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Moving far or moving often? A neglected axis of variation in hunter-gatherer mobility

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A R T I C L E I N F O

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A B S T R A C T

As one of the hallmarks of a hunting and gathering lifestyle, mobility is a primary concern for both archaeologists and ethnographers studying hunter-gatherer settlement systems. Most research considering hunter-gatherer mobility, however, concentrates primarily on the total distance moved by a group per annum. This paper develops a novel metric, the Distance/Frequency Index (DFI), which describes a continuum between relatively frequent, short moves and relatively infrequent, long moves, and is derived to be orthogonal to total distance moved per annum. Multiple regressions of the DFI on a series of important demographic, social, and economic variables demonstrate that it correlates positively with population density and negatively with group size, percentage hunting in the diet, mean annual precipitation, and effective temperature. Analyses of a more recently collated subset of these data suggest that the correlations with group size and effective temperature are particularly robust. The DFI can also be related to a number of measures of occupation intensity and duration derived from archaeological assemblages, and to existing models of residential and logistical mobility. The DFI thus provides a valuable second axis of variation in hunter-gatherer mobility.

1. Introduction

Mobility has long been a primary concern of archaeologists studying prehistoric hunter-gatherers, due to the belief that it is one of the foundational distinguishing features of hunter-gatherers relative to agriculturalists. While this dichotomy may not be as clear as it first appears (e.g., Kelly 1992), there is no doubt that mobility is a key component of hunter-gatherer adaptation, articulating directly with demographic, social and economic practices, and conditioning important components of material culture. Most research considering hunter-gatherer mobility from both ethnographic and archaeological perspectives, however, concentrates on a single axis under which groups are regarded as practising either high or low mobility, and accordingly the major variable analysed is often the total distance moved by a group per annum (Binford 2001; Kelly 1983, 2013; Hamilton et al. 2016). While this is undoubtedly a major structural feature of mobility, it can under-represent more nuanced features of the overall mobility strategy.

Two further variables – the frequency of residential moves, and the distance of each residential move – reveal different aspects of the mobility strategy, and interface more clearly both with ethnographically-derived models and with expectations regarding the archaeological signatures of mobility. Binford's classic (1980) model of hunter-gatherer settlement systems, for example, leads to the expectation that groups moving their residential bases infrequently will engage in greater proportions of task-specific (i.e., logistical) mobility, whilst Kelly's (1983, 1995) analyses suggest that residential moves will be more frequent in high productivity environments where plant foods are consistently available. Archaeologically, whilst lithic transport distances may be an indicator of overall mobility, a number of potentially more reliable proxies at the site level are reflective of occupation duration (broadly, the inverse of move frequency). Greater lithic density, greater proportions of debitage, greater reduction intensity, and lower proportions of non-local raw materials are all viewed as indicators of longer occupations, and therefore of less frequent residential moves (e.g., Marks et al. 1991; Kuhn 1995; Morrow 1997; Surovell 2009; Barton and Riel-Salvatore 2014).

It would therefore be highly beneficial to archaeological research to examine the interactions of residential move frequency, residential move distance, and variation in the social, environmental, and subsistence variables that are generally considered to correlate with hunter-gatherer mobility patterns. Furthermore, since residential move distance and residential move frequency are necessarily closely related

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components of the mobility strategy – their product being the total distance moved per unit time – it would be beneficial to combine their effects into a single measure, providing a second major axis of variation in mobility. The analyses below thus develop a combined index of residential move distance and residential move frequency that places hunter-gatherer groups on a continuum from those that move long distances infrequently to those that move short distances frequently. Variation on this continuum is then examined with a view to identifying the social, environmental, and subsistence variables that reliably correlate with it; these correlates are likely to be informative for theory building in relation to the proxies for mobility observed in archaeological assemblages. Combining predictors of variation on this continuum with more standard measures of 'overall mobility' (i.e., distance moved per annum) and existing archaeological theory provides a more comprehensive view of the articulation of assemblage variability and mobility strategies in prehistory.

2. Methods

2.1. Data

Two datasets were analysed to examine the relationships between the newly derived Distance/Frequency Index (DFI) and a series of demographic, subsistence, and climatic data. The first, referred to below as Dataset One, was sourced from Binford (2001:60-67, 118-129), and consists of nine variables: population density, three grouping levels, three subsistence variables, and two climatic variables. The choice of variables was based on previous analyses as well as consideration of the likely correlates of hunter-gatherer mobility strategies. An additional two variables from Binford (2001) – residential moves per year, and residential move distance – were employed in the derivation of the DFI (see Section 2.2 below).

Binford's (2001) database contains data on 339 hunter-gatherer societies. Only groups that "move the entire group from camp to camp as they go about the subsistence round" (i.e., 'GRPPAT' = 1; Binford 2001:117) were retained. Groups for which there was no recorded number of residential moves per year (i.e., Binford's 'NOMOV' = 0) were also pruned from the dataset, as was one group with an anomalously low total distance moved per annum ('DISMOV') value. The pruned dataset contains information on 175 fully mobile groups. Data were retained for the nine variables detailed below, as well as the number of residential moves per year and the total distance moved per annum, which are employed in the derivation of the Distance/Frequency Index.

Prompted by reservations about the sources of the Binford (2001) mobility data expressed by Kelly (2021), Dataset Two utilises data on residential moves per year and residential move distance from Kelly (2013:80-84). To relate these data to the nine demographic, subsistence, and climatic variables from Binford (2001), groups present in the Kelly (2013) database were cross-referenced against those in the Binford (2001) database. Only groups that were present in both databases, and for which data on both residential moves per year and residential move distance were given or could be calculated from data in Kelly (2013) were retained. Where Kelly (2013:80-84) gives a range of values for a given variable, the midpoint was assumed to be representative. This cross-referencing procedure resulted in a dataset of 38 groups that comprise Dataset Two. Both Dataset One and Dataset Two are included as Supplementary Materials.

Although previous analyses have not explicitly considered the continuum between frequent, short moves and infrequent, long moves, a number of analyses have suggested variables that have generic effects on mobility. Below, a brief rationale is given for including each individual variable in the analyses of correlates of the DFI.

2.1.1. Population density

Grove (2016) found that total distance moved per annum scales as the reciprocal of population density. The interpretation of this finding (Grove 2016, 2018) is that population density is determined largely by environmental variables, and that mobility is adjusted so as to ensure that groups remain in contact across large areas for reasons of genetic or cultural exchange or to provide 'safety nets' in times of local resource scarcity (e.g., Gould 1980; Wiessner 1982; Whallon 2006). In terms of the axis of mobility considered here, higher population densities could reduce the need for frequent 'non-utilitarian mobility' (i.e., mobility for the purposes of social contact; Whallon 2006) but increase the need for occasional long moves as resources are depleted. Although populations living at high density tend to move lower distances over the course of the year (Grove 2016), there is a possibility that higher population densities also force longer residential moves on the few occasions that these do occur, since a group may have to travel further to find non-depleted foraging areas.

2.1.2. Group size

Binford (2001) presents three nested variables describing group size: Group 1 is the mean size of dispersed mobile camps ('bands'); Group 2 is mobile camp size during the most aggregated phase of the yearly cycle; and Group 3 represents the size of periodic (~annual) aggregations of multiple groups. Grove (2009) found moderate, non-significant positive effects of group size on residential move distance and, importantly for the current study, suggested that larger groups are sustained by moving often rather than moving far. All three of Binford's (2001) grouping levels are included in the analyses below, though it is expected that the size of the mobile group (Group 1) will have the strongest effect on the mobility strategy. Following Grove (2009), it is hypothesized that larger groups will be more likely to conform to a strategy of relatively frequent, short moves.

2.1.3. Subsistence

Numerous previous authors (e.g., Kelly 1983, 2013; Binford 2001; Grove 2009, 2010a) have suggested that the nature of the subsistence strategy has a strong influence on mobility patterns. In particular, groups relying significantly on hunting are found to be more mobile than those that gain the majority of their calories from either gathering or fishing. Grove (2009) found that the longer a group remains at a camp, the further it will subsequently have to move when the camp is relocated. This is interpreted in terms of Binford's (1982) 'complete radius leapfrog pattern', suggesting that when a group relocates it must move a distance greater than or equal to the diameter of the foraging radius it has depleted. This effect, however, was only significant for groups deriving the majority of their calories from hunting, in line with the contention that the accumulation of butchery debris could force a group to relocate before they have depleted a given area. Such debris can attract both parasitic insects (Yellen 1977) and social carnivores (Potts 1988), both of which make continued occupation problematic. It is therefore hypothesized that groups obtaining a large proportion of their calories from hunting will be more likely to engage in frequent, short moves.

2.1.4. Climatic variables

Climatic variables are frequently found to exert influence on various aspects of hunter-gatherer mobility (e.g., Kelly 1983; Binford 2001; Venkataraman & Kraft, 2017; Grove 2018). Two basic climatic variables were extracted from Binford (2001). Effective temperature (ET) was designed by Bailey (1960) to simultaneously reflect both the warmth and the length of the growing season; it is thus a measure of primary productivity which will have knock-on effects at higher trophic levels. As higher ET values equate to higher productivity, groups experiencing higher ET should, *ceteris paribus*, deplete resources more slowly and therefore not have to relocate as often. Conversely, however, one could argue that groups experiencing higher ET should not have to move as far when they do relocate, as they will have depleted a smaller foraging radius. Therefore, whilst higher ET should certainly equate to lower total annual mobility, whether it should lead to frequent, short moves or infrequent, long moves remains an open question.

The second climatic variable included is mean annual rainfall (Binford's (2001) 'CRR'). This is a baseline precipitation variable and should have directional effects similar to ET, under the assumption that sufficient precipitation is as important to primary productivity as is a sufficiently temperate growing season. Again, greater productivity linked to increased precipitation should lead to lower overall annual mobility, but whether the strategic response involves frequent, short moves or infrequent, long moves remains unclear. Grove (2009) found relatively weak, negative effects of precipitation on relocation distances among hunter-gatherer groups, and subsequent research (e.g. Grove, 2010a) suggests that the effects of climatic variables interact with the effects of the subsistence strategy. Hunter-gatherers in the tropics are more likely to rely on a greater proportion of gathered (plant) resources (Grove, 2010a:1918ff.), and thus to harness primary productivity directly, whereas for those in temperate and (particularly) arctic areas much plant biomass is inedible, and thus a greater reliance on hunting is the norm.

2.1.5. Data preparation

All variables except percentages of gathering and hunting in the diet were natural-log-transformed prior to analysis to ensure approximate normality of distributions. As there were instances of missing data in the three group size variables (Group 1: 24 missing; Group 2: 17 missing; and Group 3: 42 missing) a data imputation procedure was used to maintain full sample size in all analyses. For each of these three variables, the mean of the logged data was used in place of missing entries. All variables were then standardized (i.e., z-scored) prior to analysis. It should be noted that this form of data imputation exerts no bias on the statistical analyses since a bivariate regression necessarily passes through the bivariate mean; when using standardized variables, the bivariate mean is located at (0,0). As Dataset Two is a subset of Dataset One, with mobility data extracted from Kelly (2013) rather than Binford (2001), the two datasets were subject to the same data preparation protocol.

2.2. The distance/frequency Index (DFI)

The following analyses consider the position of each hunter-gatherer group on a continuum from those that move short distances frequently to those that move long distances infrequently. A suitable index is therefore required to indicate the position of each group on this continuum. Since numerous previous analyses (e.g., Binford 2001; Kelly 1983, 2013; Grove 2009; Hamilton et al. 2016) have considered the correlates of the total distance moved by a group per annum, the desired index should ideally be independent of this variable. In his analysis of regional patterns of Folsom mobility, Amick (1996:420) plots distance per residential move (here denoted d) against annual frequency of residential moves (here denoted f) for a sample of 21 extant hunter-gatherer groups. Since total distance moved per annum by a given group (t_i) is then equal to the product $d_i f_i$, t is constant when $d = tf^{-1}$ (or, equivalently, when $f = td^{-1}$). Amick (1996:420) therefore plots isoclines of total distance moved per annum, allowing for a visual comparison of levels of mobility. A comparable plot for the sample of 175 hunter-gatherer groups comprising Dataset One is shown as Fig. 1a, with Supplementary Fig. S1a showing an equivalent for the sample of 38 groups comprising Dataset Two.

An equivalent plot of $\ln(f)$ against $\ln(d)$ transforms the isoclines of constant t into straight lines perpendicular to a line of slope 1 from the bivariate origin (Fig. 1b; see Supplementary Fig. S1b for an equivalent treatment of Dataset Two). A 45° counter-clockwise rotation of this plot yields an abscissa that fulfils the requirements for the index identified above (Fig. 1c; see Supplementary Fig. S1c for an equivalent treatment of Dataset Two). In Fig. 1c, the abscissa represents $\ln(d/f)$, with the ordinate representing $\ln(t)$. This figure demonstrates that the log of residential move distance divided by move frequency ($\ln(d/f)$) is orthogonal to, and therefore uncorrelated with, total distance moved per annum. Lower (negative) values of this Distance / Frequency Index (DFI) indicate a strategy of relatively frequent, short moves; higher (positive) values indicate a strategy of relatively infrequent, long moves. Assuming, for instance, that a group moves a total distance per annum of 150 km, they could do so via 3 moves of 50 km, yielding a DFI of 2.81; towards the other end of the spectrum, they could travel the same total distance via 50 moves of 3 km, yielding a DFI of −2.81. This measure permits analysis of the mobility strategy as a feature of mobility which is independent of the total distance that a group moves per annum.

2.3. Statistical analyses

The DFI was regressed on the nine independent variables using Bayesian linear multiple regression. The advantage of the Bayesian approach in this case stems not from the incorporation of prior information, but from the treatment of the regression coefficients as random variables rather than as fixed, unknown quantities. As all variables were standardised prior to analysis, the regression was run without a constant term. The analysis employed diffuse (noninformative) Jeffreys priors, with the joint prior distribution assumed to be proportional to the reciprocal of the disturbance variance. These assumptions yielded analytically tractable posterior distributions (i.e., there was no need for sampling chains or further parameterization). Marginal posterior distributions of the regression coefficients are t-distributions, with the

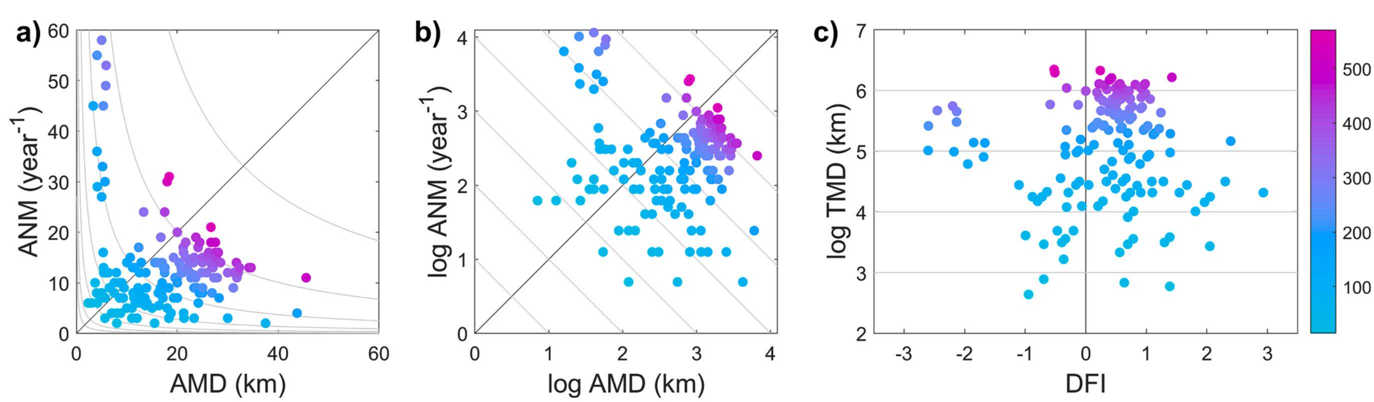

Fig. 1. a) shows average move distance (AMD) plotted against average number of moves per year (ANM) for dataset one. Grey lines are isoclines of total distance moved per year (as per Amick 1996); the black line begins at the bivariate origin and has a slope of unity. b) shows the same plot with logged data; note that the grey isoclines are now perpendicular to the black line. c) shows a 45° counter-clockwise rotation of b). After rotation, the abscissa is equal to the Distance/Frequency Index (DFI) and the ordinate to the log of total distance moved per year (TMD; in km). The colour scale represents total distance moved per year.

posterior distribution of the disturbance variance being inverse gamma. Regression coefficients with 95 % equitailed credible intervals not including zero were considered informative correlates of the DFI. This is directly equivalent to the t-statistic given for each coefficient in a frequentist regression with $\alpha = 0.05$, which tests the null hypothesis that the coefficient is zero and rejects that hypothesis if the coefficient value divided by its standard error falls beyond a critical value of the t-distribution determined by the α value and the degrees of freedom of the model.

Increases in the values of independent variables yielding negative coefficient distributions tend to increase the likelihood of frequent, short-distance moves; increases in the values of independent variables yielding positive coefficient distributions tend to increase the likelihood of infrequent, long-distance moves. Once the informative independent variables had been identified, a second model was run containing only these variables; the validity of this reduced model was checked by comparing its sample-size-corrected AIC value (Akaike 1973; Burnham et al. 2011) to that of the full model. Analyses were run separately on Dataset One and Dataset Two, though only the second (reduced) model was run on the smaller Dataset Two. All analyses were carried out in Matlab R2019b (MathWorks Inc, Natick, MA, USA); all code is provided as a supplementary material.

3. Results

3.1. Dataset One

Results of the initial model in which the DFI was regressed on all 9 independent variables are shown in Fig. 2 and Table 1. From this initial analysis percentage hunting, the size of the mobile group (Group 1), and ET are all informative correlates of the DFI; furthermore, population density and CRR merit retention in a reduced model as their marginal posterior distributions show very low (<10 %) probabilities of crossing the zero line.

Fig. 3 and Table 2 show results of a reduced model using just these five independent variables. This model demonstrates that CRR is an informative correlate of the DFI. Population density has a 0.0248 probability of crossing the zero line, close to the 2.5 % criterion that would be applied in two-tailed frequentist test, but its 95 % credible interval suggests that it should remain in the model. Model comparisons via the sample-size-corrected AICc (Akaike 1973; Burnham et al. 2011) confirm this interpretation: the AICc for the full model is 395.46, that for the reduced model is 389.19, and that for a reduced model without population density is 391.05. This is sufficient to demonstrate that the reduced model (including population density) is the best compromise between complexity (i.e., number of parameters) and goodness of fit. Taken together, the five independent variables in this model explain approximately 49 % of variance in the DFI. A plot of observed against predicted values of the DFI for Dataset One is shown in Fig. 4.

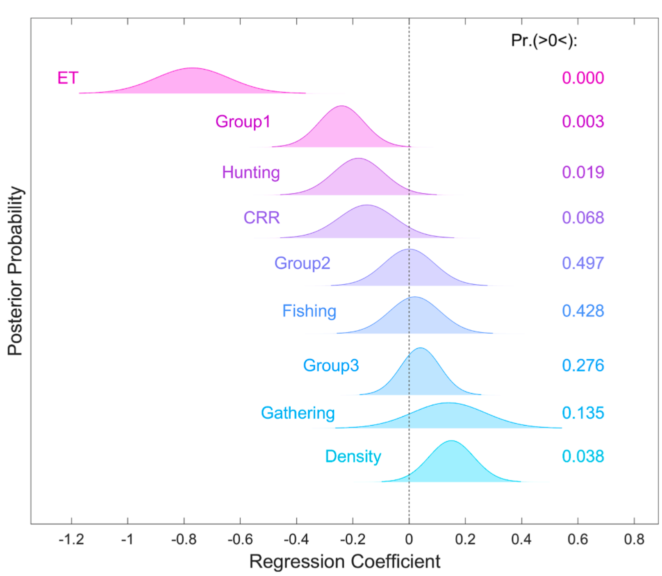

Fig. 2. Results of the initial model for Dataset One. Marginal posterior probability distributions are shown for each independent variable. Pr.(>0 <) indicates the probability that the value of the regression coefficient crosses the zero line (dashed black line) in the direction of opposite sign to its mean.

3.2. Dataset Two

Fig. 5 and Table 3 show results of the reduced model using Dataset Two. ET remains an informative correlate of the DFI, and group size also shows a substantial correlation, though note that the credible interval crosses zero, with ~ 3 % of the distribution being positive (thus, in a frequentist analysis, this variable would not be considered significant). This marginal result for group size is likely caused by the smaller sample size of Dataset Two, and the equivalent reduction in the degrees of freedom of the t-distribution. The AICc value for a model that includes both ET and group size (AICc = 98.45) is lower than that for either all five variables (AICc = 98.73) or for a model including only ET (AICc = 98.88), suggesting that group size should be retained in the model. Taken together, ET and group size explain approximately 41 % of the variance in the DFI when using Dataset Two. A plot of observed against predicted values of the DFI for Dataset Two is shown in Fig. 6.

When employing Dataset Two none of population density, percentage hunting, and CRR (mean annual rainfall) are returned as informative correlates of the DFI. Furthermore, the effects of population density and CRR are of opposite sign in the two analyses (both show negative means when analysing Dataset One and positive means when analysing Dataset Two); this strongly suggests that, pending future analysis, neither should be seen as informative correlates of the DFI.

In summary, the results of analyses on these two datasets demonstrate robust negative relationships between the DFI and ET and group size (i.e., as ET and group size increase, hunter-gatherer groups tend towards more frequent, shorter moves). Further data and further analyses will be required to fully investigate the putative effects of population density, percentage hunting, and mean annual rainfall (CRR).

4. Discussion

The above results show that two variables act as robust, informative correlates of the DFI; these variables can be related to classic models of residential mobility based on the need to avoid excessively depleting resources in a given foraging area. A basic extension of Binford's (1982) 'complete radius leapfrog model' can be developed by assuming that a group of a given size exploits a given area, γ, of habitat per day. Denoting occupation duration in days by δ, minimum total annual mobility T is given (as per Surovell 2000) by:

$$T = 2\sqrt{(\delta\gamma)/\pi} \bullet (365/\delta) \quad [1]$$

This equation formalises Binford's (1982) suggestion that a group must move at least twice the depleted foraging radius when it relocates, and multiplies this distance by the number of moves per year. This admittedly crude model suggests that, *ceteris paribus*, the 'frequent, short moves' strategy will lead to greater total annual mobility than the 'infrequent, long moves' strategy; this is in fact exactly the pattern found by Surovell (2000) in his analysis of Paleoindian residential mobility. This simple result suggests that there must be factors beyond basic energetics that favour a strategy of short, frequent moves; the current study suggests that these factors are greater primary productivity (indexed by ET) and larger group size. Below, these two factors are discussed in more detail; the other three factors included in the reduced model and found to be informative correlates of the DFI when using Dataset One

Table 1
Results of the initial model for Dataset One. Credible correlates of the DFI (determined via the 95 % credible interval) are marked by a 'C'; variables that approach credibility are marked by an 'A'. Pr.(>0 <) indicates the probability that the coefficient value crosses the zero line in the direction of opposite sign to its mean.

	Mean	SD	95 % Cred. Int.		Pr.(>0 <)	Cred. Vars.	t-Distribution Parameters Mu	Sigma	Nu
Density	0.1461	0.0825	−0.0157	0.3080	0.0382	A	0.15	0.08	170
Gathering	0.1425	0.1294	−0.1114	0.3964	0.1347		0.14	0.13	170
Group3	0.0427	0.0722	−0.0989	0.1843	0.2763		0.04	0.07	170
Fishing	0.0171	0.0943	−0.1680	0.2023	0.4276		0.02	0.09	170
Group2	0.0008	0.0901	−0.1760	0.1775	0.4966		0.00	0.09	170
CRR	−0.1500	0.1008	−0.3478	0.0478	0.0681	A	−0.15	0.10	170
Hunting	−0.1819	0.0872	−0.3529	−0.0108	0.0186	C	−0.18	0.09	170
Group1	−0.2353	0.0843	−0.4008	−0.0699	0.0028	C	−0.24	0.08	170
ET	−0.7664	0.1258	−1.0133	−0.5196	0.0000	C	−0.77	0.13	170
Sigmaˆ2	0.5367	0.0596	0.4324	0.6657	1.0000		83.00	0.02	*IG

*IG indicates the inverse gamma distribution. Variables are listed in order of decreasing mean. Sigmaˆ2 represents the disturbance variance.

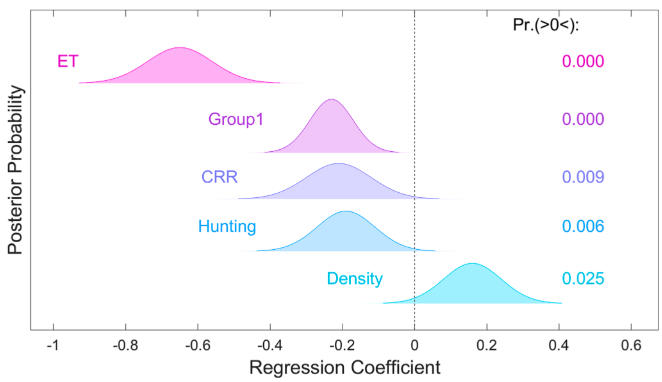

Fig. 3. Results of the reduced model for Dataset One. Marginal posterior probability distributions are shown for each independent variable. Pr.(>0 <) indicates the probability that the value of the regression coefficient crosses the zero line (dashed black line) in the direction of opposite sign to its mean.

(population density, percentage hunting, and mean annual precipitation) are also briefly discussed, as these may be relevant to future analyses of larger datasets.

4.1. Group size

In the analyses of both Dataset One and the smaller Dataset Two, larger group sizes are associated with more frequent, shorter moves. This may simply be because it is impractical to move a large group over long distances. Larger groups therefore ultimately move further during the course of a year (Surovell 2000; Grove 2009), but do so via many relatively short residential moves. Living in larger groups is therefore an energetically expensive strategy, although it may bring many social and subsistence-related benefits such as increased task specialisation and the ability to engage in coordinated, large-scale hunting activities. Assuming that resources are depleted at a constant rate per capita per unit time, and that resources closest to the residential camp are depleted first, large groups may quickly exhaust local areas, making daily foraging increasingly inefficient due to transport costs. Whilst task-specific subgroups could continue to range further in search of particular resources, the rapid depletion of gathered resources from the local region caused by a large group would necessitate regular relocations of the residential base (Sahlins 1972; Kelly 1995). The relationship between group size and task-specific foraging (i.e., logistical mobility) is considered in greater detail below.

4.2. Effective temperature

Higher values of ET are associated with more frequent, shorter moves in both Dataset One and Dataset Two. Figs. 4 and 6 show substantial scatters of points with intermediate values of the DFI, with tails showing both high and low values (as would be expected in normally distributed data). As ET is a strong negative correlate of the DFI, and is also broadly negatively correlated with absolute latitude, the strategy of frequent, short moves might be expected to predominate in the tropics. Fig. 7 plots the geographical distribution of Dataset One: groups within one standard deviation of the mean value of the DFI (~68 % of data) are plotted in black; those below one standard deviation from the mean (~16 % of data) in red, and those above one standard deviation from the mean (~16 % of data) in green. This is an arbitrary discretization of continuous data that allows for a depiction of the relative geographical prevalence of groups strongly aligned with the frequent, short-move strategy (in red) and the infrequent, long-move strategy (in green). As anticipated, the majority of frequent, short-move strategists (when discretized in this way) are located in the tropics, and the majority of infrequent, long-move strategists are located further from the equator (with a particular prevalence in North America). However, this is not exclusively the case; some groups outside the Tropics practice frequent, short moves and, conversely, not all groups in the Tropics follow this strategy. This suggests that there are important mitigating factors related to other correlates of the DFI.

Of particular interest here are three groups that do not fit this general

Table 2
Results of the reduced model for Dataset One. Credible correlates of the DFI (determined via the 95 % credible interval) are marked by a 'C'. Pr.(>0 <) indicates the probability that the coefficient value crosses the zero line in the direction of opposite sign to its mean.

	Mean	SD	95 % Cred. Int.		Pr.(>0 <)	Cred. Vars.	t-Distribution Parameters Mu	Sigma	Nu
Density	0.1595	0.0812	0.0003	0.3188	0.0248	C	0.16	0.08	170
Hunting	−0.1899	0.0758	−0.3386	−0.0411	0.0063	C	−0.19	0.08	170
CRR	−0.2097	0.0882	−0.3827	−0.0367	0.0089	C	−0.21	0.09	170
Group1	−0.2333	0.0616	−0.3541	−0.1125	0.0001	C	−0.23	0.06	170
ET	−0.6494	0.0873	−0.8208	−0.4780	0.0000	C	−0.65	0.09	170
Sigmaˆ2	0.5314	0.0583	0.4292	0.6574	1.0000		85.00	0.02	*IG

*IG indicates the inverse gamma distribution. Variables are listed in order of decreasing mean. Sigmaˆ2 represents the disturbance variance.

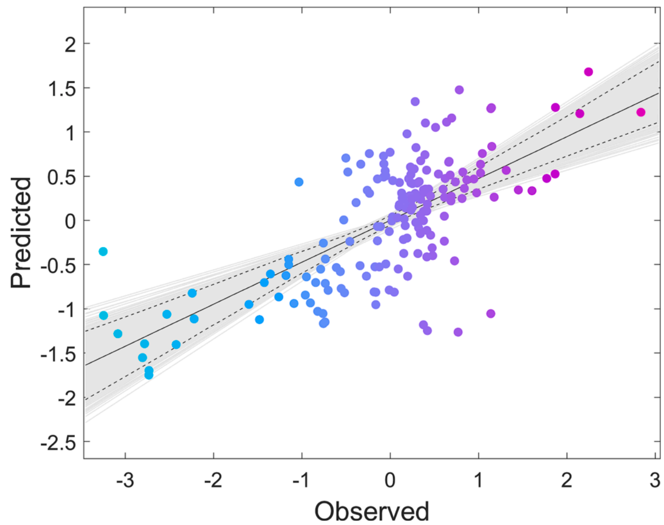

Fig. 4. Values of the DFI predicted by the reduced model plotted against observed values for Dataset One. Grey lines show 1,000 calls from the marginal posterior distributions of the coefficients and the disturbance variance. The solid black line shows the mean result; the dashed black lines show the 95% credible intervals around this mean. The colour scale represents the observed DFI.

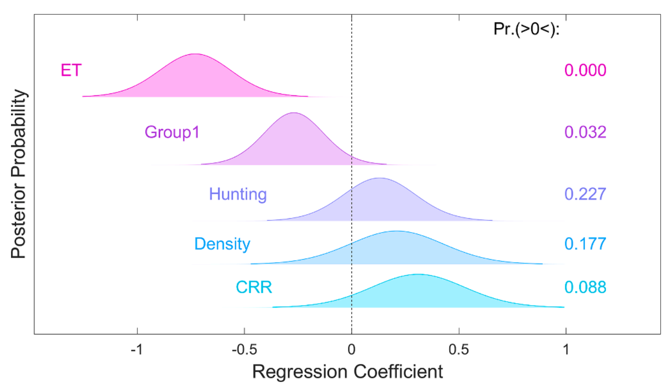

Fig. 5. Results of the reduced model for Dataset Two. Marginal posterior probability distributions are shown for each independent variable. Pr.(>0 <) indicates the probability that the value of the regression coefficient crosses the zero line (dashed black line) in the direction of opposite sign to its mean.

latitudinal pattern (i.e., the three green points in Fig. 7 that fall within the tropics). These are the Vedda (or Wanniyalaeto; their language is referred to as 'Vedda'), tropical forest foragers of Sri Lanka, the Cholanaickan (also referred to as Cholanaikkan or Sholanaikan), who inhabit the Nilambur Valley forests of Malappuram in the Kerala region of southern India, and the Nharo (referred to as Naron in earlier ethnographic accounts) of the central-western Kalahari, Botswana (Bleek 1928; Barnard 1979, 1980; Roberts et al. 2018; Seligmann and Seligmann 1911; Vahia et al. 2017; Seetha 2014). In each case, the relatively high DFI values may be caused by generally low mobility, coupled with disproportionately low numbers of moves per year. Mobility is limited among the Vedda due to their specialisation on tropical forest prey within the available areas of the complex Sri Lankan ecosystem (Seligmann and Seligmann 1911; Roberts et al. 2018), among the Cholanaickan due to their rapidly declining population size and strict territorial organisation (Seetha 2014; Vahia et al. 2017), and among the Nharo by territorial boundaries tied to movement between waterholes (Barnard 1980). Barnard (1980:116) notes that the Nharo "do not migrate in band-size groups", but that individuals "move from band to band freely", a pattern that might disguise greater levels of individual mobility than is apparent from the average figures given in Binford (2001). Each of these groups also suffers the coupled effects of diminishing habitat and encroaching agriculture to some extent. The Vedda demonstrate long-standing relationships with neighbouring agricultural populations, the Cholanaickan population now consists of less than 200 individuals, and has approximately halved in the past 30 years (Vahia et al. 2017), and Barnard (1980) describes marked differences in spatial organisation among some Nharo bands due to the depletion of game and the effects of contact with neighbouring ethnic groups that have occurred since an earlier census (Bleek 1928).

In a comparable plot of Dataset Two (see Supplementary Figure S2), the Baffinland Inuit emerge as an extreme outlier, practicing a strategy of frequent, short moves despite occupying a latitude of 65′ North, close

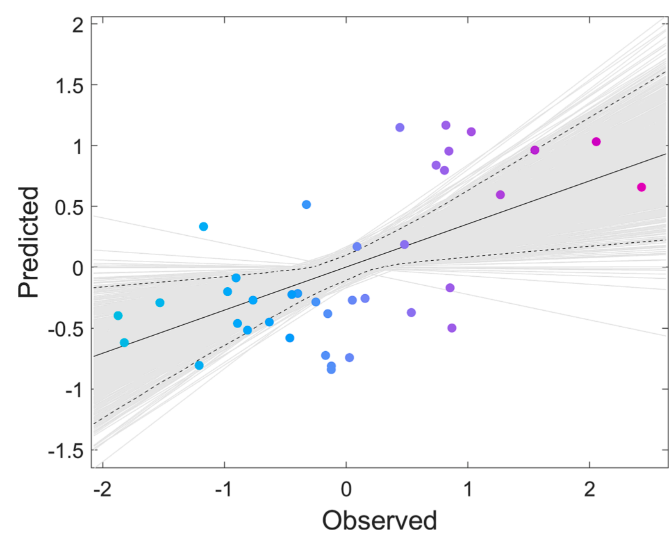

Fig. 6. Values of the DFI predicted by the reduced model plotted against observed values for Dataset Two. Grey lines show 1,000 calls from the marginal posterior distributions of the coefficients and the disturbance variance. The solid black line shows the mean result; the dashed black lines show the 95% credible intervals around this mean. The colour scale represents the observed DFI.

Table 3
Results of the reduced model for Dataset Two. Credible correlates of the DFI (determined via the 95 % credible interval) are marked by a 'C'. Pr.(>0 <) indicates the probability that the coefficient value crosses the zero line in the direction of opposite sign to its mean.

	Mean	SD	95 % Cred. Int.		Pr.(>0 <)	Cred. Vars.	t-Distribution Parameters		
							Mu	Sigma	Nu
CRR	0.3098	0.2310	−0.1457	0.7652	0.0879		0.31	0.22	33
Density	0.2053	0.2255	−0.2395	0.6501	0.1772		0.21	0.22	33
Hunting	0.1322	0.1799	−0.2226	0.4870	0.2269		0.13	0.17	33
Group1	−0.2730	0.1474	−0.5636	0.0176	0.0323	C	−0.27	0.14	33
ET	−0.7327	0.1769	−1.0815	−0.3839	0.0001	C	−0.73	0.17	33
Sigma^2	0.7056	0.1853	0.4312	1.1484	1.0000		16.50	0.09	*IG

*IG indicates the inverse gamma distribution. Variables are listed in order of decreasing mean. Sigma^2 represents the disturbance variance.

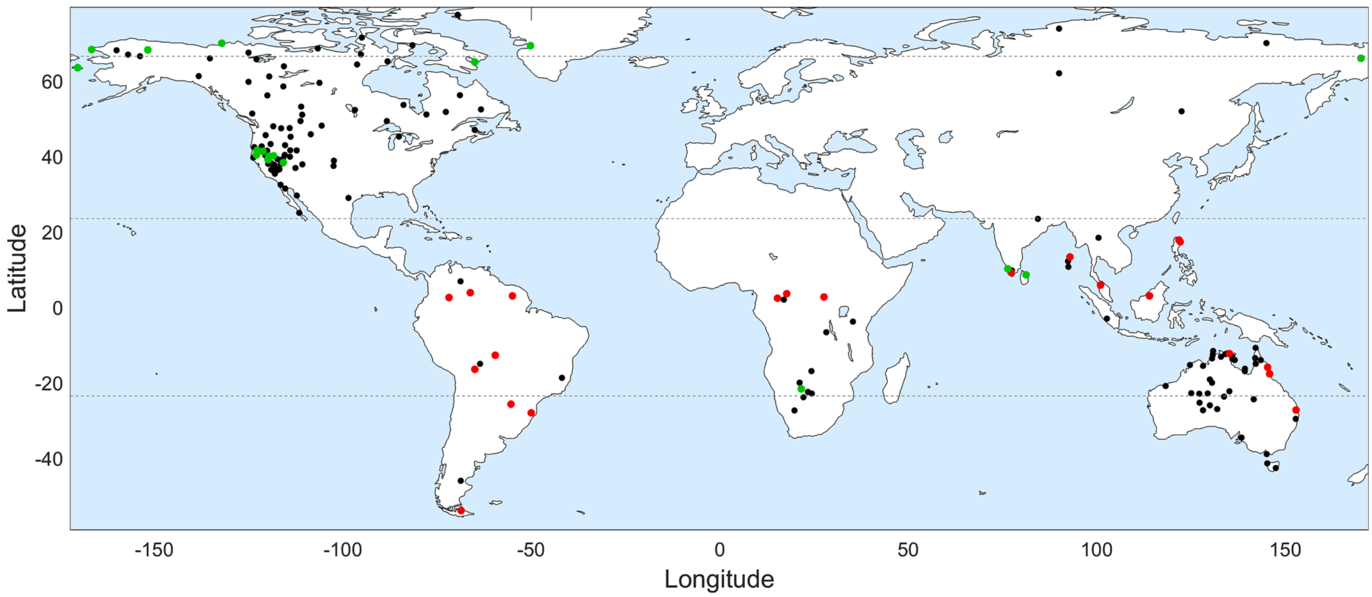

Fig. 7. Geographical locations of the Dataset One sample. Red points show groups with an observed DFI less than −1 (these groups move short distances frequently); green points show groups with an observed DFI greater than 1 (these groups move long distances infrequently). All other groups are shown by black points. The Arctic Circle and the Tropics of Capricorn and Cancer are shown as dashed grey lines.

to the Arctic Circle. In the analyses of Dataset Two reported above, group size is the only other informative correlate of the DFI, with larger groups on average more likely to engage in frequent, short moves. The Baffinland Inuit, however, have a group size of 12, lower than the median for the dataset (17); this suggests that there must be additional variables, not explored in the current analyses, that explain this strategy. Kelly (2013:283) notes some uncertainty relating to Hantzsch's (1977) data on the Baffinland Inuit, suggesting that the group may have moved more frequently, and moved further from the coast than they otherwise would have done due to Hantzsch's presence among them. This data point might therefore appear as an outlier in the above analysis due to the inconsistencies of ethnographic data collection rather than because it represents the typical mobility strategy of this group. It should further be noted that, when employing Kelly's (2013) data (Dataset Two), the Vedda do not emerge as an outlier in terms of the DFI as they do when employing Dataset One. The other two groups highlighted above as outliers in the analysis of Dataset One (the Cholanaickan and the Nharo) do not feature in this smaller dataset.

4.3. Other variables

Higher population densities are associated with less frequent, longer moves in Dataset One, but do not emerge as an informative correlate of the DFI in Dataset Two. Although total annual mobility among high-density populations is relatively low (Grove 2016), results of the Dataset One analysis suggest that individual residential moves in such populations could cover relatively long distances. It should be noted that the DFI effectively partials out (i.e., controls for) total annual mobility, and that this result therefore reveals a different dimension of mobility in relation to population density. Population densities tend to be higher when environmental productivity is higher, and in such circumstances, there is generally greater reliance on gathered plant resources (and equivalently less reliance on hunting; see Grove, 2010a). It is plausible that habitation of high-productivity environments that facilitate high population densities and a primary reliance on plant resources is a stable, preferred state for hunter-gatherer populations, ensuring maximum energetic efficiency (as per the model described by equation [1]). Given that population density is not an informative correlate of the DFI in Dataset Two, however, any firm conclusions must await future analyses.

Greater percentages of hunting in the diet are associated with more frequent, shorter moves in Dataset One, but do not emerge as an informative correlate of the DFI in Dataset Two. Hunting is a more prevalent strategy when environmental productivity is lower (or when a large proportion of the primary biomass is inedible for humans), as occurs further from the equator (Grove, 2010a). Hunting is never the sole means of subsistence; in Dataset One, only 23 % of groups rely on hunting for more than 50 % of their calories, and only 3.5 % rely on hunting for more than 75 % of their calories. Hunting does, however, exert a disproportionate effect on various aspects of group social organisation, including mobility, and may also be crucial in shaping the nature of a group's technological strategy (e.g., Oswalt 1976; Torrence 1983). Within Dataset One, there is also a significant, positive correlation between the percentage of hunted foods in the diet and group size (Group 1); there is evidence that larger groups are required for a strategy that relies on big game hunting, and also that hunters must relocate frequently so as to avoid accumulations of butchery debris (Yellen 1977; Potts 1988) or because they have scared off the herbivore herds on which they rely. Though the depletion of plant resources is often considered to be the trigger for a residential move (e.g., Kelly 1992), as seen in the Batek of tropical rainforest Malaysia (Venkataraman & Kraft, 2017), it may be that accumulation of debris, rather than depletion of resources, is also a powerful stimulus to movement (see also Grove 2009). There are therefore sound, logical reasons for expecting a substantial reliance on hunting to lead to a higher frequency of residential moves but, given the ambiguous result of the Dataset Two analysis in this respect, future studies will be required to further explore this relationship.

4.4. Discrepancies between the two datasets

There are many sources of potential error associated with ethnographic data on mobility: while the data in Dataset One were collated by Binford (2001) and the data in Dataset Two by Kelly (2013), the original data were collected by multiple different individuals at different times and for different purposes. Some data were collected during long-term studies, while others were collected as short-term estimates of the 'annual round'; some studies therefore present aggregate data, while others represent single datums. Given these vagaries, this section briefly summarises the key differences between the Binford (2001) and Kelly (2013) databases (with the caveat that they can only be compared in relation to those groups that appear in both).

Supplementary Figure S3 plots the correlations between the two datasets for number of moves per year ($r(36) = 0.77$, $p < .001$), total distance moved per year ($r(36) = 0.52$, $p < .001$), and residential move distance ($r(36) = 0.46$, $p = .003$). The two datasets show statistically significant correlations on all three variables, but there are also a few notable discrepancies, all of which result from higher estimates in the Kelly (2013) database than in the Binford (2001) database. The significant outliers (those data points that are more than two standard deviations from the isoline) are given in Supplementary Table S1. It is worth noting that the data on just five groups (the Baffinland Inuit, Montagnais, Ngadadjara, Squamish, and Tsimshim) account for all the statistically defined outliers, and that when these groups are removed, the correlations between the two datasets improve considerably (number of moves per year $r(31) = 0.92$, $p < .001$; total distance moved per year $r(31) = 0.94$, $p < .001$; residential move distance $r(31) = 0.83$, $p < .001$). Though there is relatively strong concordance between Dataset One and Dataset Two (on the 38 groups that appear in both datasets), the strategy of analysing multiple datasets, examining their similarities and differences, and accepting as informative only those results that are consistent across datasets may help to alleviate some of the problems associated with analysing ethnographic data.

4.5. Archaeological correlates of the DFI

The DFI describes a continuum of mobility strategies from relatively frequent, short moves (indicated by lower negative values) to relatively infrequent, long moves (indicated by higher positive values). The results reported above demonstrate that the DFI correlates robustly with both effective temperature and group size across the two datasets considered. It can also be expected, however, to correlate with a number of directly observable archaeological variables, most of which relate directly to the intensity or duration of site occupation of hunter-gatherer sites. An important caveat relates to the fact that the analyses above consider distances travelled and numbers of moves per annum; such resolution is rarely available in archaeological investigations, but generic trends governing the articulation of residential relocation distances, move frequencies, and occupation durations are nonetheless likely to be informative.

Larger groups and longer occupation durations would be expected to lead to greater accumulations of material at archaeological sites, though this can be measured in different ways. Grove (2009), analysing data from Dobe !Kung camps provided in Yellen (1977), demonstrated that the absolute limit of scatter (a proxy for site size) increases with both occupation duration and group size. In archaeological cases, where both the duration of occupation and the size of the occupying group are unknown, it is impossible to assess the relative impact of (varying) group size versus (varying) occupation duration on the quantity and spatial extent of material found at a given site. Accordingly, the archaeological correlate of these variables is usually reduced to a measure of ‘occupation intensity’ (e.g., Starkovich 2017). Limit of scatter is rarely an available metric in archaeological studies; the majority of sites are not fully excavated, and, even if this were the case, defining the ‘true’ limits of the settlement, and establishing contemporaneity of occupation across the total area, is difficult. Instead, researchers have estimated material (lithic) accumulation rate per unit of sediment / unit of time as a proxy for occupation intensity (e.g., Ashton and Lewis 2002; Ashton and Hosfield 2010; Mellars and French 2011; Tryon and Faith 2016). This proxy assumes constant sedimentation rates (see Dogandzic & McPherron, 2013; French 2016), which must be inferred from reliable dating of sequences (French 2016; Tryon and Faith 2016), as well as systematic recovery of lithic material (French 2016). Moreover, the agent-based model of Gravel-Miguel et al. (2021) suggests that the majority of hunting armatures could be lost in areas of low archaeological visibility, suggesting that caution must be taken when using the distribution and density of archaeological material as representative of demographic variables. Nonetheless, this proxy can be valuable when comparing different occupation levels within a site.

The use of the measure of lithic accumulation rates as a proxy for diachronic or geographic variation in occupation intensity (and, from there, mobility) also assumes a limited influence of alternative behavioural factors —such as changes in artefact use and function, patterns of manufacture and discard, and raw material supply— on these accumulation rates (French 2021: 32). This is unlikely to have been the case, but such technological behaviours can themselves function as proxies for the facets of mobility encompassed in the DFI. The longer a group spends at a site, the more likely it is that they will need to revive existing tools or make new ones; since these activities produce more debitage than they do retouched tools, the ratio of retouched tools to debitage should decline over time (e.g., Kuhn 1995; Barton and Riel-Salvatore 2014). The advantage of this proxy for occupation duration is that it does not depend on restrictive assumptions and is independent of the volume of material recovered (though note that some recovery methodologies bias against full collection of debitage, and that the measure of retouch frequency can be combined with that of total material recovered/unit volume to additionally inform on mobility strategies (i.e., logistical or residential) (Barton et al. 2013)). This ratio is dependent, however, upon the accurate identification of tools within the assemblage (French 2016); this may be confounded by the use of expedient tools, informal artefacts, or unretouched flakes which might not always be counted as tools (Holdaway & Douglass, 2012).

Assuming that foragers initiate an occupation whilst in possession of a full operational toolkit, and that they may have transported elements of that toolkit over considerable distances, the proportion of non-local raw materials in an assemblage should also decline as occupation duration increases (e.g., Surovell 2000). The interpretation of this proxy depends to some extent on the scope of task-specific mobility (see below) as well as the availability of raw material. Tomasso and Porraz (2016), for example, found that a large quantity of lithic material was imported long distances to Palaeolithic sites in the Liguro-Provençal Arc of Italy and France, likely because high-quality flint was not locally available. Surovell (2009:101ff.) combines the ratio of local to non-local raw materials and the ratio of debitage to non-local retouched tools into his Occupation Span Index (OSI), and demonstrates via analysis of materials from Puntutjarpa rockshelter that the OSI is positively correlated with artefact density (measured as number of artefacts per square metre). The OSI provides a valuable measure of occupation duration, and importantly it does not conflate occupation duration with group size as crude lithic density measures can do.

In his study of the Mousterian lithic assemblages of West-Central Italy, Kuhn (1995) suggests that groups with high levels of residential mobility may face periods in which they do not have access to – or have yet to identify – reliable sources of raw material. Such groups are therefore more likely to extensively retouch existing tools and to more fully exploit cores. Reduction intensity and relative tool size (when comparing assemblages of similar age belonging to the same technocomplex) might therefore be useful proxies for residential mobility, a finding supported by some subsequent analyses (e.g., Marks et al. 1991; Morrow 1997; Clarkson 2013). It should be noted, however, that such conclusions are not universally supported; Tryon and Faith (2016), for example, did not find the expected correlations between reduction intensity, tool size, and residential mobility in their work at Nasera. This could indicate that not all groups with higher residential mobility fall into the pattern proposed by Kuhn (1995).

Finally, groups that practice low residential mobility, and therefore occupy individual sites for extended periods, may be more likely to engage in task-specific or logistical mobility. In Binford’s (1980) classic model, foragers engage in high residential mobility but low logistical mobility, whereas collectors demonstrate the opposite pattern. More recent research (e.g. Grove, 2010a; Grove and Dunbar 2015) views logistical mobility as a form of fission–fusion social organisation, noting that it is essential for the maintenance of large groups that remain in a given locality for extended periods of time, as is also the case for non-human primate groups (e.g. Korstjens et al. 2006; Lehmann et al. 2007). Such logistical trips can take individuals dozens of kilometres from their primary occupation site and can span several days (Kelly 1983). This has the potential to introduce distant lithic material, brought back from these trips to the occupation site (Brantingham 2006), which could on occasion confound the predicted relationship between the quantity of local lithic materials and the DFI discussed above.

The foregoing considerations suggest that higher values of the DFI – indicating a strategy relatively infrequent, long moves – will in most cases be associated at individual archaeological sites with greater accumulations of material, lower ratios of retouched tools to debitage, lower frequencies of non-local raw materials, lower reduction intensity, and a greater reliance on logistical mobility. When combined with the environmental and demographic correlates of the DFI established above, a scenario such as that depicted in Fig. 8 emerges.

4.6. Related models of forager mobility

The DFI characterizes the extent to which a hunter-gatherer group relies on frequent, short moves or infrequent, long moves in the pursuit of subsistence resources. There are, however, related models that characterize the move-length distribution of a given hunter-gatherer group in cases where a reasonable sample of move lengths have been recorded. Of particular interest here are those models that consider classes of random walks, such as Lévy walks, in the characterisation of hunter-gatherer mobility (e.g., Brown et al. 2007; Grove, 2010a; Miramontes et al. 2012; Raichlen et al. 2014). A Lévy walk implies a negative power-law move length distribution, such that longer move lengths are proportionately less likely to occur. Formally, the probability of a move of length m is given by $\Pr(m) = cm^{-\alpha}$, with $1 \le \alpha \le 3$. The distribution is necessarily curtailed at some minimum move length $m_{\min}$, and $c = (\alpha - 1)m_{\min}^{\alpha-1}$ is a constant that normalizes the probability distribution such that the integral is equal to unity (Schreier and Grove 2010, 2021); note that power laws with $\alpha < 1$ cannot be normalized. The exponent α then characterizes the move length distribution, with higher values of α indicating that short move lengths are proportionately more likely and longer moves lengths proportionately less likely than they would be under lower values of α. Empirically, a power-law can be fitted to a sample of move lengths for a given hunter-gatherer group via maximum likelihood methods (Newman 2005; Edwards et al. 2007; Schreier and Grove 2010) to derive the exponent characteristic of the move length distribution (e.g., Brown et al. 2007; Grove 2010b; Raichlen et al. 2014). Theoretically, exponents could then be compared between groups to examine whether they are affected by, for example, variation in social or ecological variables; thus far, however, systematic studies have been precluded by the very small number of hunter-gatherer groups for which there are sufficient samples of individual move distances.

The DFI, by contrast, can be calculated from the simple combination of mean move distance and annual move frequency or from either of these variables in combination with total distance moved per annum. Such data is available for a relatively large number of hunter-gatherer groups (e.g., Binford 2001; Kelly 2013). A higher DFI value indicates a pattern of relatively infrequent, long-distance moves; as such, there should be a negative relationship between the power-law exponent, α, and the value of the DFI. Although currently impossible to test empirically in hunter-gatherers, preliminary simulations (not shown) suggest that this is indeed the case; movement patterns generated from power-laws with relatively low α values generate relatively high DFI estimates. This logically leads to the question of whether the empirically hard-to-measure power-law exponent can be predicted from the empirically easy-to-measure DFI. Such efforts will be complicated by the fact that the DFI is a measure ultimately reliant on an estimate of the *mean* move distance; the mean is rarely an appropriate measure of power-law behaviour, and indeed power-laws with $\alpha \le 2$ have no finite mean (Newman 2005). Calculations employing the median, which is finite for $\alpha > 1$, may be more appropriate, as may be considerations of truncated power laws, which limit the region over which power-law behaviour holds to some distance range $m_{\min} \le m \le m_{\max}$ and are therefore more easily normalized.

Thus far, some of the most important insights from the study of Lévy walks in relation to human foraging come from cases in which their assumptions are violated. For example, the initial interest in Levy walks as foraging models arose from the finding that they represent an optimal search algorithm for foragers searching without prior knowledge for randomly distributed, static, non-depleting, low density resources (e.g., Viswanathan et al. 1996, Viswanathan et al., 1999). The assumption of random search, however, hardly seems appropriate to foraging groups with intimate and extensive knowledge of their environments (see Schreier and Grove 2010, 2014, 2021 for similar arguments). By contrast, hunter-gatherer groups may be following an established seasonal round, moving between known locations, and in some cases cleaning, repairing and reoccupying previous camps (e.g., Yellen 1977; Haas et al. 2019).

A second relevant weakness of Lévy walk models is that what appear to be power-law distributions may in fact arise from the superposition of two different modes of mobility (Benhamou 2007; see Grove, 2010a for a hunter-gatherer application). Broadly, these two modes represent

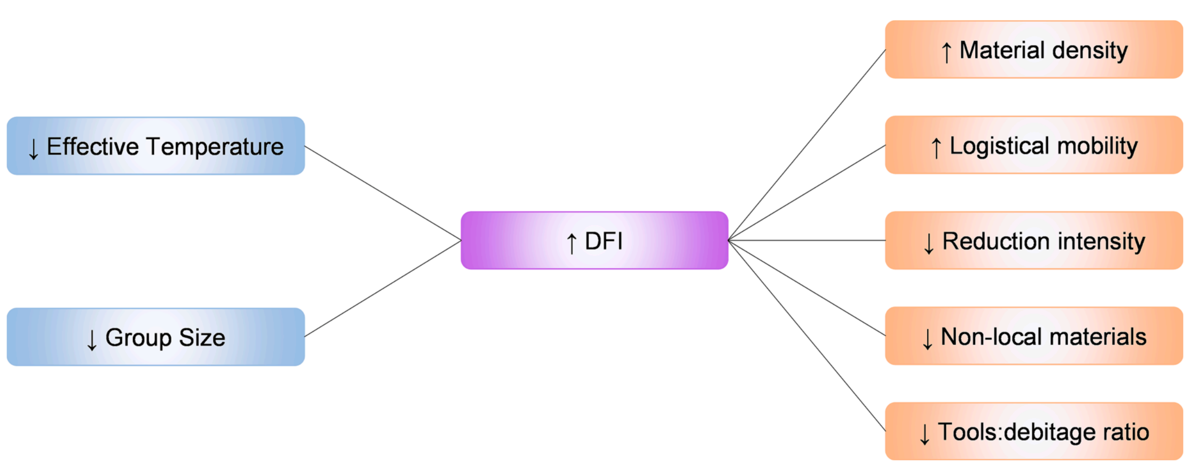

Fig. 8. Correlations between effective temperature and group size (blue boxes), the DFI, and observable archaeological variables (amber boxes). Arrows indicate directions of effects (for example, a decline in effective temperature correlates with an increase in the DFI – suggesting a strategy of relatively infrequent, long moves – which in turn suggests an increase in material density at associated archaeological sites).

movements within and between patches; in relation to the issue of random search, foragers might move between known high-productivity patches, but then search locally within them for resources. In human foragers, this two-mode system could be fruitfully adjusted to examine the balance between residential moves and foraging trips that begin and end at the same residential base; the latter could be further divided into gathering trips within the foraging radius and task-specific logistical forays that stray further from the residential base. In this vein, a model developed by Perreault and Brantingham (2011) elegantly describes the forager-collector continuum by examining the number of foraging moves a group makes before returning to its residential base.

The study of logistical mobility may prove to be particularly fruitful ground for such models, and could be profitably related to the DFI via Binford's original (1980) distinction between 'foragers' and 'collectors'. One axis of this distinction states that "foragers move consumers to goods with frequent residential moves, while collectors move goods to consumers with generally fewer residential moves" (Binford 1980:15). In relation to the current study, 'foragers' would be expected to show lower (negative) DFI values, with 'collectors' showing higher (positive) DFI values. In addition, groups with higher DFI values should be more likely to engage in logistical mobility so as to compensate for their relatively low residential move frequencies. Finer-grained analyses of these factors in cases where data are of sufficiently high resolution could help to unite within-group and between-group models of hunter-gatherer mobility.

4.7. A second axis of variation in hunter-gatherer mobility

The finding that the DFI correlates reliably with environmental and social variables, and the ability to integrate it with established proxies of mobility based on elements of material culture in archaeological assemblages, both suggest that it represents a major axis of variation with considerable potential for characterising hunter-gatherer mobility. Total distance moved per annum is the most often used index of mobility, and is justifiably the primary axis along which mobility is measured; the design of the DFI such that it is orthogonal to this primary axis, however, provides a second, independent axis with which to qualify important aspects of the mobility strategy. Much as the first two principal components of a multi-dimensional dataset often provide a powerful shorthand description of the total variation present, so the use of total annual mobility in conjunction with the DFI provides substantial explanatory power in describing variation in hunter-gatherer mobility in just two dimensions. As the DFI is easy to calculate – from data that are widely available for ethnographically documented hunter-gatherer groups – it will likely prove a useful adjunct to existing methods for studying mobility.

5. Conclusions

The Distance/Frequency Index (DFI) characterises hunter-gatherer mobility along an important and often neglected continuum between frequent, short moves and infrequent, long moves. Within both datasets analysed, the DFI correlates negatively with effective temperature and group size. Archaeologically, the DFI maps onto a series of metrics that can be obtained from many assemblages, correlating positively with material density and negatively with reduction intensity, ratios of retouched tools to debitage, and frequencies of non-local raw materials. In relation to classic models of hunter-gatherer settlement systems, higher values of the DFI imply a greater reliance on logistical mobility. It is suggested that the DFI forms an analytically useful second axis of variation in hunter-gatherer mobility, and that it should in future be analysed alongside total distance moved per annum to provide a more comprehensive picture of the mobility strategy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and code uploaded as supplementary files

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Appendix A. Supplementary materials

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.104266.

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