the actual quantities of artifacts found at the site: materials which are archaeologically common are consistently well-represented in the simulated assemblages as well. Indeed, a Spearman's rank correlation test indicates a moderate and highly significant association between these variables ($r_s = 0.365$, $p < .001$), even if we exclude materials from sources that were, within our simulations, also exploited directly from the Bau ($r_s = .23$, $p = .01$). What is clear, however, is that several raw material types which are not archaeologically represented, or are very poorly represented, contributed rather substantially to the simulated assemblages (see also Figure 4). This could result from either a) an inability to accurately predict optimal sources at certain camps, perhaps due to the use of different resource selection criteria at these, or due to changes in the availability and/or characteristics of specific sources over time, or b) an underutilization of locations where non-represented raw material types should have been favoured.

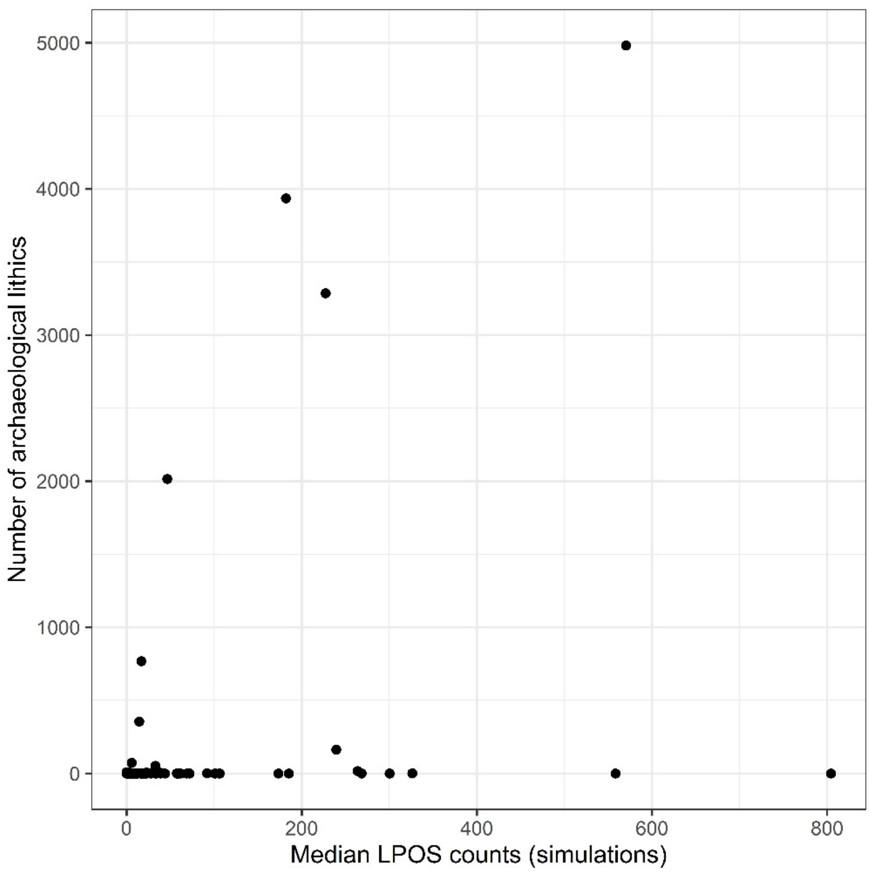

Figure 6: **Archaeologically observed raw material frequencies and simulated variability among LPOS.** The median incidence of 90 raw material types among the LPOS discarded at the simulated Bau over 320 simulations, plotted against their archaeologically observed frequencies. Under modelled conditions, LPOS (imported lithics) consist exclusively of personal gear items transported by the agent during residential moves.

5.5. *Regional patterns*

A map of hypothetical camp locations, color-coded by their broad compatibility with archaeological observations at the Bau (Figure 7), evidences substantial spatial patterning under modelled conditions. Red in the figure denotes camps which contributed exclusively archaeologically non-represented materials to the simulated Bau assemblages, while green identifies locations where all materials procured by the agent and eventually discarded at the simulated Bau are known to have actually been used by the inhabitants of the site. Camps with mixed contributions are shown along a palette diverging towards either extreme from a light blue center. Clear clustering with a typically gentle grading from zones of high compatibility to low compatibility ones can be observed.

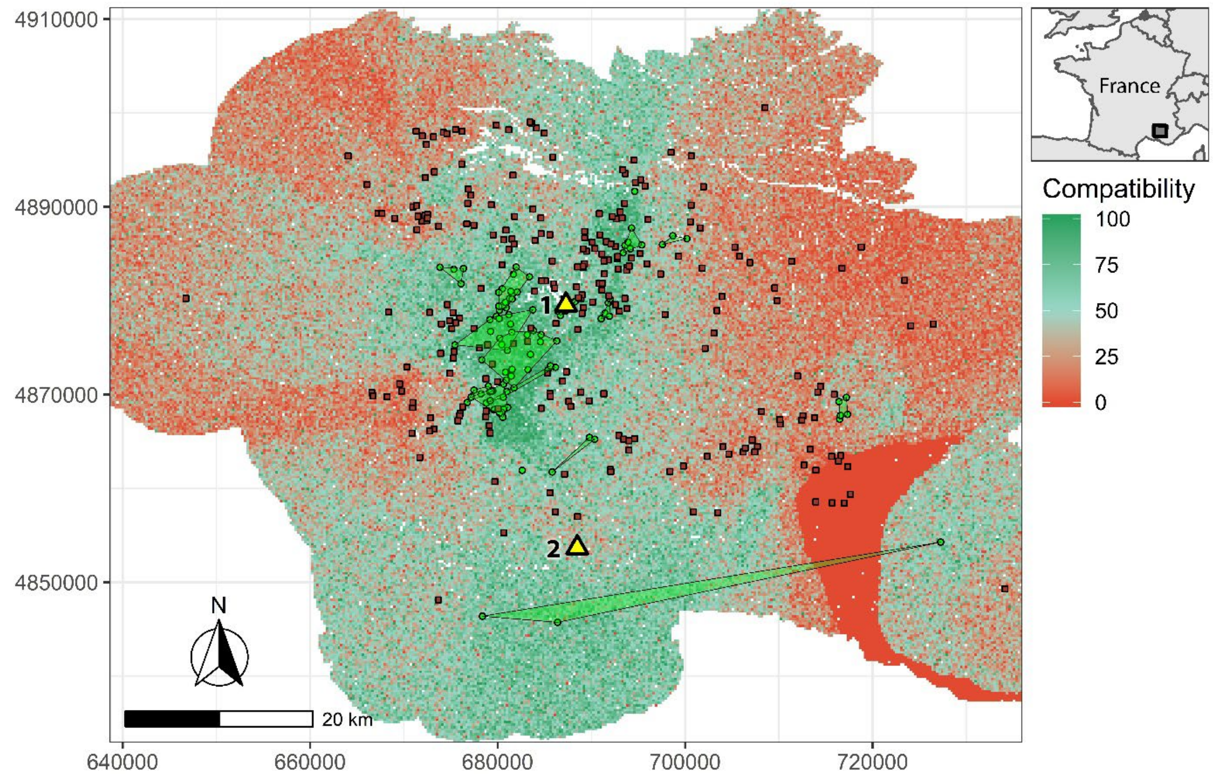

Figure 7: **Compatibility of possible camp locations with archaeological observations at the Bau.** Compatibility raster map created from the 85,808 virtual sites included in the 320 simulations. At each of these locations the agent procured raw materials from a small subset of sources that would have appeared to be locally optimal, and eventually transported and discarded some of these at the Bau. The colours indicate the mean proportion of such materials (number of items), aggregated across all simulations, that originate from source areas that are archaeologically represented at the Bau. If all lithics procured at and transported from a given location *x* to the Bau are fashioned from archaeologically represented raw materials, location *x* is considered to be 100% compatible with observations at the site and appears in green. Conversely, if all such lithics are made of materials which are not present in the Bau assemblages, the compatibility of location *x* is considered to be zero, and the location appears in red. Sources of archaeologically represented raw material types are indicated by green circles, while red squares denote sources lacking evidence of archaeological exploitation at the Bau. Green polygons represent convex hulls encompassing sources from archaeologically exploited source areas. Yellow triangles indicate the two Middle Palaeolithic sites discussed in the text, namely: 1) the Bau de l'Aubesier, and 2) La Combette. The raster resolution is 256 m. Coordinates are given in UTM (zone 31N).

This patterning is important because it shows that, although our minimally realistic model assumes a uniform utilization of the landscape as a starting point, simulations can be used to identify areas which are unlikely to have been inhabited by hominins who also resided at the Bau. This is because, if past behaviours are adequately captured by the extreme parameter ranges employed here (see Methods), and it can be assumed that drivers of lithic resource selection did not vary dramatically from site to site, materials from archaeologically non-represented sources should have made their way into the Bau if predominantly red areas were indeed regularly occupied. It is interesting to note in this context that the other site in the region for which relatively compatible raw material data is available, La Combette (2 in Figure 7), was not inhabited during the occupation of the Bau and is indeed located in a relatively low compatibility area – only 39% of the materials procured by agents occupying this location and contributed to the simulated Bau assemblages are of an archaeologically represented type.

The patterning further shows that simulations can be used to detect potential problems in the sourcing dataset. The sharply delimited, crescent-shaped zone of consistently incompatible locations at the south-east of the Bau is most likely an artifact resulting from such problems. Throughout this entire area a single source (ID = 324) was identified as worthy of exploitation, and it yields high-quality materials which are nevertheless not found at the Bau. It is unclear whether this artifact may be the result of changes in the characteristics of this source (e.g., degree of exposure) since the Bau was last inhabited, or of the presence of even more attractive sources in or near this area between ca. 100 ka and 200 ka, containing raw material types represented by the few unprovenanced lithics at the Bau.

Interpreting areas of high compatibility (i.e., green) is more difficult, since compatibility values provide no indication of whether and/or how often hominins may have actually occupied a specific area. However, if areas identified in Figure 7 as highly compatible were indeed preferentially inhabited, we would expect the quantities of artifacts procured by our simulated agent while residing there to be more strongly correlated with archaeologically observed frequencies than the baseline (see section 5.4 above). It should be emphasized here the *degree* to which specific archaeologically represented raw material types were exploited at a given location does not factor into how we defined compatibility above. If we consider the strength of such a correlation across locations above different threshold values, there is indeed evidence of a clear trend: eliminating locations with low compatibility values tends to result in stronger Spearman's rank correlation coefficients (Figure 8). This therefore hints at the possibility that the inhabitants of the Bau did favour areas shown in green in Figure 7, but validation using compatible raw material data from other, contemporaneous sites in the region is required to determine whether this was indeed the case.

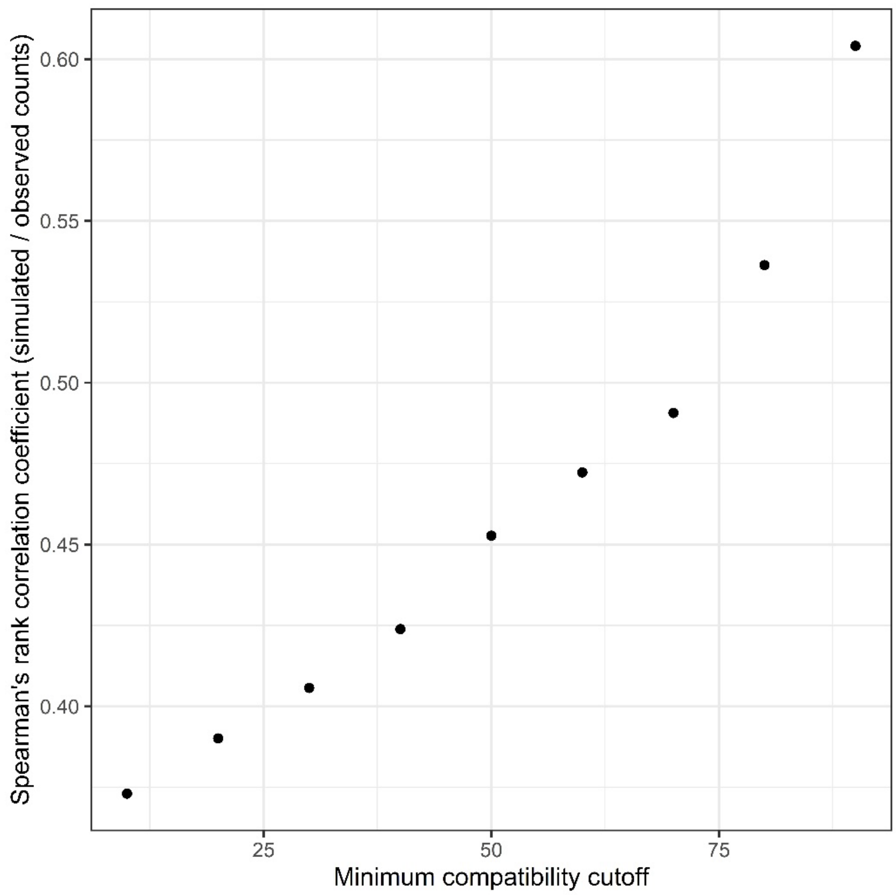

Figure 8: **Strength of association between raw material type frequencies in simulated LPOS and archaeological lithics at the Bau at different compatibility thresholds for contributing camps.** LPOS data consists of the aggregated raw material contributions to the virtual Bau (320 simulations) from all camps whose compatibility values are greater than the given threshold. These compatibility values refer to the mean percentage (number of items) of raw materials transported from said camps to the virtual Bau that originate from sources of raw material types that are evidenced at the site. See also Figure 7.

6. Discussion:

6.1. *The optimal candidate hypothesis still holds*

In this paper we introduced and applied a novel minimally realistic agent-based model to examine the potential pathways through which lithic raw materials may have been incorporated into the archaeological assemblages found at the French Middle Palaeolithic site of the Bau de l'Aubesier. We did this in view of ascertaining whether the hypothesis we recently put forward to explain the apparent avoidance of a very large number of sources in the region over a period of ca. 100,000 years, including some yielding high-quality materials and found in close proximity to the site, could hold if we factored in residential mobility and the concomitant import of materials from other sites. According to our hypothesis, sources were avoided because, from the perspective of a hominin intending to collect materials on her or his way to the Bau, better alternatives (i.e., higher quality and/or lower access costs) would have been available. But what of other camps such hominin stayed at? Would the raw materials that are represented at the Bau have been targeted at such camps also, or is it the case, perhaps, that materials procured as supplies for other sites would only have reached the Bau in negligible quantities?

Our simulations indicate that, under conditions of minimal realism (see section 3.1), we can expect ca. 0.6 to 47.1% of the total mass of lithics present at the Bau, perhaps slightly more (see 5.2), to have been imported from other sites. Our approach, which is not intended to emulate the past (see 3.1), does not allow us to further narrow down this range (see 4.5 for why measures of centrality should be treated with caution), but we can note that the relative amount of imported stone (i.e., lithics procured at other sites, or LPOS) will depend on the durations of continuous habitations of the Bau, as anticipated (see, e.g., Meignen et al. 2009), and to a lesser degree on the likelihood of implements having been discarded or lost outside the site (see 5.2). We know of no reliable way of improving our estimates for probabilities of off-site discard, which here refer exclusively to the abandonment of items during daily foraging activities, but the available lithic and faunal evidence is not suggestive of primarily ephemeral, very short-term stays (see section 2). In light of this, the lower end of this range is probably more representative of the amount of LPOS (i.e., imported materials) present at the Bau, particularly since our estimates for the degree of residential mobility are already positively shifted relative to ethnographic observations (see section 4.5.1s.1).

On the other hand, our results indicate that the importation of lithics as elements of personal gear could account for the presence of nearly all (16 of 17) raw material types found at the Bau without the need to invoke a misidentification of locally optimal sources as an explanation (cf. Chapter 4). Indeed, individual simulated Bau assemblages consistently yield most of the 17 archaeologically exploited raw material types (median = 15, with 13 present in 98% of the 320 simulations), and collectively almost all, despite only five having been exploited directly from the site by our agent. For this alternative explanation to hold, however, a minimum (see 5.3) of 17% of the analyzed artifacts recovered at the Bau - those made of materials from locally sub-optimal sources (see Chapter 4) – must have been imported to the site from other camps. This figure is well within the range observed in our simulations. In other words, although we cannot rule out the possibility that only a negligible quantity (i.e., 0.6% or so) of the lithic materials present at the Bau were imported from other sites, such a scenario may not be needed to explain the observed raw material variability.

There is, however, the matter of those lithic types which should be present at the Bau, but which nevertheless are not. In fact, the simulated assemblages are always more variable in raw material composition (36-79 unique types per simulation) than would be expected from archaeological observations (cf. Brantingham, 2003). More importantly, 13 seemingly unused types appear in 100% of our virtual assemblages, with a further 27 types appearing in 95% or more. Does this then mean we should rule out a scenario whereby the importation of stone from other sites explains important aspects of raw material variability at the Bau? We think not, for at least two reasons.

First, we know that our approach to identifying optimal candidates has important limitations, notably the fact that we evaluate all sources regardless of their distance to a site (see 3.3.6). While distance (or rather, effort) almost certainly did play a role, we had no reliable means of establishing a cut-off threshold that could be generalized to arbitrary camps. As a result, the misidentification of sources as optimal exploitation targets can be expected to be a common occurrence in our simulations – 25-33% observed at the Bau, after all (see section 5.1) – and may well be impossible to eliminate. The second factor to consider is how the landscape was actually utilized in the past. Our model assumes uniform habitability of the area and a random selection of camping locations, but this is just a baseline expectation (see 3.1). As shown in Figure 7, throughout substantial portions of the region, the extent of which is probably underestimated given our preceding observation, our agent exploited mostly or exclusively raw materials which are in fact represented at the Bau. If our agent preferentially resided in such areas, we would expect considerably fewer archaeologically invisible types at the virtual Bau.

Given the above, two scenarios are possible: first, it may indeed be that only negligible quantities of materials were imported to the Bau from other sites. In this case the presence of materials from locally sub-optimal sources could be due to an overly aggressive approach to filtering out viable procurement locations (see Chapter 4) resulting from, for example, an incomplete understanding of the drivers of raw material selection. Alternatively, our simulations are also consistent with a scenario in which materials were imported to the site by hominins who preferentially inhabited only certain areas of the region. Importantly, both scenarios are premised on hominins possessing excellent navigational abilities as well as detailed knowledge of the available lithic resources. Indeed, it is only by allowing for an outstanding ability to filter out sub-optimal exploitation targets in light of access costs to, and benefits afforded by, available alternatives, that we can explain raw material variability at the Bau under the second scenario. Thus, aside from indicating that our recently proposed optimal candidate hypothesis could explain the avoidance of at least two thirds of sources available in the region over some 100 millennia even if we assume that raw materials were regularly transported between camps, the results presented here also strengthen our previous conclusions regarding the spatial abilities of the Neanderthal occupants of the site.

6.2. *Neanderthal territories – what can raw materials tell us?*

The second scenario outlined above does raise the possibility that the areas of regular, direct resource exploitation around the Bau may have been somewhat smaller than previously suggested, more in line with ethnographic observations, but the overall conclusion that the Bau evidence is inconsistent with foraging radii smaller than typically seen with anatomically modern humans still stands (see Chapter 4). After all, a maximum of ca. 40% of the materials found at the site could have originated from sources found within a one-hour radius, and even simulations using the most extreme parameter combinations failed to produce assemblages where 60% of the materials were imported from other camps.

But what of the areas regularly used in the context of residential mobility by Neanderthal groups who inhabited the Bau (i.e., home ranges *sensu* Marlowe, 2005)? Unfortunately, our implementation of a minimally realistic model does not allow us to directly answer questions regarding the extent of such territories because we did not simulate discrete social units (see 3.3.2) nor the specific settlement strategies such units may have followed at a given time. Consequently, we are only able to provide insights into the possible extent of the combined territories frequented by individuals who at some point resided at the Bau, regardless of their social group affiliation. This is still informative with regard to the site's total sphere of socio-economic influence, however (i.e., site catchment – see Bailey and Davidson 1983 and Boyle 1998 for a review), and we contend here that this is the most reliable scale at which raw material data can be interpreted for most Middle Palaeolithic contexts. To assume provenance data can inform us of home ranges is to assume, amongst other things, that a) traces left by discrete Neanderthal groups can be archaeologically differentiated, and b) that such home ranges, and indeed groups, are stable over time. Both of these assumptions are problematic (e.g., Binford, 2006; Wobst, 1978). As noted above, if the lithic data from the Bau is informative with regard to landscape use beyond the site's direct exploitation territory, its sphere of socio-economic influence can be expected to have covered only part of the study region, although only maximal limits can be hinted at based on the available data (see 5.5).

6.3. *Further insights from the formulation and implementation of a minimally realistic model*

Aside from enabling a refined understanding of landscape use and resource selection at the Bau, our simulations allow us to make a series of observations of wider relevance. During our model calibration procedure, it became clear that a long total occupation of the site is difficult to reconcile with the available archaeological evidence (see section 4.5.1.1) notwithstanding the thick and rich sequence preserved at the site (see section 2). If the cumulative occupation of the Bau amounted to ca. 100 years or less, as would be the case with an average of ca. 8 cohabitating tool users (see 4.5.1.2), and if we can assume the *region* was inhabited throughout the entire 100 – 200 ka period, a large number of discrete locations must have been available and used for residential stays. Indeed, 1,000 sites would be needed to explain a 100-year cumulative habitation if the Bau was of a typical size for the region, and more if the Bau was among the richer, as it appears to have been the case. Using these figures, the Bau can be expected to have been revisited some 700 times assuming relatively long stays of ca. 50 days, or some 9,000 times if much shorter stays of ca. 4 days happened to be the norm. This, in turn, would imply an average time between revisits of ca. 143 and 11 years, respectively.

To what extent site revisits may have been clustered in time at the Bau is difficult to say given the available information on dates and sedimentation rates, but it is very likely that there were periods of frequent occupation followed by long gaps without human habitation. By itself, such clustering has no bearing on the preceding observations, although it would result in some differences in visible raw material selection signals if habitation clusters also coincided with differences in degrees of residential mobility. Indeed, since under the conditions modelled here increased residential mobility would increase the proportions of materials imported to the Bau from other sites, where access costs to sources would be different, we would expect proportionally more noise in variables quantifying procurement effort. The previously documented weaker influence of terrain variables in the upper layers at the Bau may therefore represent simple differences in the average lengths of individual occupation episodes without necessarily implying changes to raw material selection criteria or provisioning strategies (see Wilson and Browne, 2014).

Insight into the expected frequency and clustering of habitation episodes is also of consequence to understanding the possible role of lithic recycling as well as the theoretical potential of inter-site refitting studies. From the perspective of provenance studies, the impact of lithic reuse is important to consider because, amongst other things, it: a) influences the number of procurement episodes that may be expected to have taken place at a site and consequently the representativeness of the preserved resource selection signal; and b) may result in the displacement of lithic materials over distances exceeding the range of individual mobility, leading to an inflated estimate of a site's true sphere of socio-economic influence (cf., section 6.2 above). At large sites such as the Bau resource selection signals should be representative regardless of the degree of recycling, but the possible impact of lithic displacement via recycling deserves closer examination (see Turq et al., 2013).

Our results suggest that the opportunities for reusing previously abandoned materials, which in our model need *not* be waste (cf., Romagnoli, 2015), were likely plentiful. Indeed, even if habitation episodes were not clustered and revisits only occurred once every ten, or even every one hundred years or more, sedimentation was in most circumstances likely too slow to render such materials invisible (see section 5.1). This is consistent with the relatively common evidence of recycling of patinated lithics observed at many sites (e.g., Turq et al., 2013). If unused supplies were left behind, either cached in expectation future demand or simply to avoid carrying heavy rocks over substantial distances during residential moves (see 3.3.4) in an area where toolstone is easy to find, recycling may be expected to have played a role at the Bau notwithstanding the resource-rich environment in which the site is found (cf. Amick, 2014). From an archaeological perspective, the reuse of such partially worked materials, plausibly by completely unrelated groups, could well be impossible to detect, however, unless patination could be demonstrated to have occurred very quickly. Fortunately, while such recycling would affect our ability to reliably identify territories exploited by discrete hominin groups (see above), it has no bearing on interpreting raw material data in terms of a site's sphere of socio-economic influence. Indeed, only the recycling *and* subsequent off-site transport of previously imported materials (i.e., discarded personal gear items, as modelled here) would be of consequence (cf. Turq et al., 2013).

At the Bau such recycling is unlikely to have played a role, because raw material sources are abundant throughout the likely home ranges of hominins who inhabited the site (see Figure 7). In other contexts, however, where lithic resources are less readily available, such scavenging may have taken place on occasion and could explain the presence of *some* implements, and possibly curios, fashioned from unusually distant materials (cf. Duke and Steele, 2010). On the other hand, this type of recycling is unlikely to have played a very substantial role (Amick, 2014; see also Cuartero et al., 2015; Romagnoli, 2015) even under conditions of raw material scarcity, so it is doubtful that the re-incorporation of previously curated items (*sensu* Binford – see Shott, 1996) into personal toolkits could result in greatly distorted estimates of a site's catchment area in any context. Thus, unless substantial quantities of minimally worked materials were regularly transported between sites, the presence of more than a handful of lithics procured from very distant sources (e.g., 50+ km), as evidenced at several Middle Palaeolithic sites (e.g., Artenac, France - Meignen et al., 2009; Grotta del Cavallo, Italy – Romagnoli, 2015), is best explained by either unusual degrees of individual mobility or inter-group exchanges, depending on the distances involved (cf. Turq et al., 2013: 650).

In terms of lithic refitting, the possibility of reconstructing reduction sequences across sites is alluring. Indeed, since the recovery location of each refitted piece is known, it should be possible to trace the sequence of raw material movements across space, plausibly reflecting the mobility of a single individual or group. But is this a research avenue that is worth pursuing? Quite aside from the very substantial technical challenges refitting involves, and the added complexity *any* form of reworking (i.e., during recycling) implies, our results suggest that it is most likely not. Indeed, even using very conservative estimates for group sizes, on-site discard rates, and lengths of habitation, we would expect to see assemblages that are somewhat larger than archaeologically attested. If our lower estimate for on-site discard rates (one in five) is reasonable, a large majority of personal gear items must have been discarded in the course of daily activities away from residential sites (cf. Binford, 1979; see Luedtke, 1976). Thus, even if habitation episodes were clustered in time and consisted of revisits by a single group which made regular use of but a handful of known archaeological sites, the baseline expectation is that only a small portion of plausibly refitting pieces would have been transported between such sites. If habitation episodes were in fact not clustered, searching for refits across sites becomes largely a fool's errand. Under the conditions modelled here, the imported materials originated from virtually all camps included in the simulations, with each camp contributing only a very small number of items (12 on average, with a maximum of 109 observed across the 320 simulations). Considering that, as noted above, several hundred sites would be needed to explain a continuous habitation of the region *and* the presence of a site like the Bau, the probability of finding refits that are informative with regards to the movement of a discrete hominin group are very small indeed, even if refits could be evaluated for all archaeologically recovered pieces at little or no cost.

In short, based on our results, and in the absence of inter-group exchange, we can conclude that raw materials can be informative with regard to the maximal extent of a site's area of socio-economic influence, and of the minimal extents of areas directly exploited by its inhabitants for resources, if we are able to model resource selection in light of the network of available alternatives. Raw materials may also inform us of the areas most likely to have been frequented within the daily exploitation territories and beyond (see also e.g., Frahm, 2016; Ekshtain et al., 2014). What they likely cannot do, however, except perhaps in very unusual circumstances, is inform us of which areas were regularly exploited by specific hominin groups in the past, and how (e.g., circulating or radiating mobility strategies), particularly beyond a site's zone of regular, direct resource exploitation. Consequently, we should be very wary of interpreting archaeological raw material data in ethnographic terms.

These insights demonstrate that simulations of minimally realistic models (MRMs) of the kind proposed here are useful not only in testing specific hypotheses about the past (e.g., our optimal candidate hypothesis), but also in evaluating the potential of different avenues of research. Indeed, the advantages of MRMs are many: like null models, they can allow us to examine which variables influence outcomes the most, and to explore whether specific mechanisms (e.g., selective land use) played a role (see 3.1 and 5.5) but, unlike null models, they prevent us from inadvertently simulating impossible realities and present us with more easily interpretable outcomes, thereby lending greater validity to our conclusions. As shown in section 5.5, they can also allow us to identify aspects of our data that require closer examination, and ultimately they enable us to make specific quantitative predictions (e.g. resource use at arbitrary landscape locations) that may be easily rejected or supported by archaeological observations. On the other hand, developing an MRM is hard, not least because it requires a more careful consideration of parameters and assumptions than either neutral or realistic models. We consider this to be an advantage, however, as it forces us to grapple with issues that are ultimately profoundly relevant, such as the scales at which questions may be asked of the archaeological record.

7. Conclusion:

The design and implementation of a minimally realistic model of raw material management has allowed us to overcome an important limitation of a previously proposed explanation for the avoidance of lithic resources in the region surrounding the Middle Palaeolithic site of the Bau de l'Aubesier. Our findings indicate that, as long as we reject a uniform habitation of the region, the exclusive targeting of resources deemed optimal according to a cost/benefit analysis is consistent with the available data even if we allow for residential mobility and the concomitant import of non-negligible amounts of materials from other residential sites, where procurement costs would have been different. These findings lend further weight to our earlier suggestion that the level of spatial knowledge and navigational abilities of Neanderthals already matched our own. They also support the conclusion that these hominins regularly exploited territories comparable in size, though perhaps not exceeding (cf. Chapter 4), those exploited by ethnographic hunter-gatherer populations. Together with the plausibly substantial import of materials from other sites, which our simulations show can be expected with mobile populations, the results indicate that it is a mistake to view the presence of semi-local materials (e.g., procured from beyond the expected daily foraging radius) as indicating logistical mobility (cf. Romagnoli, 2015; Duke and Steele, 2010). Beyond this, our results highlight the usefulness of minimally realistic models, which extends beyond the simple evaluation of specific hypotheses about the past. As discussed above, MRMs can reveal alternative, simpler potential explanations for certain observations, such as the decreased importance of terrain variables in the upper levels at the Bau, as well as research avenues that are worth pursuing further.

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Supplementary Information

Lithic raw material resource management and group mobility at the French Middle Palaeolithic site of the Bau de l'Aubesier: Application of a minimally realistic agent-based model

A BLIND APPLICATION OF THE BAU-DERIVED RESOURCE SELECTION MODEL TO THE MIDDLE PALAEOLITHIC SITE OF LA COMBETTE

Some of the results presented in the main manuscript assume that the logistic model of resource selection we recently developed for the Bau (see Chapter 4) can be meaningfully applied to predict lithic resource utilization at arbitrary camp locations throughout the study region. Said model predicts the probability (hereinafter, P_{S1}) that a given source belongs to the set S_1 of sources known to have been exploited at the Bau on the basis of the costs of accessing such source from the site, quantified in terms of minimum travel times (see Methods in the main text for details of how these were computed), and the source's intrinsic characteristics (e.g., the quality of the raw materials and the extent over which they are found). Previous work (Chapter 4) demonstrated that, at least at the Bau, P_{S1} values are good proxies for degrees of source utilization. To test whether we can meaningfully predict and use P_{S1} values as proxies for resource utilization at other sites as well, using the model developed at the Bau, one of us (CMP) predicted P_{S1} values for 346 sources in the area, replacing access costs from the Bau with access costs from La Combette, a younger Middle Palaeolithic site located further south (see Figure 2 in the main text). CMP further applied three different options to filter out sources that are unlikely to have been utilized at the site regardless of their P_{S1} values, due to the presence of better alternatives on the way to La Combette (see *Hypothesis 2* in Chapter 4). Importantly, these predictions were done without knowledge of raw material variability at La Combette. Data on raw material frequencies, on the other hand, was compiled by LW and CB without prior knowledge of the model CMP used to predict P_{S1} values, or of the filtering method used to reduce the sample to sources viable for exploitation from the site. We then tested for a significant correlation between estimated archaeological raw material frequencies (see below) and predicted P_{S1} values using nonparametric Spearman's rank correlation tests. It should be noted that these two variables are fully independent (see Chapter 4 for details).

The provenance data available for La Combette is not entirely compatible with that available for the Bau, however. Although at both sites lithics are traced to so-called source areas, which may consist of one or more sources (i.e., locations where similar raw materials may be procured), such sources in the La Combette dataset can belong to multiple source areas. Consequently, matching up source areas, and therefore raw material frequencies for the two sites was not a simple process. As an admittedly imperfect solution, we calculated the maximum possible number of pieces (hereinafter, MPP) from La Combette that could have originated from a specific source – this ensured that no sources were underrepresented, but it also meant that many were likely overrepresented. To illustrate, if source area *X* in the La Combette dataset consists of three sources, such that *X* = {1, 2, 3}, and accounts for 10 archaeological pieces, and source area *Y* also consists of three sources, such that *Y* = {1, 2, 4} (note overlap with *X*), and accounting for 20 archaeological pieces, source 1 was assigned a value of 30, source 2 a value of 30 as well, source 3 a value of 10, and source 4 a value of 20. While these values therefore do not represent real lithic counts, it is assumed here that they constitute a sufficiently robust proxy for the latter to allow for meaningful detection of significant associations with predicted resource selection probabilities.

The results are as follows:

Filtering option 1: P_{S1} values and MPPs were considered for all sources reachable within three hours from La Combette along least-cost paths, and which are deemed as plausibly exploitable (i.e., with P_{S1} values within the 95% confidence interval of the alternative with the highest P_{S1} value on the way to La Combette - see Chapter 4 for more details). With this sample the variables show a strong, positive, and statistically significant correlation ($r_s = 0.659$, $n = 13$, $p = 0.014$).

Filtering option 2: P_{S1} values and MPPs were considered for all sources which are deemed as plausibly exploitable (see above), regardless of their distance from La Combette. With this sample, the variables show a moderate, positive, and statistically significant correlation at alpha level 0.05 ($r_s = 0.483$, $n = 112$, $p < 0.001$).

Filtering option 3: P_{S1} values and MPPs were considered for sources deemed optimal for exploitation (i.e., with no better alternatives available on the way to La Combette). With this sample, the correlation between the variables is not statistically significant at an alpha level of 0.05 ($r_s = 0.332$, $n = 14$, $p = 0.247$).

We interpret these results as indicating that P_{S1} values are adequate proxies for the utilization of resources not only at the Bau, but also at other locations throughout the region. Allowing for some uncertainties in P_{S1} value estimation (i.e., considering all plausibly exploitable sources rather than only those deemed optimal) produces results that are clearly superior but, as at the Bau, it is unclear whether this is because such uncertainties mask the influx of material brought in from other sites, where procurement costs would have been different, and/or to the fact that no distance filter was applied under filtering option 3. Indeed, a source may appear as optimal, in the sense of there being no better exploitation alternatives on the way to La Combette, but such source may have nevertheless been located too far from the site to have been targeted by hominins residing there. Since our goal in this manuscript was to evaluate the possible effects of raw material input from other sites, in the context of residential mobility, we used filtering option 3 to predict raw material use throughout the region.