

# **Sociality and Proximity in Hunter-Gatherer Settlements**

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*This is to certify that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been previously submitted for any degree or other purposes.*

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*Aaron Heath Olsen*

For Annika.

## Abstract

The hunter-gatherer settlement is human sociality inscribed on the landscape. Captured in the spaces between the dwellings and other domestic features is the decision to be near other people, but also to maintain some degree of distance. For the archaeologist, those spaces offer a glimpse into the motivations and lives of people spanning the depth of human history. But to interpret them requires an understanding of how space, behaviour and context relate to one another. Studies of domestic spacing in contemporary hunter-gatherer settlement have largely concentrated on population density as a measurable variable. As a byword for poor living standards, the high population densities observed in some hunter-gatherer communities have attracted attention, particularly since low population densities appear to be the norm among many other communities. Various hypotheses have been put forward to explain this variability in population density, but none offer an adequate explanation. In most cases, entire cultural groups that do not confirm to expectations may be found.

The aim of the present study is to investigate the determinants of household separation in hunter-gatherer settlements. The study proposes that two neurobiological phenomena play a key role: ‘social homeostasis’ and ‘social buffering’. Social homeostasis is the tendency of individuals to modify their social behaviour to minimise the opposing stresses of social crowding and loneliness. Social buffering describes the phenomenon by which the human stress response is reduced through physical proximity to social affiliates, especially friends and family. Data are compiled from ethnographic and archaeological observations of hunter-gatherer societies made over the last two centuries. Statistical analysis shows that household separation varies with household size (number of people per household) and community size (number of people per settlement), consistent with the modification of social interaction to maintain social homeostasis. It is further shown that physical proximity is greater between households that practice high risk hunting strategies, consistent with the social buffering of the uncertainty of protein provisioning. The findings of the present study have implications for interpretation of archaeological sites and for our understanding of how humans interact with and are impacted by the built environment.

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# Chapter 1

## INTRODUCTION

In September 1822, an English naval officer and explorer by the name of William Edward Parry encountered the Iglulingmiut winter village of Iglulik. Set back from the frozen shoreline of Iglulik Island in the Canadian Arctic, the village consisted of a tight cluster of five whalebone houses (Lyon 1824, pp. 235–236). In describing the dwellings, Parry (1824, p. 358) remarked that:

‘... their extreme closeness and accumulated filth, emitted an almost insupportable stench, to which an abundant supply of raw and half-putrid walrus flesh in no small degree contributed’

The Iglulingmiut were certainly not wanting for land within which to distribute themselves. So their choice to combine a predilection for rotten meat with high density living likely seemed a surprising one to Parry. The stench of putrefaction aside, the noise of other people, potential for conflict and greater likelihood of disease transmission that accompany high density living mean that it is often equated with a lower standard of living in contemporary urban environments (e.g. Cramer et al. 2004; Fassio et al. 2012; Mouratidis and Yiannakou 2022; Satu and Chiu 2019; although see also Başkan et al. 2017). Yet, the Iglulingmiut are not an isolated case (e.g. Draper 1973). Moreover, the imposition of contemporary urban standards on hunter-gatherers has a fraught history. The expected benefits of resettling hunter-gatherers in more ‘modern’ conditions are often not realised, the disruption to their traditional lifestyle instead resulting in a range of societal problems (e.g. Billson 1990; Bishop 1974; Condon 1981; Petersen 1986; Thomas and Thompson 1972; Waldram 1987). To the Iglulingmiut, high density living may well have been the obvious choice.

Two centuries after Parry’s encounter with the Iglulingmiut, it remains unclear why some hunter-gatherers choose to live in high density settlements, while others opt for more spacious living conditions. The present study seeks to redress that gap in our understanding by investigating possible determinants of household separation in hunter-gatherer settlements.

## 1.1 The Hunter-Gatherer Settlement

The first question that should be resolved in any hunter-gatherer study is the meaning of the term ‘hunter-gatherer’. It is a term that has stubbornly defied any attempt by anthropologists and archaeologists alike to codify its meaning (Pluciennik 2004; Warren 2021). Following Kelly (2013, p. 22), it is used in the present study as a heuristic device, embracing for the purpose of analysis that subset of humanity who rely on wild plants, wild animals or both for at least part of their normal subsistence. Included within this scope is the vast ‘middle ground’ of human subsistence behaviour, in which hunting and gathering may be a part of a diverse subsistence strategy (Denham and Donohue 2022, 2023; Smith 2001). No typological constraints or generalisations are assumed of these people. Their grouping together merely provides the means to consider the variability in human behaviour inherent to the practice of hunting and gathering.

The term ‘settlement’ also deserves clarification from the outset. It is applied in the present study to any area inhabited by a social group for domestic tasks, such as cooking, eating and sleeping. Although this term may evoke a sense of permanence, it is used expansively in this study to encompass any length of occupation. While it is acknowledged that short-lived hunter-gatherer sites are commonly described as ‘camps’, use of the term ‘settlement’ in this way has precedent (Chang 1962; Grøn and Kuznetsov 2004; Whitelaw 1994; Wiseman 2014). The reason for this semantic liberality is twofold. Firstly, in the absence of a widely-used generic expression that encompasses both temporary camps and permanent settlements, it avoids cumbersome repetition of both terms in tandem. Secondly, it seeks to avert any inference of a typological distinction between camps and settlements, let alone one that is material to the present study. After all, the transience of even the most enduring settlement becomes apparent when viewed at a large enough timescale.

Hunter-gatherer settlements provide an unbroken link between the earliest humans and the estimated 5 million individuals practicing hunting and gathering as a primary mode of subsistence today (Tucker 2022). The physical features of those settlements, whether captured in the archaeological record or observed by anthropologists, have the ability to provide insights into the behaviours of hunter-gatherers and humans more broadly. The same can be said of the spatial distribution of those features. The spatial distribution of animal bone fragments about a campsite tells a story of social interaction and food sharing that is repeated over tens of millennia and thousands of kilometres by multiple human lineages (Enloe 2003; Gabucio et al.

2018; Waguespack 2001). An understanding of the importance of population density or internal spacing of households within hunter-gatherer societies may tell an equally compelling story.

## 1.2 Space and the Hunter-Gatherer

A motivator of efforts to understand the spatial characteristics of contemporary hunter-gatherer settlements is the potential to apply that understanding to the interpretation of past hunter-gatherer sites (e.g. Binford 1978a; Coddling et al. 2016; O'Connell 1987; Whitelaw 1983; Wiessner 1974). The underlying premise of such lines of investigations is the 'ethnographic analogy', which holds that contemporary hunter-gatherers behave in much the same way hunter-gatherers would have behaved in the past (Allen 1996; Currie 2016; O'Connell 1995). Analogical reasoning is critical to archaeological investigation (Wylie 1982). But it is clear that the ethnographic analogy cannot be assumed to be valid across the full spectrum of hunter-gatherer behaviour (Bailey 1983; Currie 2016; Hayter 1994; Murray and Walker 1988). Wolverton and Lyman (2000) clarified the limitations of the ethnographic analogy by drawing a distinction between two types of analogy: immanent and configurational. Immanent analogies are those that relate to intrinsic properties (e.g. common biological traits) and configurational analogies are properties that are contingent upon a particular sequence of events (e.g. diverse cultural traits). A general theory of hunter-gatherer behaviour that is based on immanent analogy could be reliably applied to the interpretation of the archaeological record to understand past hunter-gatherer behaviour.

Among contemporary hunter-gatherers, settlement population densities have been observed to vary widely (Binford 1991a; Fletcher 1990; Hewlett et al. 2019; Whitelaw 1983, 1989, 1991). Hewlett et al. (2019) report average population densities for six different hunter-gatherer groups that differ by up to two orders of magnitude. The low density settlements of the Ngatatjara of Western Australia (820 people/km<sup>2</sup>) contrast starkly with the high density settlements of the Aka of the Congo (87,000 people/km<sup>2</sup>). The average population density of an Aka settlement exceeds that of the most densely populated cities (Estoque 2017, p. 104; Satu and Chiu 2019, p. 545; Thapa 2017, p. 224). In a contemporary urban environment, a high population density might be explainable by an economic analysis that considers the cost of housing and travel times to work, amenities (e.g. hospitals, schools and stores) and family and friends (Bettencourt 2013; Palm et al. 2014). Such considerations are unlikely to be a concern for most hunter-gatherers. Why then do some hunter-gatherers choose high density living, while others do not?

The population density of hunter-gatherer settlements appears to both decrease as population size increases and to vary independently of population size (Fletcher 1990; Whitelaw 1989, 1991). The prevailing hypothesis for population-dependent scaling of population density is that, as population size increases, individual households will space themselves further apart to avoid potentially stressful social interactions with strangers (Whitelaw 1989, 1991). Recent mathematical modelling ostensibly lends support to this hypothesis (Lobo et al. 2022). But a cursory inspection of the derived model reveals that it does not obey the principle of dimensional homogeneity (i.e. the physical dimensions on each side of the model equation are different). The model is evidently not correctly formulated, undermining support for this hypothesis. A suggested explanation for variation in population density independent of population size is the practice of sharing food to reduce the risk of shortfalls ('risk pooling'). It is reasoned that close spacing of households facilitates risk pooling by allowing monitoring of what others have and preventing hoarding (Whitelaw 1983, 1989, 1991; Wiessner 1982). This hypothesis is based on an apparent correlation between high density settlements and ecological contexts in which individual household production is deemed to be unreliable. But this hypothesis cannot explain the existence of relatively high density settlements in which risk pooling is not practiced, such as those of the Mikea of Madagascar (Tucker 2000, 2004). At present, there is no clear consensus as to why some hunter-gatherers live in high density settlements or why population densities vary so widely.

A greater understanding of the determinants of household separation in contemporary hunter-gatherer settlements would have potential implications for a range of fields, including archaeology and public policy. The hunter-gatherer settlement is a physical manifestation of human behaviour, which in turn is a response to the physical and cultural environment in which an individual exists. Invoking the ethnographic analogy, an understanding of the relationship between these variables may provide a way of interpreting the separation of dwellings represented in the archaeological record. The spatial characteristics of past settlements may provide gateway to investigating the contexts in which past settlements were created, evolved and were eventually abandoned. A greater understanding of the reasons for the spatial behaviour of hunter-gatherers may also allow for more sensitive engagement with extant hunter-gatherers, guiding housing and settlement policies that are suited to their needs.

### 1.3 Thesis Statement

The aim of the present study to investigate the determinants of household separation in hunter-gatherer settlements. In pursuit of that aim, two neurobiological phenomena that have not been previously considered as potential determinants of household separation in hunter-gatherer settlements are investigated: ‘social homeostasis’ and ‘social buffering’.

Social homeostasis is the tendency of individuals to modify their social behaviour to minimise the opposing stresses of social crowding and loneliness (too much and too little social interaction) (Matthews and Tye 2019). Variance in household size (number of people per household) and community size (number of people per settlement) may be factors that elicit adjustment of social interaction rate through modification of physical proximity.

Social buffering describes the phenomenon by which the human stress response is reduced through physical proximity to social affiliates, especially friends and family (Hostinar et al. 2014; Kikusui et al. 2006; Kiyokawa and Hennessy 2018; Sanchez et al. 2015). It is proposed that closer physical proximity between households is a way of buffering the stress response to the uncertainties of the hunter-gatherer lifestyle, particularly the acquisition of protein.

The following non-competing hypotheses are therefore put forward:

- A. Reliance on high risk hunting strategies (e.g. encounter hunting, breathing hole hunting, hook and line fishing and trap fishing) predicts closer household separation in hunter-gatherer settlements than low risk hunting strategies (e.g. migration hunting, net fishing and protein gathering), the increased physical proximity between social affiliates in separate households mitigating the stress of uncertainty through ‘social buffering’.
- B. Smaller community size (number of households per settlement) predicts closer household separation in hunter-gatherer settlements, the increased physical proximity between households increases the rate of social interaction, counteracting the perception of social isolation in smaller communities due to a limited number of social connections.
- C. Greater household size (number of individuals per household) predicts greater household separation in hunter-gatherer settlements, thereby maintaining a constant mean rate of social interaction that balances the stresses of social interaction and perceived social isolation (i.e. maintains ‘social homeostasis’).

Statistical methods (general linear model and nonlinear regression) are used to test the validity of the proposed hypotheses against a cross-cultural data set compiled from ethnographic and archaeological sources. The data are drawn from observations of hunter-gatherer societies made over the last two centuries in locations across Africa, North America, South America, Australia and Asia.

## **1.4 Thesis Structure**

A ‘traditional’ structure has been adopted for this thesis consistent with the quantitative nature of the present study. Chapter 1 (‘Introduction’) has outlined above the background and reasons for undertaking the study and the hypotheses now put forward for explaining variability in household separation between hunter-gatherer settlements. Chapter 2 (‘Literature Review’) explores in more detail the previous work on which the present study is built. The various explanations proposed for the observed variability in household separation and population density within hunter-gatherer settlements are critically examined. In Chapter 3 (‘Theoretical Framework’), various neurobiological mechanisms are considered that may explain household spacing in hunter-gatherer settlements, which form the basis of the present hypotheses. Chapter 4 (‘Methodology’) describes in detail the approach taken to testing the hypotheses put forward in this study, including methods of data acquisition and analysis, and the reasons for taking this approach. Chapter 5 (‘Results’) presents the findings of the study their relevance to the present hypothesis, including a summary of the compiled ethnographic data set as well as its analysis. Chapter 6 (‘Discussion’) considers the implications of the results of the study and places them in a broader context. Finally, Chapter 7 (‘Conclusions’) summarises the major contributions of the study, its implications for the fields of archaeology and anthropology and possibilities for further study.

## Chapter 2

### LITERATURE REVIEW

The purpose of this chapter is to provide an overview of previous studies that have sought to understand the determinants of household spacing in hunter-gatherer societies. Provided below is a summary and critical appraisal of those studies, highlighting the pathway taken in reaching the hypotheses presented in Chapter 1.

#### 2.1 Anatomy of a Settlement

Human settlements are defined as much by their physical elements as the people who inhabit them. The mere mention of the word ‘city’ is enough to conjure an image of architectural streetscapes and jagged skylines. The hunter-gatherer settlement is no different. For many people their thoughts likely turn to clusters of small dome-shaped huts, thatched with grass or bark, interspersed with open hearths. It was a scene such as this that appears to sufficiently captured the attention of a hunter-gatherer the Iberian Peninsula around 13,800 years ago that they chose to engrave it in stone (García-Diez and Vaquero 2015). Notably absent from that depiction, reproduced in Figure 2.1, are the people who inhabit those huts. Clearly the built form has long been considered worthy of representation in its own right.

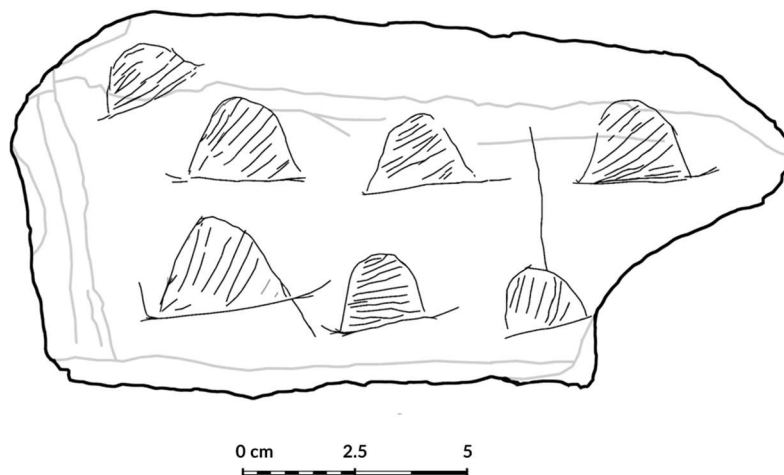


Figure 2.1 – Reproduction of the engraved surface of a stone slab dating to ca. 13,800 BP, interpreted as depicting a hunter-gatherer settlement (García-Diez and Vaquero 2015)

The physical evolution of the hunter-gatherer settlement closely tracks the major technological developments of the Pliocene and Pleistocene. Early hominins likely built nests in trees or on the ground, similar to those of contemporary great apes (Fruth and Hohmann 1996; Groves and Pi 1985; Koops et al. 2011; Stewart et al. 2011). These structures leave little trace in the archaeological record owing to the perishability of the branches twigs and leaves from which they are constructed. But with the appearance of worked stone tools in the archaeological record at around 3.3 Mya (Harmand et al. 2015), hominin occupation sites began to leave an indelible impression on the landscape thanks to a familiar physical component of modern settlements: discarded rubbish. The control of fire by *Homo erectus*, perhaps as early as around 1.7 Mya, foreshadowed the addition of formal hearths for cooking and warmth (Beaumont 2011; Berna et al. 2012; Gowlett and Wrangham 2013; Gowlett 2016; Hlubik et al. 2017). Shelter structures may have appeared around the same time (Leakey 1971), although the timing of this development is contested (Gamble 2023; Potts 1988, pp. 257–258). By the time *Homo sapiens* emerged around several hundred thousand years ago (Mounier and Mirazón 2019), settlements would have been instantly recognisable: people gathered around hearths, possibly some form of shelter from the elements and the spaces in-between littered with occupation debris. This conjunction of people, objects and space is clearly the precursor to the modern built environment, placing encampments, villages, towns and cities on a continuum that connects the modern world with the early origins our species.

Overlaid on the physical structure of a settlement is the social structure of the inhabiting community. Lévi-Strauss (1953, pp. 533–534) observed that among some societies ‘spatial configuration seems to be almost a projective representation of the social structure’ (see also Howitt 1904). Whitelaw (1983) translated this observation to a measurable settlement characteristic. He found that among the !Kung of the Kalahari, inter-dwelling distance was positively correlated with kinship distance, as determined by the number of primary genealogical linkages between members of different households within a settlement. In other words, members of different households that are closely related tend to live near one another. The same relationship has been observed among many other hunter-gatherer and nomadic societies (Domínguez-Rodrigo and Cobo-Sánchez 2017; Dyble et al. 2016; Gabrilopoulos et al. 2002; Gargett and Hayden 1991; O’Brien and Surovell 2017; O’Connell 1987; Tucker 2000; Whitelaw 1989, 1991). It is important to note that this correlation does not extend to absolute distance. Among the !Kung, a parent and daughter may live less than 10 metres apart (Yellen 1977, p. 238), whereas among the Pintupi of Western Australia the separation may be more

than 100 metres (Gargett and Hayden 1991, p. 18). It also appears unlikely to be a universal law. Lévi-Strauss (1953, p. 534) caveated his observation by stating that ‘among numerous peoples it would be extremely difficult to discover any such relation’. Nevertheless, in many hunter-gatherer settlements relative distance between households appears to be a predictor of social distance.

Of interest in the present study are the absolute spatial characteristics of hunter-gatherer settlements. The variance in population density observed among hunter-gatherer settlements is representative of a variance in the number of people inhabiting a certain absolute area.

The relationship between settlement area and population size has long attracted the attention of archaeologists, originally as a potential path to investigation past demographics. Naroll (1962) proposed that the population size of a settlement could be estimated by simply dividing the total dwelling floor area by 10 m<sup>2</sup>/person. The simplicity of this approach prompted interest and debate in equal measure (e.g. Aurenche 1981; Birch-Chapman et al. 2017; Brown, 1987; Casselberry 1974; Clarke 1974; Cook and Heizer 1965, 1968; Kolb 1985; LeBlanc 1971; Porčić 2012; Schacht 1981; Wedel 1979; Wiessner 1974). Noting that many hunter-gatherers perform the majority of their domestic tasks outside their dwelling, Wiessner (1974) argued that settlement area is likely to be a more accurate predictor of population size than dwelling floor space for these societies. In fact, dwelling floor area has proven to be a relatively reliable predictor of population in mobile hunter-gatherer settlements, more so than for sedentary communities (Cook and Heizer 1965, 1968; Porčić 2012). By contrast, the prediction of population size based on settlement area for hunter-gatherer settlements is complicated by an apparently nonlinear relationship between these two variables and a high degree of variance in settlement area for a given population size (Fletcher 1990, 1991; Whitelaw 1989, 1991).

While problematic for predictions of past demographics, observations of nonlinear scaling of settlement area with population size and a variance in population density that at least matches modern urban environments open the door to investigation of arguably less prosaic aspects of human behaviour (Whitelaw 1983, p. 63).

## **2.2 The Ambiguity of Area**

Before considering previous investigations of potential determinants of population density in hunter-gatherer settlements, it is first important to understand the ambiguities inherent to

measurements of settlement area. There is no single method for quantifying the area of a settlement. Measurements vary depending on how the boundary of a settlement is defined.

Hunter-gatherer settlements rarely have a clearly defined boundary. Instead, to enable the settlement area to be measured, a boundary must be approximated based on the extent of physical features of the settlement. The delimiting features used to define the boundary often varies between studies. In some cases, a boundary is defined according to the limit of domestic features, such as dwellings and hearths (e.g. Politis 1996, 2007; Whitelaw 1989, 1991), while in others it may be defined based on the limit of scattered occupation debris (e.g. Bartram et al. 1991; Hitchcock 1982). The measured area of a settlement may differ depending on which physical features are used to define the boundary. The limit of scatter is typically larger than limit of structures and increases with duration of occupation as debris accumulates around the periphery of a settlement over time (Grove 2009; Yellen 1977). For larger settlements, where the extent of debris beyond the domestic space is small compared with the overall extent of the settlement, the difference in area determined by limit of scatter versus limit of structures may be negligible. But for smaller settlements the difference in area may be substantial.

The measurement of settlement area further requires a polygon to be defined that circumscribes the relevant settlement features. It is the area of that polygon that is measured to provide an approximation of the area of the settlement. Like the delimiting features used, the form of the circumscribing polygon used can also vary. A concave polygon ('concave hull') is well-suited to describing settlement area where the features are contiguous. This is often the case for urban areas, where property boundaries, roads, paths and walls form an uninterrupted traceable path (e.g. Adhikari and de Beurs 2017; Cesaretti et al. 2016; Lo and Welch 1977; Marshall 2007; Nordbeck 1971). A concave hull conforms to the often dendritic form of settlements, providing a good estimation of the utilised land area occupied by the settlement. But where settlement features are not contiguous, determination of which features should be connected to form the perimeter of the polygon becomes less clear. A convex polygon ('convex hull') resolves this problem as there is a unique solution to the problem of finding the smallest convex polygon that encompasses a set of discrete points (Asaedi et al. 2017) (Figure 2.2). A convex hull is often used for determining the area of hunter-gatherer settlements where the boundary is delimited by scattered debris or discrete dwellings (e.g. Whitelaw 1989, 1991; Yellen 1977). Except for cases where the delimiting features of a settlement have a convex form (e.g. Wiessner 1974), the area determined by a convex hull will necessarily be larger than that

determined by a concave hull. The choice of polygon form, like the choice of delimiting features, can affect area measurement.

It is clear that when referring to settlement area, it is important to accurately specify how that area is defined. Direct comparisons of area between different settlements or the same settlement over time are meaningless if the definition of area varies (Batty and Kim 1992). With this in mind, we can turn our attention to previous studies that have sought to explain the scaling of hunter-gatherer settlement area with population size and the extreme variance in area that is independent of population size.

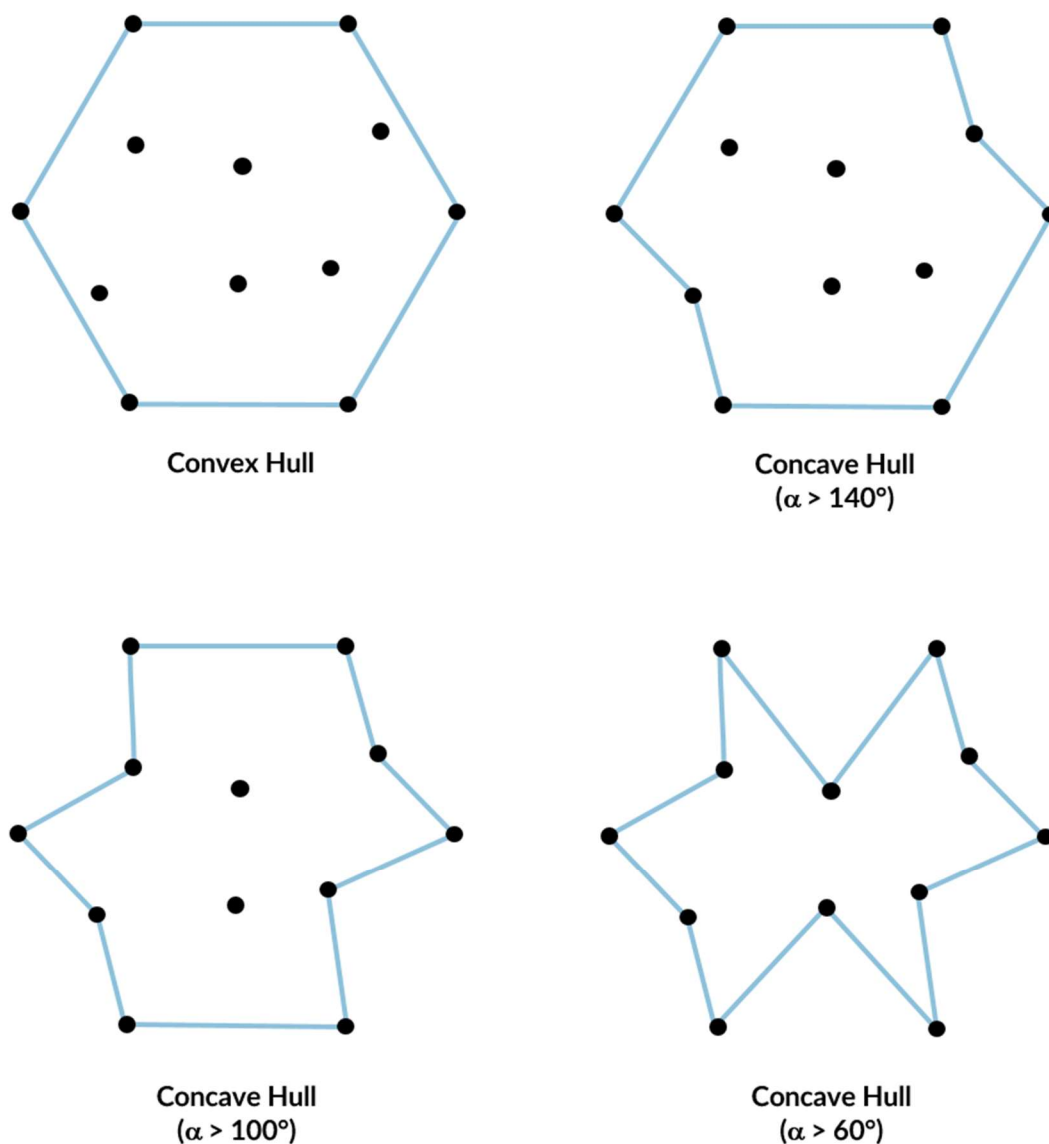


Figure 2.2 – The unique convex hull and different concave hulls for varying maximum external polygon angle ( $\alpha$ ) that encompass a single set of discrete points

## 2.3 Scaling of Population Density with Population Size

Various authors have reported a nonlinear increase in hunter-gatherer settlement area with population size, such that larger population sizes predict lower population densities (Fletcher 1990; Hamilton et al. 2018; Lobo et al. 2022; Whitelaw 1989, 1991; Wiessner 1974). Two hypotheses have been proposed to explain population-dependent scaling of hunter-gatherer settlement area: the ring model hypothesis, which argues that scaling of area is due to arrangement of households in a roughly circular formation (Wiessner 1974), and the social interaction stress hypothesis, which argues that scaling of area is due to the desire to avoid strangers in larger settlements (Whitelaw 1989, 1991). As discussed in the following Sections, the evidence for each hypothesis is lacking.

### 2.3.1 The Ring Model

Wiessner's (1974) suggestion that settlement area is a more accurate predictor of population size than dwelling floor area for hunter-gatherers was accompanied by a proposed a model to describe this relationship. Wiessner assumed that hunter-gatherer settlements could be described as having a roughly circular form, with dwellings arranged at the periphery. A consequence of this arrangement is that the open area at centre of the settlement would increase in size nonlinearly as the number of dwellings increases (Figure 2.3).

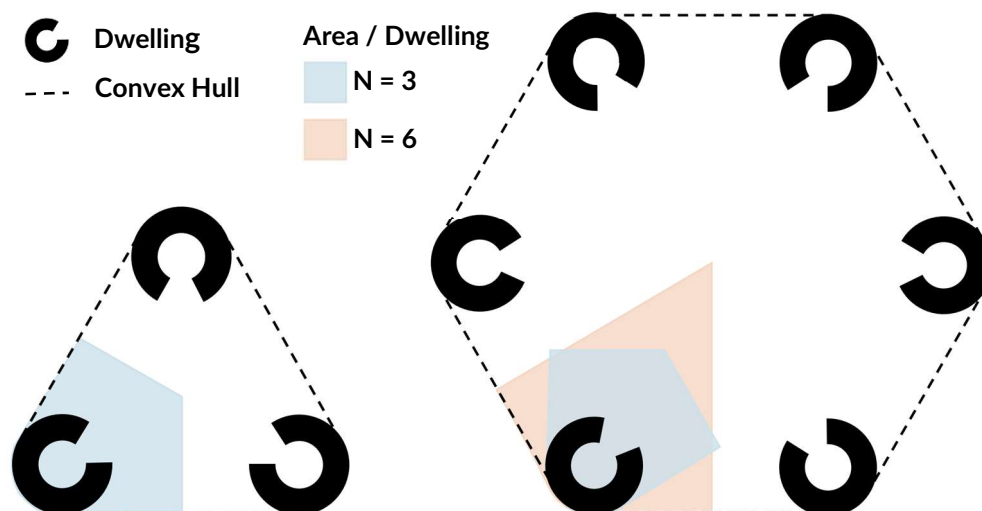


Figure 2.3 – Schematic illustration of the ‘ring model’, showing the difference in area per dwelling between a three-dwelling settlement and a six-dwelling settlement, where settlement area is defined as the convex hull encompassing all dwellings. Concentration of dwellings at the periphery of the settlement means that the area per dwelling increases as the number of dwelling increases.

The ring model proposed by the von Thünen model drew upon earlier work by Nordbeck (1971), who attempted to describe the allometric growth of modern urban areas. Nordbeck proposed that the population,  $P$ , of an urban settlement could be estimated based on measurement of the area of ‘land use’. Nordbeck (1971, p. 56) defines settlement area as a concave hull delimited by dwellings. The relationship takes the form:

$$A = a \cdot P^b \quad (2.1)$$

where  $a$  is a variable that describes shape of a city and  $b$  is a scaling constant defined as the dimension of measurement relative to the dimension of population growth. According to Nordbeck, the scaling exponent,  $b$ , should be equal to  $2/3$  because population growth in a city occurs in three dimensions, while the measurement of area is in two dimensions.

Nordbeck’s reasoning for ascribing population to three dimensions is slightly more complicated than saying that cities grow upwards as well as outwards. Nordbeck likens the population density profile of an urban area to the topography of a volcano: a rapid increase is observed from the outer rural areas to the peak of the inner ring where high density housing is most common, before dropping off into the ‘crater’ of the central business district where fewer people reside. In essence, he is saying that a city grows *as if* the population was being distributed in three dimensions. That could be because of increased height of the city through construction of multi-storey apartments, or because decreasing property sizes allows for more people in the same two dimensional space.

It is nevertheless useful to consider the case where population growth does expand into three dimensions (i.e. upwards) to understand the implications of Nordbeck’s model. If volume scales as the  $2/3$  power of area, then:

$$R^2 \propto (h \cdot R^2)^{2/3} \quad (2.2)$$

where  $h$  is the mean height of the settlement,  $R$  is the mean settlement radius and  $h/R$  is constant. In other words, the mean height of a city increases proportionally (although not necessarily equally) with its mean radius. Equivalently, the mean radius of an individual property within a city could decrease proportionally with increasing radius to achieve the same effect. In either case, implicit in the constant scaling exponent of  $2/3$  is that population *growth* within a city is evenly distributed in two dimensions (i.e. isometric) (Fotheringham et al. 1989).

Nordbeck found that Swedish urban areas scaled with an exponent of 0.664, in good agreement with his model. But various other authors have reported urban areas that fail to conform to Nordbeck's prediction, with scaling exponents being found both above and below  $2/3$  (e.g. Adhikari and de Beurs 2017; Boyce 1963; Lee 1989; Stewart and Warntz 1958; Woldenberg 1973). The assumption of universal isometric population growth is evidently incorrect, at least in the case of modern towns and cities.

Wiessner's adaptation of Nordbeck's model to hunter-gatherer settlements relied on the assumption that hunter-gatherer settlements are typically ring-shaped. This assumption was based on the plans of 16 !Kung settlements later published by Yellen (1977). On that assumption, Wiessner argues that population growth is concentrated at the perimeter of hunter-gatherer settlements and is therefore limited to one dimension. Following Nordbeck's definition, the scaling exponent,  $b$ , for temporary hunter-gatherer settlements is therefore  $2/1$ . Read and LeBlanc (1978) subsequently added the assumption of constant separation between dwellings at the perimeter, ensuring the assumption of isometric population growth is met.

Wiessner tested her model against the measured area of the !Kung settlements. Because the settlements were assumed to be ring-shaped, the area is naturally defined as a convex hull delimited by the dwellings arranged at the assumed settlement perimeter. Linear regression of the log-log transformed population and area data found a scaling exponent of 1.96, consistent with Wiessner's model.

Despite the good agreement with the !Kung data, it is plainly apparent that Wiessner's model is not applicable to all hunter-gatherer settlements. While the settlements of certain hunter-gatherer groups do consistently adhere to a ring shaped layout, such as the Efé and Mbuti of the Congo (Fisher and Strickland 1989; Ichikawa 1979; Turnbull 1961), the settlements of many others deviate from this model. Whitelaw (1989, Table 7.6) found that from a sample of 433 settlements only 90 could be described as ring-shaped, meaning only 21% met the assumption of Wiessner's model. As noted by Whitelaw (1983, p. 49), any model based on the assumption that hunter-gatherer settlements are typically ring-shaped is 'behaviourally inappropriate'.

Although the ring-model is evidently flawed, the underlying premise of the model is nevertheless sound. The area of a polygon circumscribing a set of points is a function of both the arrangement and distance between those points. By concentrating dwellings in a single dimension within a two-dimensional settlement (e.g. the periphery), the area defined by a

convex hull that circumscribes those dwellings will scale non-linearly with the number of dwellings (Porčić 2012, p. 74). In fact, the area defined by a convex hull will only scale linearly with population size if the dwellings are distributed evenly, such as in a grid or straight line. Highly regular patterning of a population in two dimensions is improbable in the absence of urban planning. And while linear hunter-gatherer settlements are known, such as the dry season settlement of the Kua of Botswana (Bartram et al. 1991), these are even less common than ring-shaped settlements (Whitelaw 1989, Table 7.6). The uneven arrangement of dwellings in space is almost certainly a contributing factor in the nonlinear scaling of hunter-gatherer settlement area with population size when defined by a convex hull.

The ring-model is clearly an over-simplification. But it is plausible that the scaling of settlement area with population size is at least partly due to the arrangement of dwellings in space.

### 2.3.2 Social Interaction Stress

Whitelaw (1989, 1991) presented an alternative hypothesis that sought to relate variance in settlement population density to variance in the separation of households. On the premise that social interactions between strangers are more stressful than those between family and friends, Whitelaw argued that the average stress of social interaction increases with settlement population size as the average social distance between people increases. Whitelaw hypothesised that hunter-gatherers seek to counteract increasing stress of social interaction by distancing themselves from each other, thereby reducing the frequency of social interaction.

The mechanics by which mean household spacing increases as mean social distance increases is not fully elaborated by Whitelaw. Two mechanisms appear possible: (i) each household separates itself from *all other households* to reduce the overall interaction rate within the settlement; and (ii) each household separates itself from any *adjacent socially distant households*, but maintains close spacing with socially proximate households. Both mechanisms appear to be contemplated. In a recent publication by Whitelaw and co-workers the second mechanism is explicitly described (Lobo et al. 2022, p. 70), while the first mechanism is implicit in the modelling of that study (as discussed in the following Section).

A problem with the first mechanism is that if, as shown by Whitelaw (1983) for the !Kung, socially proximate households tend to camp closest to one another, then it acts by directly increasing the distance between friends and family (Figure 2.4). The desired increase in spacing between socially distant households would only be an indirect consequence. The idea that the

members of a household would distance themselves from the people they are socially closest to in order to avoid interaction with strangers elsewhere in a settlement is counterintuitive. Furthermore, while the mechanism can evidently achieve the aim of reduced interaction between strangers (albeit at the expense of reduced interaction with people they want to interact with), it would require collective action across the entire settlement. All households would need to comply otherwise the participating households would bear the cost of reduced interaction with family and friends, while potentially having no effect on the rate of interaction with strangers. On the assumption that the formation of hunter-gatherer settlements is spontaneous rather than planned, this mechanism appears unlikely.

The second mechanism is ostensibly more plausible. It achieves the goal of reduced interaction with strangers without the need for collective action. In settlements where familiar households tend to be located near one another (Whitelaw 1983), spatially discrete clusters of households consisting of socially proximate groups would form (Figure 2.4). Such clustering of ‘bands’ in hunter-gatherer settlements is a known phenomenon (e.g. Bartram et al. 1991; Domínguez-Rodrigo and Cobo-Sánchez 2017; Grier and Savelle 1994; Whitelaw 1989, 1991). In clustered settlements, mean household spacing would increase with population size if the cluster size remains reasonably constant (i.e. the number of clusters increases as population size increases) because inter-cluster separation is greater than intra-cluster separation.

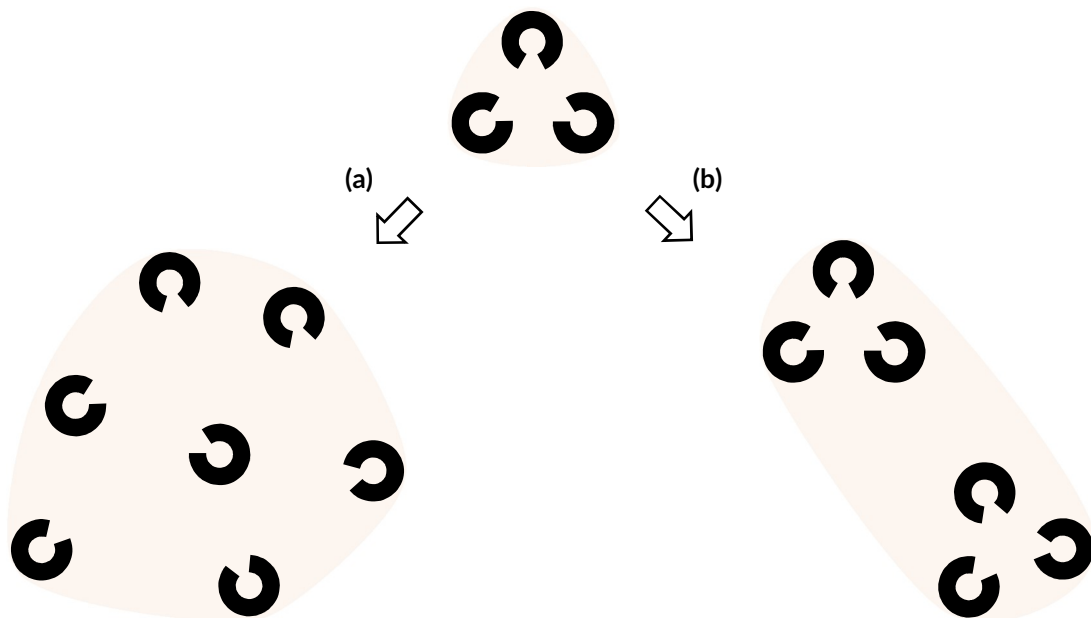


Figure 2.4 – Schematic illustration of the proposed mechanisms by which social stress may act on household separation; specifically by: (a) increasing the distance between all neighbouring households; or (b) by increasing the distance between socially distant neighbouring households

While the second mechanism appears plausible, Whitelaw’s study was exploratory. He sought only to propose an explanation for an observed negative correlation between population size and population density. Settlement area was measured as the convex hull delimited by dwellings with a half metre buffer around each, so it is also plausible that observed correlation is at least partly due to dwelling arrangement. Whitelaw does not provide any evidence that either household separation or the number of clusters in a settlement increases with population size to support his hypothesis.

A relationship between social interaction stress and the scaling of area with population size may exist. But, the absence of any evidence that either the mean household spacing or number of household clusters increases with population size means that Whitelaw’s social stress hypothesis is unsubstantiated.

### 2.3.3 Settlement Scaling Theory

A recent attempt has been made by Lobo et al. (2022) to formalise Whitelaw’s social stress hypothesis using the framework of ‘settlement scaling theory’. Settlement scaling theory posits that various universal population-dependent scaling relationships emerge from balancing the costs and benefits of social living (Bettencourt 2013). It has been most frequently applied to understanding the scaling of urban settlement area with population size, but has also been used to investigate relationships between population size and various other spatial and economic variables, such as land rents, transport network lengths, gross domestic product, employment rates and patent filings (e.g. Arbabi et al. 2019; Bettencourt 2013; Bettencourt and Lobo 2016; Cesaretti et al. 2016; Codd 2020; Lobo et al. 2013, 2020; Ortman and Coffey 2017; Ortman et al. 2014, 2015, 2016).

By attempting to balance the energetic benefits and costs of social interaction, Lobo et al. (2022) derive an expression that ostensibly describes the relationship between settlement area and population size in hunter-gatherer settlements. The benefits of social interaction are considered to follow from the promotion of cooperative behaviour, while the costs are considered to be ‘communicable disease, food-sharing demands, conflict, noise, and more’ (Lobo et al. 2022, pp.73–74). The expression derived by Lobo et al. has the form:

$$A \approx \left( \frac{G}{\rho L_0} \right)^2 P^{2(1-\gamma)} \quad (2.3)$$

where  $A$  is settlement area,  $P$  is settlement population size and  $G$  and  $\rho$  are the respective energetic benefit and cost of social interaction per capita per second (see also Ortman and Coffey 2017). The term  $L_0$  is defined as the ‘baseline distance at which proximity costs are felt regardless of relatedness’ and the term  $\gamma$  represents the population dependence of social ‘relatedness’, capturing Whitelaw’s hypothesis of increasing social stress with increasing social distance.

To derive a discrete value for  $\gamma$ , Lobo et al. cite a decrease in relatedness within hunter-gather settlements reported by Walker and Hill (2014). They found that relatedness decreases as the negative 1/4 power of population size. Substituting that exponent directly into Formula (2.3), Lobo et al. predicted that settlement area would scale as the 3/2 power of population size (i.e.  $A \propto P^{1.5}$ ).

Lobo et al. found good agreement between their model and the hunter-gatherer data set compiled by Whitelaw (1989, 1991). When controlling for ecological zone, regression analysis of Whitelaw’s population-area data using a function of the form of Formula 2.3 yields a scaling exponent of 1.53 ( $R^2 = 0.78$ ; 95% CI [1.47, 1.60]). Deviating only marginally from the predicted scaling exponent of 1.5, this finding appears to support Whitelaw’s hypothesis that physical distance is used in hunter-gatherer settlements to buffer increasing social interaction stress as social distance increases. But the model proposed by Lobo et al. suffers from a number of problems.

A first problem is that the inclusion of the  $\gamma$  term in Formula 2.3 is only consistent with the first mechanism for avoiding interactions with strangers described in the preceding Section (i.e. each household separates itself from *all other* households). The second mechanism, which describes the formation of clusters of families and friends, would not be described by a power law relationship. Assuming mean cluster size does not change with population size, the change in household separation should asymptote as population becomes large relative to cluster size. That asymptote cannot be described by a simple power law. As already noted, the collective action of all households to avoid one another required by the first mechanism is behaviourally implausible.

A further flaw in the model of Lobo et al. is laid bare by dimensional analysis. The principle of dimensional homogeneity requires that the units of measurement on each side of an equation are equivalent (Sterrett 2009). Although not made clear by Lobo et al., it can be assumed that  $G$  and  $\rho$  have the same dimensions as both serve the same purpose: translating abstract costs

and benefits to energy losses and gains. The term  $G/\rho$  is therefore dimensionless, as is population size,  $P$ . That leaves settlement area,  $A$ , with units of  $\text{m}^2$  on the left side of Formula 2.3, and the inverse square of the baseline distance for feeling negative proximity effects,  $(1/L_0)^2$ , with units of  $\text{m}^{-2}$  on the right side. As there is an inconsistency between the units on each side of the equation, the model formulated by Lobo et al. violates the principle of dimensional homogeneity and, for that reason at least, cannot be correct.

Further inspection of the model reveals another major flaw: it does not describe the intended effect of population size on settlement area. Lobo et al. follow the hypothesis of Whitelaw (1989, 1991) that increasing social distance with population size translates to increasing spatial distance, with space being used as a buffer to reduce stressful interactions with strangers. The effect of ‘relatedness’ (or social distance) on settlement area in Formula 2.3 can be understood by considering the hypothetical situation where  $\gamma$  is zero (i.e. relatedness does not decrease with population size). In that case settlement area,  $A$ , increases as the square of population size,  $P$  (i.e.  $A \propto P^2$ ). The scaling exponent is greater than the scaling exponent of 1.5 predicted if relatedness does decrease. The model of Lobo et al. predicts that as relationships within a settlement become more socially distant, physical proximity and population density will actually *increase*. This outcome is contrary to the central proposition of increasing physical distance with increasing social distance.

That is not to say that the model supports the contrary position that population density is actually negatively correlated with relatedness. Dimensional analysis has shown that the model of Lobo et al. is incorrect. To understand why, it is necessary to look at how Lobo et al. derived Formula 2.3 and the assumptions of settlement scaling theory more broadly.

The application of settlement scaling theory to the population-area relationship is described by Ortman and Coffey (2017, p. 665) as follows: ‘when people create settlements, they arrange themselves in space so as to balance the costs of moving around inside the settlement with the benefits that accrue from the resulting social interactions’. Apparent within this statement is a fatal error at the heart of settlement scaling theory. The cost of movement decreases with proximity, while the frequency of social interaction (and therefore benefits of that interaction) increase. There is no trade-off to be made.

Ortman and Coffey’s paradoxical description of settlement scaling theory is not merely a case of poor wording. It carries through to the general model applied throughout settlement scaling theory. The balance between movement cost and social benefit is described by the formula:

$$G \frac{P}{A} = \varepsilon A^{H/D} \quad (2.4)$$

where  $\varepsilon$  is the cost of movement per metre,  $H$  is the fractal (Hausdorff) dimension of a path in  $D$  dimensional space (in this case 2) and  $G$ ,  $P$  and  $A$  as defined above (Bettencourt 2013). The term on the left side of the equation,  $GP/A$ , describes the benefit of social interaction, which decreases as settlement area increases (holding population constant) due to a decreasing rate of social interaction. The term on the right side of the equation,  $\varepsilon A^{H/D}$ , describes the cost of movement within the settlement, which increases as settlement area increases because greater distances must be covered. So the left side of the equation describes a *decreasing benefit* as settlement area increases, while the right side describes an *increasing cost* as settlement area increases. Both terms point to the same conclusion: a smaller settlement area is more favourable. The fact that Formula 2.4 can be solved to provide population dependent scaling of settlement area indicates that the formulation of the terms within the equation must be incorrect. It is not surprising then that various authors report deviations from the predictions of settlement scaling theory across an array of urban environments (e.g. Burger et al. 2022; Hutson et al. 2023; Xu et al. 2023).

As it happens, Lobo et al. omitted the movement cost from their formulation, arguing that the cost of movement is negligible for hunter-gatherers because their settlements are relatively small. This is a questionable assumption, given that the model is applied to a data set in which the area of some settlements exceeds 1 km<sup>2</sup> (Lobo et al. 2022; p. 77). Moreover, it is a cost term that was previously deemed integral to settlement scaling theory in other studies of similar sized settlements (e.g. Ortman and Coffey 2017; Ortman et al. 2014, 2015, 2016). Nevertheless, with movement cost excluded and the cost of social interaction included, their cost-benefit relationship takes the form:

$$G \frac{P}{A} \approx \rho \frac{L_0 P^\gamma}{R} \quad (2.5)$$

where all variables are as defined above. The source of the dimensional inhomogeneity in the model of Lobo et al. becomes apparent when interrogating the cost and benefit terms in this equation.

The benefit of social interaction described by the left side of Formula 2.5 increases as population density ( $P/A$ ) increases. This is a reasonable proposition because the rate at which people encounter one another is proportional to the number of people in a given area

(Bettencourt 2013; Collette and Webb 1976). Furthermore, various studies have found that cooperation does indeed increase as frequency of interaction or physical proximity increases (Christiansen and Pedersen 2018; Duffy and Ochs 2009; Kabo et al. 2014; Kraut et al. 1990; Salazar Miranda and Claudel 2021). However, the cost of social interaction described by the right side of the equation is not similarly dependent on population density. The social cost term on the right side of the equation should also increase as population density increases. The cost of communicable disease, for example, is dependent on the rate of transmission, which increases with social interaction frequency and therefore population density (Alirol et al. 2011; Arbel et al. 2022; Li et al. 2018; Sy et al. 2021). The model of Lobo et al. inappropriately omits the role of interaction rate in the cost of social interaction.

The cost per interaction term on the right side of Formula 2.5 is instead multiplied by a dimensionless modifier: the distance at which costs become ‘significant’ relative to the radius of the settlement,  $L_0P^\gamma/R$ . According to Lobo et al. (2022, p. 73),  $L_0$  is determined by the ‘range of effective sensory perception’. Terms such as ‘effective’ and ‘significant’ are relative, so their meaning within the context of a mathematical model is opaque without a defined point of reference. It is useful again to consider the effect of this term by references to a hypothetical situation. If  $L_0$  is taken to be zero (i.e. the negative effects of social interaction are significant at any distance) the cost of social interaction would also be zero. As the distance at which the negative effects of social interaction become significant increases, the cost of social interaction becomes larger (all else being equal). Clearly this does not make sense.

It is reasonable that the cost per interaction does increase with proximity. The stress caused by a noisy neighbour increases with proximity, independent of the interaction rate. But to capture this would require an attenuation term to describe the gradual change in cost with distance. The model of Lobo et al. could thus be reformulated so that both the cost and benefit of social interaction increase with population density and the cost of interaction attenuates as people are spaced further apart:

$$G \frac{P}{A} \propto \rho \delta \bar{L} P^\gamma \frac{P}{A} \quad (2.6)$$

where  $\delta$  is the fractional attenuation of the negative effects of proximity per metre and  $\bar{L}$  is the average distance between people within the settlement. Taking the square of both sides to translate  $\bar{L}$  into two dimensions as settlement area,  $A$ , and rearranging to make  $A$  the subject gives the simplified expression:

$$A \propto \left(\frac{G}{\rho\delta}\right)^2 P^{2\gamma} \quad (2.7)$$

The principle of dimensional homogeneity is now obeyed because both sides of the equation have units of m<sup>2</sup>. Additionally, the scaling of settlement area with population size increases as  $\gamma$  increases, consistent with Whitelaw’s hypothesis. But substituting in the  $\gamma$  value of 0.25 yields a predicted scaling exponent of 0.5. No agreement is now found between this predicted scaling exponent and the scaling exponent found by regression of Whitelaw’s data.

That does not mean that Whitelaw’s social stress hypothesis is necessarily incorrect. But it does mean that it lacks any evidential support beyond the observed nonlinear scaling of settlement area with population it was proposed to explain.

## 2.4 High Density Living and the Hunter-Gatherer

In addition to population-dependent scaling, the area of hunter-gatherer settlements is observed to vary widely independent of population size (Hewlett et al. 2019). The following is an overview and critique of the explanations for variance in hunter-gatherer settlement population density so far proposed, namely the reliance on food sharing as a risk pooling strategy, the threat of predation, anticipated duration of occupation and vegetation density.

### 2.4.1 Risk Pooling

An explanation for high density hunter-gatherer settlements that has gained some traction is the practice of ‘risk pooling’. Risk pooling describes the sharing of food between households as a risk minimisation strategy. Food sharing is almost universally practiced by hunter-gatherers (Ember 2018). In contexts where the daily variance in food production is high, inter-household food sharing has been shown to provide a more stable food supply and reduced risk of calorific shortfall (Cashdan 1985; Kaplan and Hill 1985; Winterhalder 1986). Such situations are the norm for many hunter-gatherers for whom a significant part of their diet, particularly their protein intake, is subject to combined risks of failing to encounter prey and failing to capture any prey that is encountered. In many hunter-gatherer societies, individual hunters frequently return from expeditions empty handed (e.g. Bird et al. 2013; Gould 1977; Gurven 2006; Hawkes et al. 1991, 2001; Hill and Hawkes 1983; Holmberg 1969).

A causal relationship between risk pooling and household spacing in hunter-gatherer settlements was first proposed by Wiessner (1982). Wiessner reasoned that that greater visibility afforded by close spacing of dwellings, in addition to unenclosed eating and storage

areas, allows monitoring of what others have. The purported benefits of this openness are the maintenance of good relations through an overtly equitable distribution of food (Gargett and Hayden 1991; Whitelaw 1983, 1989, 1991). Conversely, Wiessner considered greater household separation to be favoured in settlements that do not practice risk pooling to avoid jealousy and conflict arising from visible disparities in accumulated food stores. The risk pooling hypothesis therefore envisages household spacing as a stabiliser of social cohesion within a settlement, responding to differences in the degree to which food resources are treated as common or private property.

Wiessner provided no quantitative evidence in support of her hypothesis. A number of published settlement plans were cited that purportedly demonstrated a correlation between close household separation and risk pooling. But casual assessment of those plans brings that support into questions. Highlighting the importance of critical quantitative analysis, one of the cited plans depicts single-person temporary shelters formed of branches with the improbably large dimensions of 10 x 20 metres (Tindale 1972, p. 243). The plans in another of the cited references do not have a scale at all (Turnbull 1965). The evidence furnished by Wiessner is therefore equivocal at best.

Several other authors have provided more explicit evidence, although based on small samples. Whitelaw (1983) found a correlation between sharing meat beyond the household and higher settlement population densities when comparing six different cultural groups (the Nunamiut, Mistassini Cree and Coastal Tlingit of North America, the Mbuti and !Kung of Africa and the Pitjantjatjara of Australia). O'Connell (1987) noted that among the Alyawarre of the Northern Territory, the few households that shared government rations were relatively closely spaced (under 10 metres) compared with the majority who do not. Gargett and Hayden (1991) compared the Alyawarre with the !Kung. The households of the !Kung, who shared food extensively, were spaced about 5 to 7 metres apart, while the households of the low-sharing Alyawarre were about 25 to 40 metres. While consistent with the risk pooling strategy, these limited examples may not be representative of hunter-gatherers more broadly.

A broader study was undertaken by Whitelaw (1989, 1991), who compiled settlement population density data from 112 cultural groups. Whitelaw observed differences in population density distributions between different ecological contexts. Invoking the risk pooling hypothesis, he argued that low population densities in certain biomes correlated with a lower risk of food shortfalls and therefore an absence of risk pooling. Two predictors of lower risk

were proposed that followed from Whitelaw's earlier study: (i) in cooler climates (arctic, boreal and temperate) the practice of freezing or drying food for long-term storage acts as a buffer to variability in food acquisition, reducing the need for risk pooling; and (ii) in contexts where small-bodied game dominates (desert and wet savanna), the value of risk pooling is diminished because there is less variability in individual hunting success (Whitelaw 1983, pp. 58–59; Whitelaw 1991, p. 168). Some contexts did not conform to these propositions, such as certain dry savanna environments where small game dominated but population density was high. To accommodate these observations, Whitelaw expanded the risk pooling hypothesis to include cooperation in the *acquisition* of food as a predictor of high population density. As visibility of what others have is of little importance for cooperative hunting, Whitelaw (1991, p. 168) suggested that close spacing of dwellings serves the additional purpose of facilitating communication and interaction between cooperating households. Whitelaw's study is largely exploratory rather than an attempt to test *a priori* hypotheses. No statistical analysis of the data was undertaken. It is therefore unclear the extent to which food storage and reliance on small game are correlated with an absence of risk pooling, or the extent to which these factors and cooperative hunting are correlated with low population density.

Of course, an absence of statistical testing does not imply the Whitelaw's propositions are incorrect. However, these propositions do not stand up to closer scrutiny. While hunter-gatherer societies do not share small game (Marlowe 2003; Marshall 1961; Rogers 1962, Tucker 2000, 2004), this is not always the case. The Aché of Paraguay share 90% of captured meat outside the family unit regardless of whether it is from small- or large-bodied animals (Kaplan and Hawkes 1993, p. 702; for further examples see Cook 1908; Williams 1974, p. 87). Food sharing among the Aché is the archetype of risk pooling behaviour (Hill et al. 1985; Janssen and Hill 2013; Kaplan and Hill 1985). Storage too is not necessarily incompatible with risk pooling, likely because the buffering capacity of stored foods is limited by the size of the surplus a hunter-gatherer can expect. The Iglulingmiut, Netsilingmiut and Copper Inuit of Canada all share food extensively despite maintaining private caches of frozen and dried meat (Damas 1972). Lastly, the proposition that cooperation in the acquisition of food predicts close spacing is contradicted by observations of the Nunamiut of Alaska. Although Nunamiut households often operate independently of one another, in some situations they 'live like a big family', hunting cooperatively and sharing captured game (Binford 1991b, p. 39; contra Whitelaw 1983:60). In these situations they nevertheless maintain relatively widely spaced households when compared with other groups (Binford 1991b, p. 39; cf. Hewlett 2019, p. 41). The

unsupported assumptions of Whitelaw’s study undermine its support for the risk pooling hypothesis, although they do not undermine the risk pooling hypothesis itself.

A problem for the risk pooling hypothesis is the existence high population density settlements in which risk pooling is not practiced. The Mikea of Madagascar rarely share meat beyond their immediate household, making efforts to keep any meat they bring into the settlement a secret (Tucker 2004, 2019). Evidently they do not practice risk pooling. Yet they have relatively closely spaced houses compared with other cultural groups, such as the Ngatatjara of Western Australia (Figure 2.5). The Mikea are not an isolated case. The Haida and Kwakiutl (*Kwakwaka'wakw*) of the Pacific Northwest practiced annual ‘potlatch’ ceremonies, in which food and other items were redistributed from the wealthy to poor (Barnett 1938; Boas 1966; Piddocke 1965; Swanton 1909). The accumulation of wealth necessary for these ceremonies is not consistent with the regular pooling of resources. Yet these groups built their dwellings so close to one another as to be almost touching (Boas 1889a, 1909; MacDonald 1983, 1989) (Figure 2.6). Clearly, the risk pooling hypothesis is unable to fully explain high population densities among hunter-gatherers.

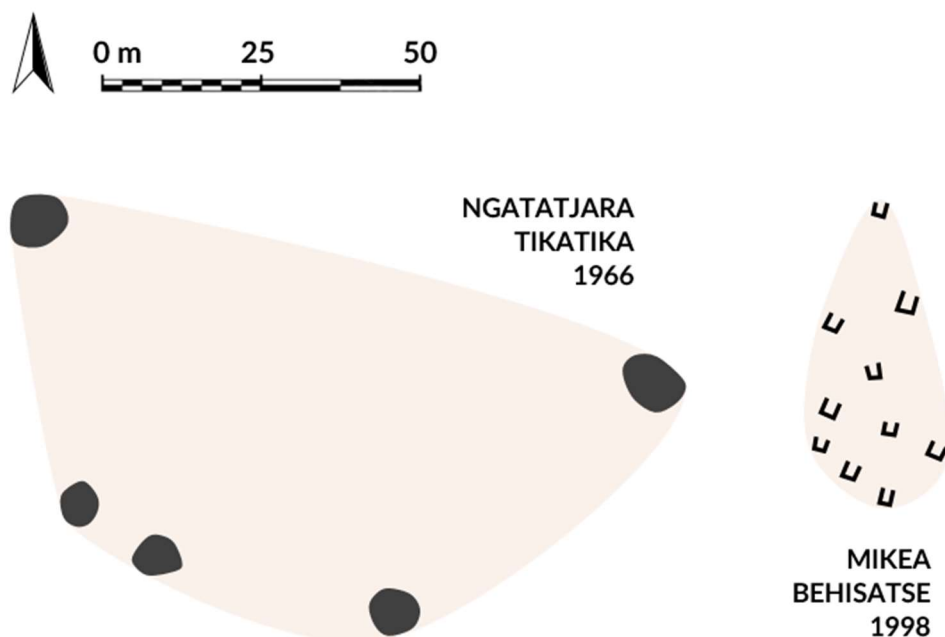


Figure 2.5 – Side-by-side comparison of the household areas in the Ngatatjara settlement of Tika Tika (Western Australia) as recorded in December 1966 (after Gould 1980) and the dwellings in the Mikea settlement of Behisatse (Madagascar) as recorded in March 1998 (after Tucker 2004)



Figure 2.6 – The Kwakiutl settlement of Xwamdasbe, Hope Island (British Columbia), photographed by Edward Dossetter in 1881 (reproduced with the kind permission of the American Museum of Natural History)

A flaw in the risk pooling hypothesis may be the confusion of causation and correlation. Of the criteria for causality outlined by Hill (1965), only temporality is generally considered to be essential: the cause must precede the effect (Fedak et al. 2015). Evidence from other fields point to cooperative behaviour, including sharing, following from close physical proximity rather than preceding it. In modern workplace environments, increased physical proximity has been correlated with a greater likelihood of both information sharing (Christiansen and Pedersen 2018) and collaboration (Kabo et al. 2014; Kraut et al. 1990; Salazar Miranda and Claudel 2021). A study by Duffy and Ochs (2009) involving the ‘prisoner’s dilemma’ game supports this relationship. They found that repeated interaction between partners predicted greater cooperation compared with random pairings. These studies point to the possibility that risk pooling may be the product of close household spacing in hunter-gatherer settlements rather than its cause. Pursuing this line of reasoning, it is a reasonable next step to propose that

risk itself may be the cause, which would explain the apparent correlation between risk pooling and high population observed by some authors.

Although there is tentative acceptance among some current authors of the existence of a relationship between risk pooling and household separation (Hamilton et al. 2018; Hewlett et al. 2019; Lobo et al. 2022), the evidence does not support a causal link. It is instead possible that the correlation between risk pooling and close household separation (or high population density) is due to them both being a product of risk itself.

#### 2.4.2 Predator Threat

The risk of attack by predators was suggested as a predictor of close household spacing by Gould and Yellen (1987) in response to a perceived problem with the risk pooling hypothesis. They noted that Ngatatjara of Western Australia have widely spaced households despite extensive sharing of game. Gould and Yellen contrasted the widely spaced households of the Ngatatjara with the closely spaced households of the !Kung of the Kalahari. Noting the absence of predators in the deserts of Western Australia, they suggested that array of large predators in the Kalahari, including lions, leopards, hyenas and cheetahs, may be responsible for close household spacing among the !Kung. They reasoned that close spacing of dwellings and hearths allows close observation of children, who are particularly vulnerable to predation. Close household spacing is therefore envisaged as an evolved cultural trait that provides greater survivability where there is a threat of predation.

In view of the discussion in the preceding section, a flaw in Gould and Yellen's appraisal of the risk pooling hypothesis is immediately apparent: it is not food sharing per se that conditions household spacing according to the risk pooling hypothesis, but sharing for the purpose of risk reduction. In a comprehensive rebuttal of the predator hypothesis, Binford (1991a) suggested that the Ngatatjara may utilise a different risk management strategy, such as the 'diet breadth' strategy (cf. Gould and Yellen 1991). An alternative explanation is that the reliance of the Ngatatjara on easily caught small game, specifically the goanna, means that there is no need for risk management (Gould 1967, 1977, 1991). Binford also cited examples of other cultural groups that do not conform to the predictions of the predator hypothesis. These included cases where households were widely spaced despite the presence of predators (e.g. the Basarwa settlement of Khutse in Botswana) and closely spaced households in the absence of terrestrial predators (e.g. the Andaman Islanders). On the available evidence, it is that close household spacing is a response to predation risk.

### 2.4.3 Residential Mobility

In addition to proposing a relationship between social interaction stress and population size, Whitelaw (1989, 1991) further hypothesised that social interaction stress is positively correlated with the duration of occupation of a settlement. Whitelaw reasoned that residential mobility acts to reduce social stress by allowing physical rearrangement of households, thereby providing those households with a degree of control over interaction with others. According to Whitelaw, as duration of occupation increases, that capacity for stress mitigation by rearrangement decreases, so increased separation is used to reduce potential social interaction stress by decreasing interaction rate. Thus, as duration of occupation increase, so too does inter-household separation.

As noted in Section 2.4.1, Whitelaw's study was purely exploratory. Whitelaw observed a negative correlation between duration of occupation and population density in his compiled data set that he sought to explain in terms of social interaction stress. No statistical analysis was undertaken, nor was any corroborating evidence provided, including no evidence of an actual increase in dwelling separation with duration of occupation.

Hamilton et al. (2018) also found a positive correlation between settlement area and length of occupation for 200 hunter-gatherer settlements compiled from 12 previous studies. However, many of the cited references from which the data were extracted do not specify how settlement area was defined (Fisher and Strickland 1989, 1991; Hamilton et al. 2018; Hitchcock 1987; Nicholson and Cane 1991) or appear to be incorrectly cited (Jones 1983). Of the remaining references, various different definitions of area are used. Most use convex hull, although one uses concave hull combined with nearest neighbour analysis (Gould and Yellen 1987). Among those that use the convex hull, some studies delimit area using the absolute limit of scatter (Bartram et al. 1991; Yellen 1977), while others delimit area using structures and activity areas (O'Connell 1987, O'Connell et al. 1991; Politis 1996). Given the inconsistency in the definition of area, the study of Hamilton et al. does not provide any meaningful support for a correlation between residential mobility and population density.

Kent and Vierich (1989; also Kent 1991) reframed Whitelaw's hypothesis somewhat, arguing that *anticipated* length of stay (not actual length of stay) predicts settlement area. They reported a correlation between settlement area and anticipated duration of occupation, as determined by survey of inhabitants at the time of establishing the settlement. But, unlike Whitelaw, who measured area as a convex hull delimited by dwellings, Kent and Vierich delimited the area of

each settlement using all structures. It is clear from Kent and Vierich's data that the observed increase in settlement area with anticipated duration of occupation is due to greater investment in the construction of ancillary structures (e.g. storage huts) when longer stays are anticipated (Kent 1991). It is not due to an increase in dwelling separation that would indicate a deliberate attempt to reduce social interaction or correspond to a variation in population density.

Notwithstanding the lack of supporting evidence, Whitelaw's hypothesis fails to explain the existence of low density temporary settlements and high density permanent settlements, which are readily found. As noted in Section 2.4.1, the Haida have closely spaced dwellings, but their settlements are permanent. The Ngatatjara move frequently, but their household separation (based on mean hearth-to-hearth distances) is reported to be around 36.7 m (Gould and Yellen 1987). A further problem with duration of occupation as a predictor of household spacing is that it only purports to explain why hunter-gatherers in permanent settlements choose low density. It fails to explain why hunter-gatherers in short-lived settlements would opt for high density living.

In view of the available evidence, it appears unlikely that duration of occupation is a determinant of household separation in hunter-gatherer settlements.

#### 2.4.4 Vegetation Density

A final hypothesis that purports to explain close spacing of households in hunter-gatherer settlements is that dense vegetation acts as a constraint. Fisher and Strickland (1991) stated that the forest acted as a constraint on Efé settlements by impeding communication if households are widely spaced, although provided no evidence to support this assertion. More recently, Hamilton et al. (2018) reported average settlement areas in arid environments approximately eight times greater than those in forest environments. Hamilton et al. hypothesised that settlement area is constrained by the physical environment in forest contexts because it is more difficult for households to maintain contact with each other.

The data set used by Hamilton et al. is the same as described in the preceding section, so it is unclear to what extent the difference in settlement area is due to differences in the definition of area. Regardless, it is clear that the constraining effect of vegetation cannot explain why high density settlements are found in environments where vegetation is sparse, such as the savanna of the Kalahari.

While it is plausible that dense vegetation and other aspects of the natural environment (e.g. steep or rocky terrain, boggy ground and water bodies) may act as a constraint on settlement area, it is clear that vegetation cannot be the sole cause of high density hunter-gatherer settlements.

## 2.5 Summary

No hypothesis has yet been suggested that adequately explains population-dependent scaling of hunter-gatherer settlement area. While the ring model of settlement layout proposed by Wiessner (1974) is clearly an oversimplification, it is also clear that the arrangement of dwellings (or other delimiting features) in a settlement plays a role in determining area. Few hunter-gather settlements adhere to the grid-like pattern that would characterise linear growth. But the extent to which household separation also contributes, if at all, is unclear as household separation data is lacking in previous studies. Nevertheless, it is plausible that social interaction stress is a further predictor of household separation, as suggested by Whitelaw (1989, 1991), although this hypothesis remains to be tested.

Similarly, no hypothesis has yet been proposed that explains extreme variance in hunter-gatherer population density, independent of population size. The sharing of food to reduce individual risk (Wiessner 1982; Whitelaw 1983, 1989, 1991), the threat of predation (Gould and Yellen 1987), duration of occupation (Whitelaw 1989, 1991) and dense vegetation (Fisher and Strickland 1991; Hamilton et al. 2018) all appear to explain variance in household separation to some degree. But in each case exceptions exist that cannot be explained. Resolution of the problem could lie in a combination of these factors. But the reported correlation between household separation and risk pooling hints at a more elegant explanation that risk itself is the common thread. Like social interaction stress, the stress associated with risk may be a critical factor in determining household separation.

The emergence of stress as a potential factor in determining both population-dependent scaling and population-independent variance in settlement area points to a possible role of neurobiological mechanisms that relate stress to proximity.

# Chapter 3

## THEORETICAL FRAMEWORK

Outlined in this chapter is the theoretical framework used for addressing the issues raised in the preceding literature review. The theoretical framework underpins the hypotheses proposed in the present study for the variance in household separation between hunter-gatherer settlements. Two concepts are addressed. The first is the neurobiological relationship between stress and the moderation of physical proximity in humans. The second is the mathematical modelling of that relationship as a way to both test the proposed hypotheses and allow predictions to be made.

### 3.1 Defining 'Household Separation'

It is apparent from the previous Chapter that most studies have sought to explain the observed variance in settlement area in terms of variation in the distance between households. However, as demonstrated by the ring model proposed by Wiessner (1974), settlement area is a function of both the separation of households and their arrangement in space. To investigate the potential determinants of household separation and their effect on the population density of hunter-gatherer settlements, household separation must be measured directly.

Like the term 'settlement area', the meaning of 'household separation' varies depending on how it is measured. It must therefore be defined in a way that ensures measurements are comparable and in a way that is appropriate for the question being asked.

A definition of household separation applied in some archaeological and ethnographic studies is the average 'nearest neighbour' distance (Fisher and Strickland 1989; Gould and Yellen 1987; Grier and Savelle 1994; O'Connell 1987). This is a specific case of the ' $k$ -nearest neighbours' method in which  $k$  is equal to one. A drawback of this definition of household separation is that it ignores the separation between clusters of households, which can vary without affecting the mean household separation (Figure 3.1). While useful for the detection of clustering (Whallon 1974), this is obviously problematic when investigating mechanisms that may act on inter-cluster household separation.

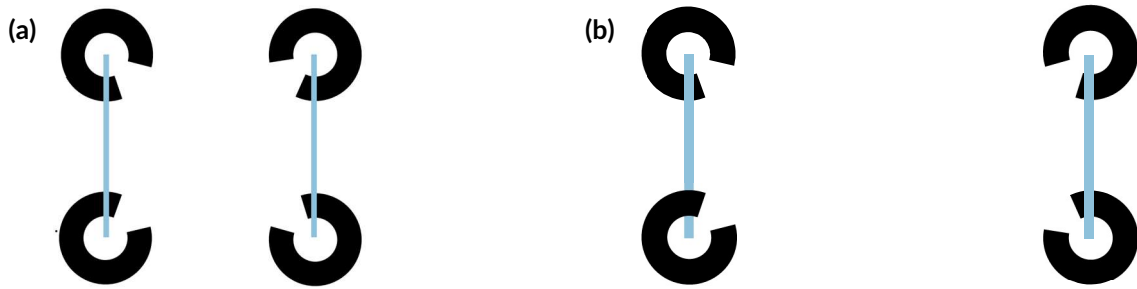


Figure 3.1 – Schematic illustration of the  $k$ -nearest neighbour method for determining household separation in which  $k = 1$ . Average household separation (as represented by the blue lines) is unchanged between (a) and (b) despite an increase in separation between household clusters.

Another definition of household separation sometimes employed is the average distance between all household pairs in a settlement (Gargett and Hayden 1991; Gurven et al. 2001, 2002). This can be considered another variation on  $k$ -nearest neighbour analysis method in which  $k$  is equal to the number of households less one. While not sensitive to clustering, this method captures the nonlinear scaling effect of household arrangement (Figure 3.2). Clearly this is a problem when seeking to disentangle the effects of variables on household arrangement and household separation.

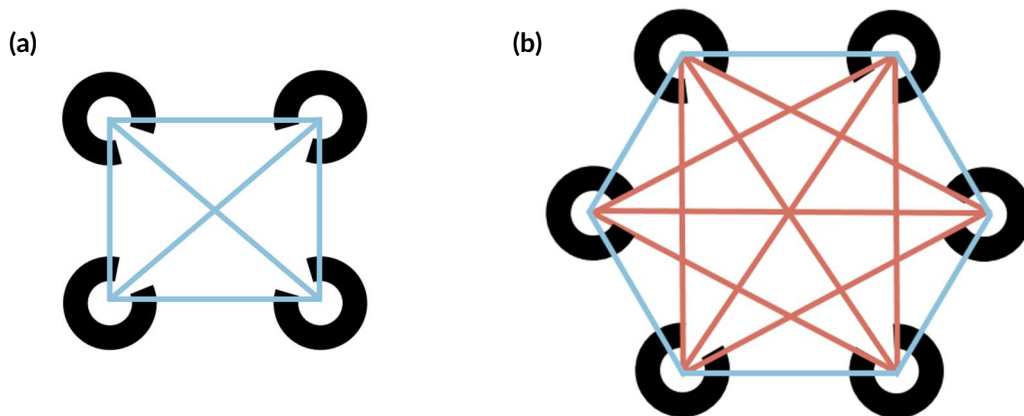


Figure 3.2 – Schematic illustration of the  $k$ -nearest neighbour method for determining household separation in which  $k = N - 1$ . Mean separation changes between (a) and (b) despite no change in separation between nodes because separation increases between non-adjacent nodes (indicated by red lines)

An alternative approach to defining household separation is the minimum spanning tree ('MST'). An MST can be defined as the shortest acyclic network connecting a set of nodes (Borůvka 1926; Kruskal 1956; Prim 1957) (Figure 3.3). For any given group of nodes a

unique MST exists. The mean distance between nodes, in this case households, can be calculated as the average across all pairs on the MST.

The MST was originally devised to solve the problem of optimising electrical network coverage (Borůvka 1926). The MST therefore treats all nodes as a connected network and omits any unnecessary (i.e. cyclic) connections. For these reasons, the MST resolves the issues inherent to nearest neighbour methods. By treating a settlement as a connected network rather than dissociated clusters of households, both intra- and inter-cluster household separations are included in the mean household separation. Furthermore, by omitting any cyclic connections it avoids layout effects caused by scaling of void space within those cycles.

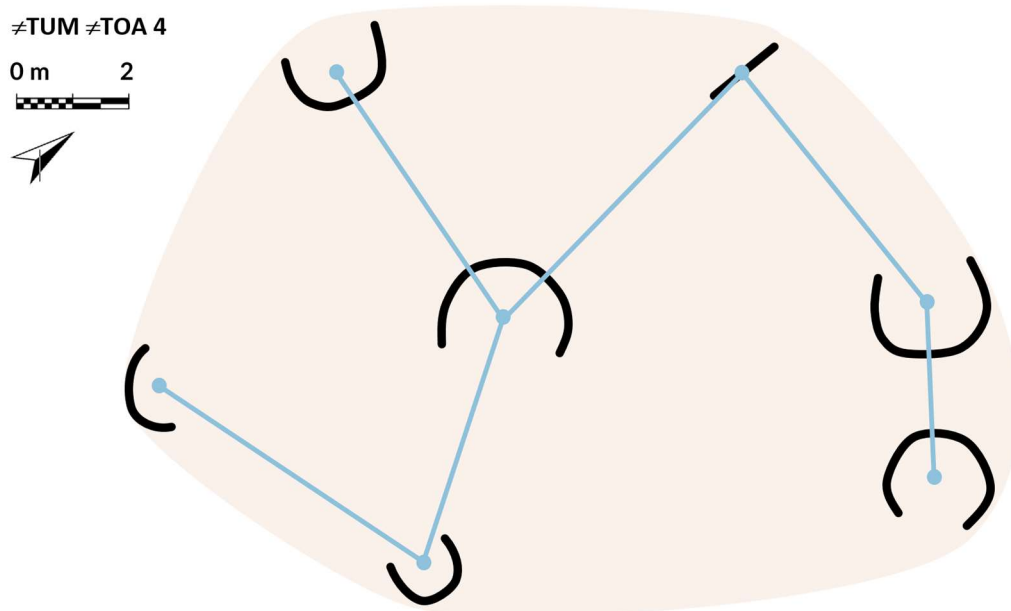


Figure 3.3 – Minimum spanning tree connecting the seven dwellings of the !Kung settlement of ≠Tum ≠Toa 4, 1968 (after Yellen 1977)

Justification for using the MST to measure household separation extends beyond mere convenience. MSTs have previously been used for quantifying the separation of buildings in studies of urban environments (e.g. Caruso et al. 2017; Pavon et al. 2024; Wu et al. 2017). They have also found application in both archaeological and ethnographic studies. They have previously been used to reconstruct cultural phylogenetic trees (Irwin 1993; Renfrew and Sterud 1969) and to characterise the growth of trade networks (Ducke and Suchowska 2022; Groenhuijzen and Verhagen 2017; Grofman and Landa 1983; Jenkins 1998). A common factor in these studies is that they relate to evolutionary processes. Except in the case of pre-planned

settlements, settlement growth is also an evolutionary process, whereby change occurs by the sequential addition of new households. Each new household positions itself in relation to an existing household and, in doing so, determines its frequency of interaction with the members of that household (noting that interaction rate is proportional to proximity). A settlement can therefore be appropriately described as a network (e.g. Dyble et al. 2016; Small and Adler 2019) in which distances between nodes reflect choices about rates of social interaction.

For the purpose of the present study, therefore, household separation is defined as the distance between nodes along the minimum spanning tree for a settlement.

## **3.2 The Neurobiology of Sociality**

Human sociality is an evolved preference for group living, inherent to which is the maintenance of physical proximity with other people (Ward and Webster 2016; Wilson 1975). The selective advantage of sociality is the promotion of cooperative behaviour between individuals. That behaviour may be simple, such as safety in numbers (Lehtonen and Jaatinen 2016; Schultz et al. 2011; van Schaik 1983), or more complex, such as the sharing resources or information or the division of labour (Apicella and Silk 2019; Henrich and Muthukrishna 2021; van Schaik 2016). The effectiveness of cooperation as an evolutionary adaptation is evidenced by its pervasiveness throughout the natural world, from bacteria (Dimitriu et al. 2014; Griffin et al. 2004; Lambert et al. 2014) to plants (Biernaskie 2011; Dudley 2015) and animals (Dugatkin 1997; Smith et al. 2012).

As a product of biological evolution, neurobiological mechanisms exist in humans that control social behaviour. By extension, those mechanisms also act on physical proximity as a means by which sociality is achieved. As hunter-gatherer settlements are a physical manifestation of human sociality, it is reasonable to propose that the neurobiological mechanisms that control sociality may be responsible for variance in the spatial characteristics of those settlements. In particular, two factors are considered in this section: the tendency to maintain a certain degree of social interaction ('social homeostasis') and the social support provided by proximity to other people ('social buffering').

### **3.2.1 Social Homeostasis**

Homeostasis is an equilibrium state at which organisms function optimally (Selye 1973; Torday 2015). In the human body, the stress response system reacts to anticipated or realised disruptions to that equilibrium state, caused by 'stressors', by releasing stress hormones

(Agorastos and Chrousos 2022; Kültz 2022; Lu et al. 2021; Ortega et al. 2021). Those hormones in turn prompt physiological, psychological or behavioural responses aimed at restoring homeostasis. The equilibrium state that describes an optimal level of social interaction has been termed ‘social homeostasis’ (Matthews and Tye 2019). Social homeostasis is a positive state. The release of reward hormones during social interaction, such as oxytocin, dopamine and endorphins, provides feelings of well-being and promotes the formation of social relationships (Vitale and Smith 2022). Social stressors, such as the perception of too much social interaction (‘social crowding’) or too little social interaction (‘social isolation’), disrupts social homeostasis and activates the stress response system.

The perception of social isolation, as distinct from the objective state of being socially isolated, is commonly termed ‘loneliness’. Loneliness is defined as a discrepancy between a desired quantity and quality of social interaction and that which is actually realised (Perlman and Peplau 1981; Smith et al. 2020; Victor and Pikhartova 2020; Wang et al. 2017). As expected for deviation from a homeostatic state, loneliness is associated with elevated stress hormones, specifically cortisol and catecholamines (e.g. Adam et al. 2006; Cacioppo et al. 2000; Doane and Adam 2010; Hawkey et al. 2003, 2006; Kiecolt-Glaser et al. 1984; Montoliu et al. 2019; Pressman et al. 2005; Steptoe et al. 2004). Individuals who perceive themselves to be socially isolated have been found to seek out or renew social connections (e.g. Cacioppo and Cacioppo 2014; DeWall and Richman 2011; Kornienko et al. 2020; Maner et al. 2007), a motivation that appears to be initiated in the reward-related regions of the brain (Inagaki et al. 2016). The feeling of loneliness may therefore be an evolved stress response that actively discourages asociality.

On the other hand, there is a limit to how much social interaction the human brain will tolerate. Like the perception of social isolation, high density environments and excessive social interaction is associated with raised cortisol levels and behavioural indicators of stress (e.g. Chan et al. 2020; Collette and Webb 1976; Desor 1972; Evans 1979; Evans et al. 1998; Loo and Ong 1984; Mackintosh et al. 1975; Tripathi 2012; Valins and Baum 1973). Naturally, social crowding may be resolved by reduced social interaction (social withdrawal) (e.g. Evans et al. 2000; Hutt and Vaizey 1966; Loo 1972; Regoeczi 2003; Sundstrom 1975; Valins and Baum 1973), thereby restoring social homeostasis.

Physical proximity clearly plays a role in restoring social homeostasis. Frequency of social interaction is positively correlated with physical proximity (Bettencourt 2013; Collette and

Webb 1976). It is well-established that a higher frequency of social interaction can reduce loneliness (e.g. Grünjes et al. 2024; Kuczynski et al. 2022; Luo et al. 2022; Macdonald et al. 2021; Schulze et al. 2020). This is especially true of interaction with close social contacts (Ji et al. 2022). Closer physical proximity therefore reduces the likelihood of loneliness, while social withdrawal is achievable by reducing physical proximity to other people.

Loneliness and social crowding are therefore opposing stressors that both vary with frequency of social interaction. The interaction rate at which the sum effect of those two stressors is a minimum represents an optimum ‘social density’ (Love and Zelikowsky 2020) and therefore a set point for social homeostasis. Because frequency of social interaction is positively correlated with physical proximity, it follows that there must also be an optimum average distance between individuals that minimises the combined stress of loneliness and social crowding.

Translating this to the hunter-gatherer settlement, it is clear proximity is at least partly a response to the neurological pressure to minimise the stresses of loneliness and social crowding. Household separation is a means by which occupants of a settlement can exert control over proximity with other people in the settlement and thereby attain that optimal social interaction rate.

### 3.2.2 Social Buffering

The preceding Section discusses moderation of physical proximity as a behavioural response to stress that acts directly on a social stressor (i.e. loneliness or social crowding) by altering the frequency of social interaction. Of course, modification of social interaction rate would have no direct effect on non-social stressors. However, closer physical proximity can nevertheless mitigate the stress response of non-social stressors through ‘social buffering’.

Social buffering describes the reduction of the stress response in an individual by the physical presence of a social affiliate (Kiyokawa et al. 2018). It is a phenomenon that has been observed in humans, non-human primates and various other animals (Hennessy et al. 2009; Kikusui et al. 2006; Kiyokawa and Hennessy 2018; Sanchez et al. 2015; Wu 2021). In humans, studies have found that a social buffering effect may be provided by the presence of parents (Hostinar et al. 2015; Seltzer et al. 2010), romantic partners (Ditzen et al. 2007; Kirschbaum et al. 1995) or friends (Adams et al. 2011; Heinrichs et al. 2003). The effectiveness of a particular social partner has been found to depend on the quality of the relationship (Albers et al. 2008; Nachmias et al. 1996), the age of the individual (Gunnar and Hostinar 2015; Kiyokawa and

Hennessy 2018) and their gender (Kirschbaum et al. 1995). Furthermore, it has been found that humans under stress self-report a greater need for social company (Sicorello et al. 2020).

The neurobiological and physiological mechanisms of social buffering are not fully understood, although it is clear that the mere presence of a social affiliate is sufficient to inhibit the stress response. Human and animal studies suggest that visual, vocal, tactile and olfactory cues may all play a role in eliciting the buffering response (Kikusui et al. 2006; Wu 2021). These cues appear to activate the reward system of the brain. Both oxytocin and endogenous opioids have also been implicated in the inhibition of the stress response by social buffering (Hostinar et al. 2014; Kikusui et al. 2006).

In the absence of modern communication technology, physical proximity is necessary for the cues that trigger social buffering to be perceived. In contexts where a stressor is ever-present, it appears a reasonable proposition that humans, including hunter-gatherers, will position themselves close enough to one another to perceive those cues and thereby mitigate the stress response. That impetus to be physically close to social affiliates may, in the case of hunter-gatherers, translate to closer spacing of households.

### **3.3 Sociality and the Hunter-Gatherer**

Social homeostasis and social buffering are human universals. It must be expected therefore that, in certain contexts, these neurobiological phenomena determine the behaviour of hunter-gatherers. Given the relationship between these mechanisms and physical proximity, it follows that they are at least partly responsible for the observed variance in spatial characteristics of hunter-gatherer settlements.

#### **3.3.1 Household Size and Proximity**

To maintain social homeostasis, any potential variation to social interaction rate should be counteracted by an adjustment to physical proximity. In the context of hunter-gatherer settlements, variation in household size (i.e. the number of people per dwelling or open domestic space) must be accompanied by an equivalent variation in household separation if the social interaction rate is held constant. Increasing household size without a compensating adjustment of household separation would eventually result in extremely high population densities and social interaction rates as household sizes become large.

The effect of household size on settlement structure has been considered previously. O'Connell (1987) considered it likely that changes in household size may precipitate changes in the size,

number and distribution of domestic structures (sun shades and hearths), although no supporting evidence was provided. On the other hand, Gould and Yellen (1987) reported no correlation between hearth-to-hearth distance and household separation among the !Kung. However, no statistical analysis of the results was undertaken to determine if a significant trend was present. In fact, Yellen (1977, pp. 114–117) had previously reported for a portion of the same data set a statistically significant difference in household area (delimited by the extent of domestic debris) between households comprising one adult and those comprising more individuals (although no statistical difference was found between the household area of the larger household sizes). To date, no clear evidence has been presented to establish whether household separation varies with household size in hunter-gatherer settlements.

To gain an understanding of the nature of the relationship between household size and household separation, it can be mathematically modelled by combining probability theory with spatial geometry.

In modelling the relationship, it is necessary to define the frequency of social interaction in terms of settlement area and population size. To do this it is useful to turn to the physical sciences. The interaction (or collision) of discrete moving objects underpins a range of physical processes, including chemical reactions (e.g. Mancini et al. 2024), estuarine sedimentation (e.g. McAnally and Mehta 2000) and the evolution of stars (e.g. Champney et al. 1995). The interaction dynamics of such systems is well-understood (Lewis 1918; Meyer and Deglon 2011; Olsen et al. 2005, 2006, 2008; Trautz 1916; von Smoluchowski 1917). For a system comprising a single particle type,  $i$ , the rate at which those particles collide or otherwise interact is proportional to the square of their number density:

$$I_i = k_{ii} \left( \frac{N_i}{V} \right)^2 \quad (3.1)$$

where  $k_{ii}$  is a rate constant (which has unit of  $\text{m}^3/\text{s}$ ) that describes particle transport,  $N_i$  is the number of particles in the system and  $V$  is the system volume.

The formula for describing the rate of particle interaction in physical systems is readily transferrable to human interaction. Population density in a settlement clearly parallels particle density, although in two dimensions rather than three. The rate constant,  $k_{ii}$ , varies depending on the nature and magnitude of particle motion. It is a reasonable proposition that the movement of hunter-gatherers within a settlement may be similarly summarised as a constant of proportionality. Indeed, the diffusive and directed particle transport processes captured by  $k_{ii}$

(Meyer and Deglon 2011) find clear parallels in the diffusive and directed components of human movement (Padgham 2012).

We can therefore define the interaction rate (per square metre per second) within a hunter-gatherer settlement as:

$$I = k \left( \frac{P}{A_M} \right)^2 \quad (3.2)$$

where  $k$  is a constant that describes the movement of people within the settlement (in units of  $\text{m}^2/\text{s}$ ),  $P$  is the population size of the settlement and the concave area,  $A_M$  is the area in which within-settlement movement is confined.<sup>1</sup>

It can be assumed that movement is largely concentrated around and between dwellings and open domestic spaces, so the distance between dwellings gives the radius of movement around each dwelling. The area in which within-settlement movement is confined can thus be approximated as follows:

$$A_M \approx N \cdot \bar{S}^2 \quad (3.3)$$

where  $N$  is the number of households in the settlement and  $\bar{S}$  is the arithmetic mean distance between households.

Substituting the approximation of  $A_M$  into Formula 3.2 and rearranging to make  $\bar{S}$  the subject gives us:

$$\bar{S} \approx \frac{1}{I^{0.25}} \left( \frac{P}{N} \right)^{0.5} \quad (3.4)$$

If interaction rate does not vary, the term  $I$  in Formula 3.4 is a constant and mean household spacing scales as the square root of household size:

$$\bar{S} \approx \left( \frac{P}{N} \right)^{0.5} \quad (3.5)$$

On the assumption that the average social interaction rate between hunter-gatherers is constant for a given set of conditions, the rate being determined as that required to minimise the stresses

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<sup>1</sup> Note that Formula 3.2 differs from the formulation of interaction rate used in settlement scaling theory (Bettencourt 2013; see also Section 2.3.3), which is the interaction rate per capita per second. That formulation can be derived by multiplying Formula 3.2 by the inverse population density,  $A/P$ .

of loneliness and social crowding, it is hypothesised that mean household separation of hunter-gatherer settlements will vary as the square root of the number of people per household.

### 3.3.2 Community Size and Proximity

A further factor that may be a potential disruptor of the balance between loneliness and social crowding is the number of other people in a settlement, as represented by either the total population size or the number of households. For the present discussion, the term ‘community size’ will be used to broadly refer to both.

As discussed in detail in Section 2.3.2, Whitelaw (1989, 1991) argued that the average stress of social *interaction* in hunter-gatherer settlements increases with community size because of a greater likelihood of encountering strangers. He hypothesised that an increase in household separation within settlements to compensate for that increased stress. The present study considers the alternate possibility, that household separation in hunter-gatherer settlements is adjusted to compensate for the scaling of perceived social *isolation* stress (i.e. loneliness) with community size.

The size of community represents a limit to the maximum number of social connections any individual may have. While in most communities that limit is likely to exceed the social needs of individuals, in very small communities it may mean that individuals have fewer social connections than desired. As noted in Section 3.2.1, loneliness is defined as a shortfall between desired and actual quantity and quality of social interaction. In other words, as community size becomes small, the likelihood of loneliness becomes large unless some other compensating change is made, approaching near certainty as population size approaches one. In such situations, closer proximity ensures the stresses of loneliness and social crowding are balanced by increasing the frequency of social interaction.

Like the relationship between household size and household separation, the relationship between community size and household separation can be mathematically modelled by combining probability theory and geometry to gain a better understanding of the nature of that relationship.

The relevant probability is whether the individual deciding the location of a household (the decision-maker or head of a household) perceives that they have fewer actual social connections within a settlement than desired. It is assumed that the desired and actual number of relationships per person within a population follows an approximately normal distribution,

reflecting the approximately normal distribution of the underlying personality traits (especially introversion-extroversion) on which these values number are likely based (Root 1931). The probability that some value of a normally distributed variable is less than some other value of another normally distributed variable is given by the cumulative distribution function for the difference between the two distributions. Invoking that function, the probability that a household head has fewer actual relationships,  $n_{act}$ , than their desired number of relationships,  $n_{des}$ , can thus be described as follows:

$$\mathbb{P}(n_{act} < n_{des}) = \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{\bar{n}_{des} - \bar{n}_{act}}{\sqrt{\sigma_{des}^2 + \sigma_{act}^2}} \right) \right] \quad (3.6)$$

where  $\bar{n}_{act}$  and  $\bar{n}_{des}$  are the respective means of the distributions of the actual and desired number of social relationships and  $\sigma_{act}$  and  $\sigma_{des}$  are respective standard deviations of those distributions.

Applied to hunter-gatherer settlements, Formula 3.6 describes the average frequency distribution of socially isolated households. To translate that frequency distribution to the spatial domain, the relationship between household separation and perceived social isolation needs to be explicated. We can define distances  $S_0$  and  $S_\infty$  that are the mean household separation for socially isolated households and households that are not socially isolated, respectively. These are the expected values for household separation in each case. Both distances correspond to the baseline situation where household size is equal to one, increasing as the square root of the average household size, as described in the preceding Section. The mean household separation in a settlement can then be defined as the product of the probability of households being socially isolated or not socially isolated with their respective mean household separations:

$$\bar{S} \propto S_\infty \cdot [1 - \mathbb{P}(n_{act} < n_{des})] - S_0 \cdot \mathbb{P}(n_{act} < n_{des}) \quad (3.7)$$

By substituting Formula 3.6 into Formula 3.7 and rearranging, the log-average household separation in a settlement can be described as:

$$\bar{S} \propto S_\infty - \frac{1}{2} (S_\infty - S_0) \left[ 1 + \operatorname{erf} \left( \frac{\bar{n}_{des} - \bar{n}_{act}}{\sqrt{\sigma_{des}^2 + \sigma_{act}^2}} \right) \right] \quad (3.8)$$

To express Formula 3.8 in terms of settlement size, we need to relate the average actual number of relationships per person,  $\bar{n}_{act}$ , to either population size,  $P$ , or number of households,  $N$ .

The perception of social isolation has been found to be more strongly correlated with a lack of non-familial relationships (i.e. friendships) than a lack of familial relationships (Mullins et al. 1987; Uruk and Demir 2003). Close friendships are more likely between people of similar social status and age and of the same gender (Ball and Newman 2013; Fischer 1982; Nicolaisen and Thorsen 2017; Verbrugge 1977). On average, a head of household is likely to find one other person of the same social status, gender and age in each other household. In a settlement with larger household sizes, there may be a number of individuals of similar age and gender in each other household. But, larger household sizes tend to follow from sedentism because the investment in large communal dwellings can be justified for longer durations of stay. Sedentism is also an apparent predictor of social stratification (Hartley 2019), so the overall number of social equivalents of heads of households is expected to decrease as household size increases (as the saying goes, ‘it’s lonely at the top’). Therefore, it is proposed that the number of households,  $N$ , is a more accurate correlate of the number of actual relevant relationships (i.e. relationships with peers) in a settlement than population size.

Another question that needs to be addressed is whether the number of households in a settlement can be properly substituted for  $\bar{n}_{act}$  in Formula 3.8. For that to be the case, the relationship between  $N$  and  $\bar{n}_{act}$  would need to be approximately linear up to a value of  $N$  where the likelihood of loneliness approaches a minimum (above such a value any deviations from linearity would have little effect). That value of  $N$  is likely to correspond to quite small settlements. The average number of friends per person in modern towns and cities has been found to range from about four to six (Dunbar 2018; Gillespie et al. 2015; Solano 1986). Above an average of four friends there appears to be little effect of additional friendships on loneliness (Thompson et al. 2024). The average number of desired relationships,  $\bar{n}_{des}$ , is therefore likely to be within this range, meaning the transition from a high to low probability of perceived loneliness likely occurs within the context of small settlements. In these contexts, most people are likely to know each other and choose to live together, so the mean rate of friends per household is unlikely to vary significantly with number of households due to decreasing familiarity. The relationship between  $\bar{n}_{act}$  and  $N$  would thus be approximately linear and is appropriate for use in Formula 3.8.

Replacing  $\bar{n}_{act}$  in Formula 3.8, we can define the approximate relationship between mean household separation and the number of households in a settlement as follows:

$$\bar{S} \approx S_{\infty} - \frac{1}{2}(S_{\infty} - S_0) \left[ 1 + \operatorname{erf} \left( \frac{\bar{n}_{des} - a(N - 1)}{\sqrt{\sigma_{des}^2 + \sigma_{act}^2}} \right) \right] \quad (3.9)$$

where  $a$  is a constant of proportionality that describes the approximately linear relationship between  $N$  and  $\bar{n}_{act}$ . Formula 3.9 is a sigmoid function with an inflection point at  $N$  equal to  $\left(\frac{\bar{n}_{des}}{a} + 1\right)$ . The inflection point represents the probability of a household head perceiving themselves to be socially isolated is 50% (Figure 3.4).

It is therefore hypothesised that an increasing sigmoidal relationship exists between mean household separation and the number of households in a settlement, where closer physical proximity compensates for the limited number of actual peer relationships possible in very small communities by providing more frequent social interaction.

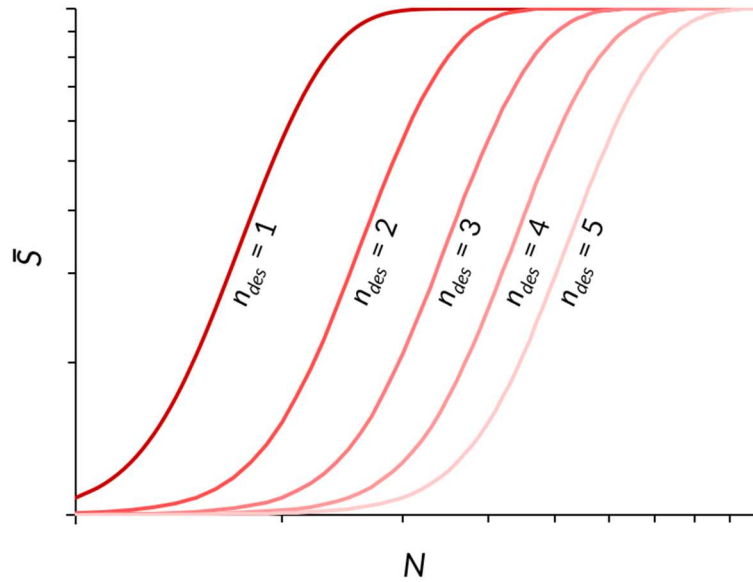


Figure 3.4 – Plot of Formula 3.9 showing the effect of varying  $\bar{n}_{des}$  on the inflection point of the sigmoid function (for constant  $S_0$ ,  $S_{\infty}$ ,  $a$ ,  $\sigma_{des}$  and  $\sigma_{act}$ )

### 3.3.3 The Uncertainty of Hunting

Social buffering is a mechanism of stress reduction that is inherent to all humans. It would certainly be relied upon by hunter-gatherers to buffer the effects of stressors outside their control. Moreover, it provides a link between contexts that give rise to stress and modification of spatial behaviour. Yet, to date, there has been little, if any, consideration of the role of social buffering in the lives of hunter-gatherers.

A recent study by Fedurek et al. (2023) reported that, among Hadza men, time spent in proximity to others within a settlement was negatively correlated with physiological stress, as measured by hair cortisol concentration. No correlation between physiological stress and within-settlement proximity was found for Hadza women. Fedurek et al. suggest that this difference may correspond to a difference between genders in the amount of control they have over social interaction. While certainly plausible, an alternative interpretation readily presents itself. In Hadza society, men focus their foraging efforts on hunting game, while women focus on gathering plant foods (Wood and Marlowe 2013; Woodburn 1968). The observed difference in stress reduction with time spent in proximity to others between Hadza men and women might be due to differences in foraging behaviour.

A key difference between hunting and gathering is predictability. Most contemporary hunter-gatherers consume a combination of both plant and animal foods as part of their normal diet (Binford 2001). In many environmental contexts, plant foods are generally considered to be a reliable and readily obtainable source of energy (Lee 1968, p. 33; Marlowe 2007; Milton 2000). By contrast, hunting typically presents a greater challenge than gathering plant foods. The reproductive success of animals depends on evolved defences to predation, such as hiding, evasion and fighting (Caro 2005; Stiner and Munro 2002). Hunting success depends on being able to find a moving animal and then, once found, being able to capture it. In contrast to gathering predictably located and stationary plant foods, hunting animals can be an unpredictable, time-consuming and dangerous pursuit (Alvard and Nolin 2002; Kaplan and Hill; 1985; McElreath and Koster, 2014). Hunting can therefore be a source of uncertainty for hunter-gatherers.

Why then do hunter-gatherers pursue meat? Meat is evidently an important part of the hunter-gatherer diet. There are no known contemporary hunter-gatherer groups that subsist on plant foods alone, but many are known that subsist almost exclusively on hunted animals (Binford 2001). While plants are a reliable source of calories, they can be relatively low in protein, fat and many nutrients compared with meat and other animal products (Leroy and Praet 2015; Leroy et al. 2023; Milton 1999). Hunter-gatherers are not necessarily aware of the nutritional benefits of consuming meat, but they would be aware of the satiety it provides compared with plant foods (Leroy and Praet 2015; Morell and Fiszman 2017). Consequently, meat is often prized among hunter gatherers (Gould 1967, p. 41; Lee 1979, pp. 41-42, 45; Maybury-Lewis 1967, p 36; Wiessner 1977, p. 61) and its provisioning can be a source of prestige and other benefits to the hunter (Hawkes 1990, 1991, 1993).

The uncertainty that unpredictable situations engender is a known stressor in humans and is associated with elevated cortisol levels (Lang et al. 2009; Lawes et al. 2022; Wirtz et al. 2013; Wu et al. 2020). Any uncertainty associated with the provisioning of an important component of the hunter-gatherer diet would certainly be a stressor. The unpredictability of hunting may therefore cause physiological stress for some hunter-gatherers, triggering a social buffering response. In the context of a hunter-gatherer settlement, that may be manifested as closer spacing of household domestic areas, such as dwellings and open domestic areas (i.e. outside areas where people sleep, cook and eat in the absence of a dwelling).

But hunting is not always unpredictable. Unpredictability comes with combining a strategy of targeting either low density or low yield (small-bodied) prey using individual-capture methods (e.g. bow and arrow, firearm, hook-and line, harpoon or trap). The predictability of hunting can therefore be improved by focussing on high density, high yield (large-bodied) prey. Hunting migrating caribou, for example, is far more reliable than hunting caribou out of migration season because the caribou are more numerous and concentrated in relatively predictable areas (Joly et al. 2021; Binford 1978b, p. 85; O'Shea et al. 2013; Smith 1985). The predictability of hunting can also be improved by using mass capture technology (Jones 2006; Madsen and Schmitt 1998; Morin et al. 2020). For example, the use of gill nets and seine nets for fishing has been found to substantially increase individual catch compared with a hook and line (Beckett et al. 2014; Smith 1985; Tucker 2000, p. 130), providing a more predictable source of protein and greater certainty. By practicing migration hunting or net fishing, individual households are able to cache large surpluses of protein, typically by drying or freezing, as a buffer for leaner periods.

Alternatively, hunting strategies that target sessile or slowly moving prey (e.g. invertebrates) or prey that rely on hiding as a defence mechanism are more akin to gathering (Jones 2006; Stiner and Munro 2002). Like plant foods, gatherable protein is predictable because the prey is easily located and captured. The Pintupi of the Western Desert region of Western Australia are recorded as capturing goannas from their burrows at an average rate of about one goanna every 10 minutes (Gould 1967), each providing sufficient protein for an adult for one day. Hunting predictability, and therefore the certainty of protein provision at the level of the individual household, depend on hunting strategy.

The observed variance in population density between hunter-gatherer settlements could be the product of reliance upon hunting strategies that differ in their risk of failure at the level of the

individual household. In settlements that rely on high risk hunting strategies, separation between households may be smaller because proximity, through social buffering, mitigates the stress of uncertainty.

### **3.4 Summary**

The three distinct hypotheses of the present study emerge from the foregoing theoretical framework. The first and second hypothesis predict that, in order to maintain social homeostasis, household separation in hunter-gatherer settlements scales as the square root of household size and as a sigmoid function of the number of households. The third hypothesis predicts that household separation in settlements where high risk hunting strategies are practiced will be smaller than in settlements that practice low risk hunting strategies, the closer proximity to social connections buffering the stress of uncertainty. These hypotheses are testable by using the MST to calculate household separation in a settlement, as discussed at the start of this Chapter.

## Chapter 4

### METHODOLOGY

#### 4.1. Research Design

The aim of the present study is to investigate the possible role of hunting strategy risk, household size and number of households as determinants of household separation in hunter-gatherer settlements. The relationship between these variables was investigated for contemporary hunter-gatherers settlements. Statistical methods (general linear model and nonlinear regression) were used to investigate the ability of each variable to explain observed variance in household separation.

#### 4.2. Data Acquisition

##### 4.2.1. Settlement Selection

The data set for the present study was compiled from primary ethnographic and archaeological studies of hunter-gatherer settlements. Settlements were taken from any time period and geographic location, subject to the following criteria being met.

Settlements included in the data set were limited to those that provide an adequate representation of hunter-gatherer behaviour in a domestic environment. For this reason, only settlements occupied exclusively or predominantly by people who relied on hunting and/or gathering at the time of observation for at least part of their regular subsistence were included. Non-residential sites, such as kill sites (e.g. Jarvenpa and Brumbach 1983, p. 180) and hunting stands (e.g. Binford 1978a), were excluded as they are not necessarily representative of behaviour in a domestic environment. As one of the main dependent variables for the present study is household spacing, settlements were further limited to those that included two or more households living in either separate dwellings or spatially discrete open domestic areas. Cave and rock shelter sites (e.g. Nicholson and Cane 1991) were also excluded as too few were identified to allow meaningful consideration of the potential physical constraints these sites place on hunter-gatherer behaviour.

A number of settlements that were included in the data set were not laid out by the inhabitants of the settlement at the time of observation, either because of a reoccupation event or because of inter-generational inhabitation of a permanent settlement. Although it is acknowledged that the layout of such settlements is not representative of the behaviour of their inhabitants, they were nevertheless the product of decisions made by previous hunter-gatherer occupants. Furthermore, inhabitant spatial behaviour is expressed as household size, addition of new dwellings and the choice of that settlement over somewhere else. On the other hand, settlements that were the result of forced resettlement or were laid out according to public planning were excluded. Such settlement may not be representative of hunter-gatherer behaviour and, in some cases, were a deliberate attempt to modify that behaviour (e.g. Thomas and Thompson 1972).

For the purpose of spatial analysis, settlements that were reported as unitary entities were treated as such. Clusters of dwellings within settlements were not treated as separate 'social situations' (c.f. Whitelaw 1991, p. 141). It is acknowledged that determining where one settlement stops and another starts can be subjective. For the present study, the view of the ethnographer is taken as being representative of the views of the inhabitants, which is considered to be the most reliable indicator of the extent of a settlement.

At a minimum, the data available for each settlement included a plan of the site, population size data, a general geographic location and a description of the subsistence behaviour of the inhabiting group of hunter-gatherers.

#### 4.2.2. Spatial and Demographic Data

Settlement plans were limited to those that described an actual settlement and included an explicit scale or a feature of known dimensions from which a scale could be inferred. Plans of 'typical' settlements (e.g. Memmot 2002, pp. 70, 76-77) were excluded as these may represent an idealised version rather than reality. Where the exact geographic location of a settlement was known, the scale was confirmed by comparison with geographic landmarks using either Google Earth or Esri World Imagery. Where a discrepancy was observed between the scale provided on the plan and that determined from georeferencing the latter was adopted (e.g. Irimoto 1981a). Archaeological plans of sites were used where population data and ethnographic observations were available contemporary with occupation of the settlement and where the archaeological signal of dwellings was clear (e.g. a stone tent ring).

Population data was limited to census data or estimates made by direct observers. Non-contemporary estimates based on dwelling numbers or other spatial characteristics of

settlements (c.f. Whitelaw 1989, 1991) were excluded as they presuppose a relationship between population and space. In the case of multiple occupations, each instance was recorded separately. However, where a settlement is continuously occupied but the population fluctuates (e.g. due to members being absent on foraging expeditions), a single instance is recorded using the maximum reported population on the presumption that the settlement was laid out with all inhabitants in mind. Where an estimated population range was reported (e.g. Vellard 1934), the middle of the range was recorded, which is presumed to be the observers best estimation of the actual population.

#### 4.2.3. Categorising Hunting Risk

The hunting strategies typically employed by the inhabitants of each settlement in the data set were recorded to investigate their relationship to household proximity. Each settlement was categorised according to whether the inhabitants practiced a ‘low risk’ hunting strategy for the full duration of occupation, or whether they relied on a ‘high risk’ strategy for at least a portion of the duration of occupation. To facilitate the dichotomous division of data, only settlements that could be appropriately described as fitting into one of the two categories were included. Where only a portion of settlement practice a low risk strategy, or it was unclear the extent to which a low risk strategy was practiced (e.g. Bartram et al. 1991, p. 105; Kent and Vierich 1989), the settlement was excluded.

Hunting strategies were ranked as either ‘high risk’ or ‘low risk’, according to the inferred risk of an individual hunter returning emptyhanded on any given hunting foray. A strategy of targeting low density or low yield prey using individual-capture methods (e.g. bow and arrow, firearm, hook-and line, harpoon or trap) was ranked as ‘high risk’, while targeting high density, high yield prey (migration hunting) or using mass capture technology (net fishing) was ranked as ‘low risk’. The targeting of easily found and captured animals (protein gathering) was also ranked as a ‘low risk’ strategy. In addition, access to a reliable source of income (e.g. from welfare, guaranteed employment or from sale of manufactured goods) to supplement hunting and fishing returns were ranked as ‘low risk’.

Pastoralism has previously been identified as providing a more predictable protein supply than hunting (e.g. Ringen et al. 2019). However, the reliability of meat and milk from pastoralism is dependent on the size of the herd maintained (Mace and Houston 1989; Moritz et al. 2017; Prins 1992) and milk production is highly seasonal and subject to collapse if there has been insufficient rainfall (Bethancourt et al. 2023; Bollig and Göbel 1997; Sadler et al. 2010; Vierich

1981, pp. 241-242). Settlements that relied on pastoralism as a protein supply were therefore excluded from the data set as it is unclear in most cases whether it provides a reliable protein supply.

The storage of protein (e.g. by freezing or drying) has also been suggested as a method used by hunter-gatherers to buffer against both seasonal and day-to-day variation in hunting success (e.g. Binford 1980; Greiser 1985; Ringen et al. 2019; Widlok 2020). But storage will only buffer against variable individual return rates if the surplus obtained on capture is sufficient to comfortably bridge the time until next capture (e.g. when using mass capture technology on targeting migrating animals) (Stein Mandryk 1993). The required surplus may be large when providing for a household and where hunting success rate is low. The storage of protein alone was therefore not considered an indicator of a 'low risk' strategy. Significantly, in all cases where either migration hunting or net fishing was practiced it was noted that surplus meat was stored by either drying or freezing.

#### 4.2.4. Measuring Household Separation

The mean household separation for each settlement was measured from digitised settlement plans using 'ImageJ' version 1.53k (National Institutes of Health) image analysis software. To measure household separation, the minimum spanning tree ('MST') was constructed for each settlement. The nodes of the MST were defined as dwellings or, where no dwellings were present, spatially discrete open domestic areas. Each individual connection on the MST was measured from the centroids of the nodes. The mean household separation was calculated for each settlement by dividing the total MST length by the number of nodes (i.e. households).

### 4.3. Statistical Analysis

#### 4.3.1. General Linear Model

A general linear model (GLM) was used to investigate the effect of hunting strategy, household size and number of households on mean household separation. Hunting strategy risk was included in the GLM as a categorical variable. Household size and number of households were included in the GLM as covariates.

While it is expected that household separations is a sigmoidal function of number of households, for the purpose of linear modelling it has been demonstrated previously that approximation using a linear relationship is preferable to omission of a covariate (Tackney et al. 2023). The relationship between household separation and number of households was

therefore modelled as a quadratic polynomial to allow for any curvature caused by unequal asymptote lengths.

During formulation of the GLM, all possible interaction terms were included. However, no evidence of a significant interaction between variables was found, so interaction terms were omitted from the final model (Beck and Bliwise 2014; Engqvist 2005). The GLM was applied to log-log transformed data to ensure normality of residuals and homogeneity of variances (homoscedasticity) for least squares regression were satisfied.

GLM analysis was performed using ‘jamovi’ version 2.3.28 statistical analysis software.

#### 4.3.2. Nonlinear Regression

Nonlinear least squares analysis was performed to determine the best fit of the sigmoidal function derived to describe the relationship between household separation and number of households (Formula 3.9). The mean household separation of each settlement was divided by the square root of household size ( $\bar{S}/\sqrt{P/N}$ ) to adjust for the effect of the number of people per household. The regression model took the form:

$$\log\left(\bar{S}/\sqrt{P/N}\right) \sim \beta_1 - \frac{1}{2}(\beta_1 - \beta_2)[1 + \operatorname{erf}(\beta_3 - \beta_4(N - 1))] \quad (4.1)$$

where  $\beta_1$  and  $\beta_2$  are, respectively, the upper and lower asymptotes of the geometric mean of ( $\bar{S}/\sqrt{P/N}$ ),  $\beta_3$  is  $\bar{n}_{des}/(\sigma_{des}^2 + \sigma_{act}^2)^{0.5}$  and  $\beta_4$  is  $a/(\sigma_{des}^2 + \sigma_{act}^2)^{0.5}$ . The antilogarithms of  $\beta_1$  and  $\beta_2$  are related, but not equal, to  $S_\infty$  and  $S_0$ .

To control for the effect of protein certainty on household separation, the model was applied to the ‘low risk’ and ‘high risk’ hunting strategy groups separately. To avoid any bias associated with non-normally distributed residuals, the ( $\bar{S}/\sqrt{P/N}$ ) data was log transformed prior to regression. No transformation was applied to the  $(N - 1)$  data.

The nonlinear least squares fitting was implemented in Excel (Microsoft Corporation) in accordance with the methodology outlined by Brown (2001). The ‘evolutionary’ solver function in Excel was used to find the best fit as it is robust to the existence of local optima. Initial values were set based on visual observation the data.

#### 4.3.3. Regression Assumptions

The standard assumptions of OLS regression of normality of residuals, homogeneity of variances (homoscedasticity) and no multicollinearity were tested for both the GLM, nonlinear regression and simple linear regression analyses. The assumption of normality of residuals was tested using the Shapiro-Wilk test (Shapiro and Wilk 1965) and the assumption of homogeneity of variances was tested using Levene's test (Levene 1960). To test the assumption that no multicollinearity, the variance inflation factor (VIF) was calculated for all variables (Shrestha 2020). All tests were performed using 'jamovi' version 2.3.28 statistical analysis software.

#### 4.3.4. Correlation

The strength of correlation between variables was determined using the Spearman's rank correlation coefficient ( $r_s$ ). The more common Pearson's correlation assumes both a linear relationship and normally distributed data (Schober et al. 2018), neither of which are satisfied across the entire collated data set. Spearman's correlation was deemed more appropriate as it describes a monotonic rather than linear relationship and does not assume a normal distribution (Schober et al. 2018). All Spearman correlation calculations were performed using 'jamovi' version 2.3.28 statistical analysis software.

# Chapter 5

## RESULTS

### 5.1. Summary of Data

#### 5.1.1. The Settlements

The data set compiled for the current study is presented in Appendix A. It comprises observations of 149 hunter-gatherer settlements, representing 42 distinct cultural groups or multi-cultural communities.

The geographic distribution of settlements and their approximate location are shown in Figure 5.1. Of the permanently populated continents (i.e. excluding Antarctica), only Europe is unrepresented in the data set. Africa and North America are the most represented, accounting for 40% (n = 59) and 35% (n = 52) of all settlements, respectively. Australia and South America are also well-represented, respectively accounting for 15% (n = 22) and 9% (n = 14), while only 1% (n = 2) are from Asia. The distribution is likely representative of differences in both the number of cultural groups practicing hunting and gathering within different regions and the intensity of anthropological investigation between those regions.

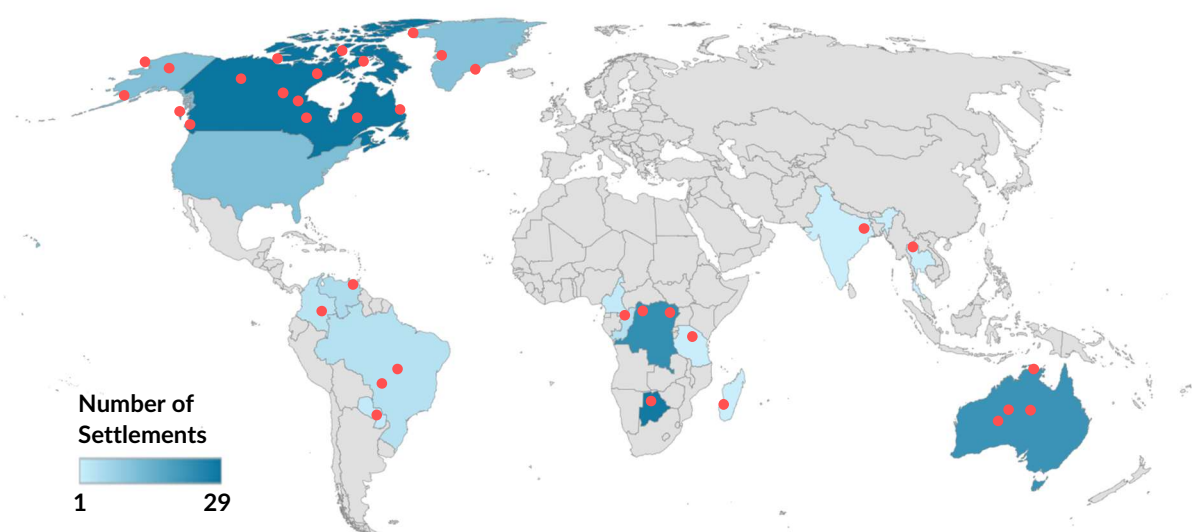


Figure 5.1 – Distribution of hunter-gatherer settlements in data set by country, showing the approximate locations in which one or more groups are concentrated (red points)

The observations span a time period of 167 years from 1831 to 1998. The frequency distribution of observations within that period is shown in Figure 5.2. The majority of observations fall within the mid- to late-20<sup>th</sup> century, with 63% (n = 93) of all observations dating to the 30-year period from the beginning of 1960 to the end of 1989. This is likely due to both an increasing interest in the hunter-gatherer lifestyle over the course of the 20<sup>th</sup> century counterbalanced by a decline in the number of people relying on hunting and gathering as a means of subsistence. Data relating to the settlements from the 19<sup>th</sup> century are based on settlement plans produced by more recent archaeological investigation supplemented with contemporary records of subsistence practices and population size.

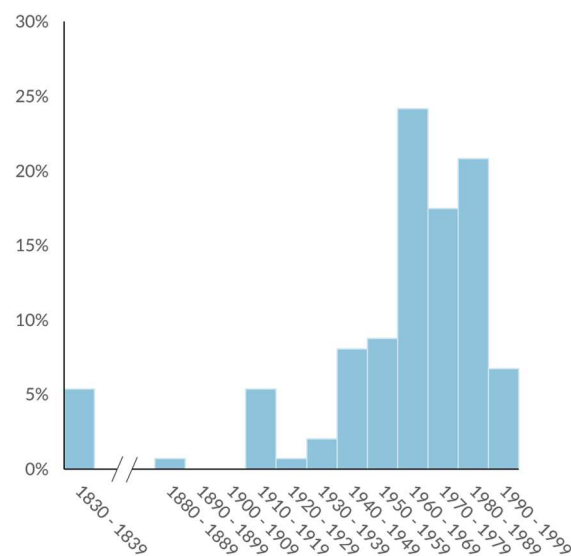


Figure 5.2 – Frequency distribution of decade in which the hunter-gatherer settlements included in the data were observed

The ecological context of each settlement was recorded based on its geographic location using the Global Ecological Zone classification system of the Food and Agriculture Organization of the United Nations (FAO 2012). All climate zones (polar, boreal, temperate, subtropical and tropical) are represented in the data set. The distribution of climate zones is shown in Figure 5.3(a). The majority of settlements were located in either a tropical, boreal or polar region, collectively accounting for 92% (n = 139) of settlements in the data set. The low representation of temperate and subtropical settlements, accounting for only 8% (n = 10) of all settlements, is likely due to greater encroachment of agriculture on traditional hunting and gathering areas in these geographic regions. The settlements spanned nine different vegetation zones. The distribution of vegetation zones is shown in Figure 5.3(b). Five of the nine vegetation zones are densely forested (tropical rainforest, tropical moist forest, tropical dry forest, boreal conifer forest and mixed vegetation

mountain systems), accounting for 45% ( $n = 67$ ) of the settlements in the data set. The remaining 55% ( $n = 82$ ) settlements were located either in more sparsely vegetated open tundra woodland, shrubland or polar regions.

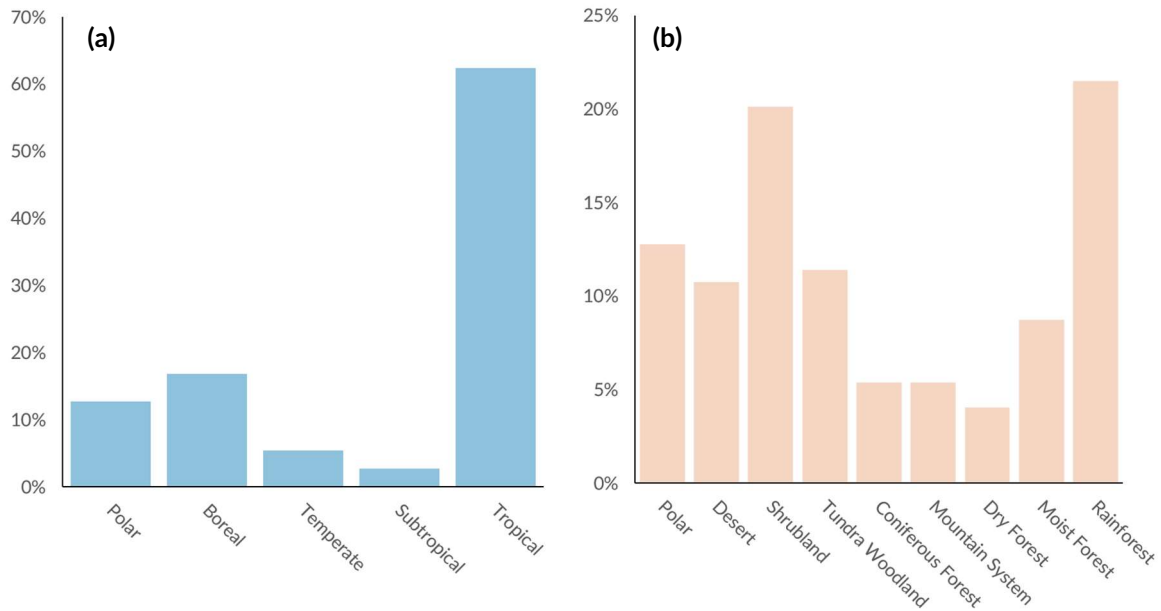


Figure 5.3 – Frequency distribution of: (a) climate zones; and (b) vegetation zones in which the hunter-gatherer settlements of the data set were located

### 5.1.2. Settlement Demographics

The population size of settlements included in the data set ranged from 2 to 600. The mean settlement population size was 86.63 ( $SD = 118.79$ ). The number of households in the settlements ranged from 2 to 81 and the average number of households across all settlements was 14.04 ( $SD = 15.6$ ). Mean household size (the number of people per household averaged across the entire settlement) ranged from 1.88 to 18.27 people per dwelling. The average of all mean household sizes across the entire sample was 5.35 ( $SD = 3.06$ ).

The frequency distribution of the log transformed settlement population size, number of households and household size area shown in Figure 5.4 together with the kernel density estimation of the probability density function. The frequency distribution and estimated probability density function are bimodal for both population size and number of households, suggestive of the presence of two separate subpopulations of smaller settlements and larger settlements. A dominant lower peak is observed corresponding to a population size of approximately 20 people and 6 households, while a secondary higher peak is observed at approximately 75 people and 18 households. The frequency distribution and estimated

probability density function for household size also shows evidence of bimodality, although it is less clear if this represents separate populations owing to the lack of resolution of the peaks.

Spearman's correlations were conducted to assess the relationship between population size, number of households and household size. As would be expected, a strong positive correlation was found between the number of households per settlement and population size ( $r_s(147) = 0.92, p < .001$ ). A moderate positive correlation was found between population size and mean household size ( $r_s(147) = 0.58, p < .001$ ), while a significant but weak correlation was found between number of households and mean household size ( $r_s(147) = 0.26, p = .002$ ).

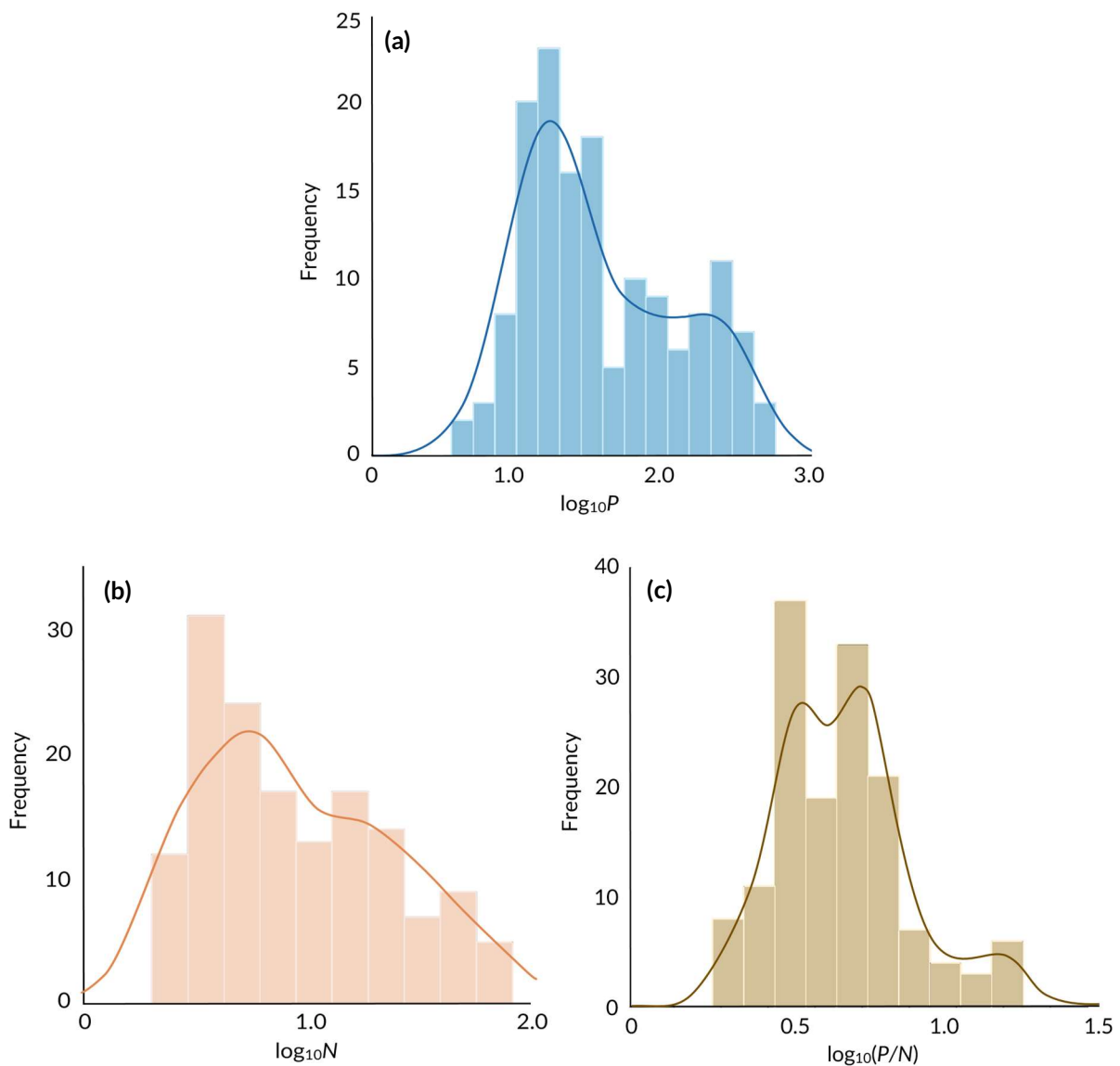


Figure 5.4 – Frequency distribution of log-transformed (a) settlement population size ( $P$ ); (b) number of households ( $N$ ); and (c) mean household size ( $P/N$ ), each overlaid with the kernel density estimation of the distribution.

### 5.1.3. Hunting Strategy and Risk

The inhabitants of 82 of the settlements included in the data set relied on a 'high risk' hunting strategy for at least part of the period of occupation of the settlement, representing 55% of the total sample. The inhabitants of the remaining 67 settlements (45% of the total sample) relied on a 'low risk' strategy for the full length of settlement occupation. Among these settlements, 18% (n = 12) practiced migration hunting, 30% (n = 20) practiced net fishing, 13% (n = 9) practiced protein gathering and 39% (n = 26) had a reliable income source.

Migration hunting was found to be limited to latitudes above the 58<sup>th</sup> parallel in Canada and Alaska. It is at these higher latitudes that seasonal migrations of caribou occur along predictable paths (Binford 1978b:170:171; Joly et al. 2021). Like migration hunting, net fishing was limited to lakes and coastal areas at higher latitudes, specifically Alaska, Canada and Greenland. It is likely that because the colder climate at these latitudes is not conducive to intensive agriculture the hunter-gatherer lifestyle is more widely practiced. The cold climate and low humidity at the higher latitudes are also conducive to long term storage of meat and fish, allowing surplus protein to be cached for leaner seasons within minimal investment of labour (Keeley 1988). Protein gathering was found to be practiced by only two groups, the Ngatatjara and Pintupi. Both reside in the Western Desert region of Western Australia and rely on easily located and captured goannas as their primary source of protein.

Regular income was almost exclusively limited to welfare in the form of rations or monetary payments, made available by the governments of Australia, Canada and Greenland in the latter half of the 20<sup>th</sup> century. Two exceptions were the Kunwinjku of the Northern Territory and Mrabri of Thailand, who received a regular income from the production of handicrafts (the former in addition to receiving welfare).

## 5.2. Household Separation

### 5.2.1. General Linear Model Analysis

The GLM developed for the present study was applied to the compiled data set to investigate whether hunting strategy risk, household size and number of households have a significant effect on household separation. For GLM analysis, the sample of 149 settlements was grouped according to hunting strategy risk ('low risk' and 'high risk'), with household size and number of households included as continuous covariates.

Summary statistics and log-transformed frequency distributions of mean household separation and mean household size for the ‘low risk’ and ‘high risk’ groups are shown in Figure 5.5. On average, the number of households per settlement in the ‘low risk’ group was larger than for the ‘high risk’ group. This is likely because some mechanisms for minimising risk (e.g. risk pooling) place a limitation on settlement size. Mean household size is similar for both groups although the median was lower for the ‘high risk’ group. This is due to the use of large communal dwellings in some settlements of the ‘high risk’ group, which were not observed in the ‘low risk’ group.

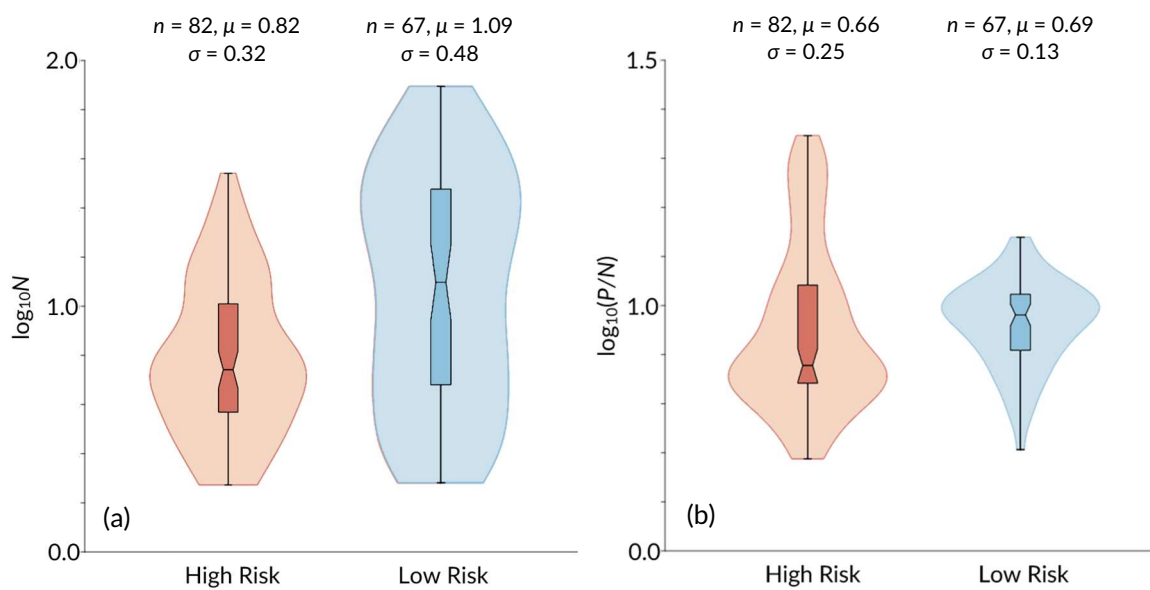


Figure 5.5 – Violin-box plots of: (a) log mean household size and (b) log number of households for the ‘low risk’ and ‘high risk’ hunting strategy groups. The sample size ( $n$ ), mean ( $\mu$ ) and standard deviation ( $\sigma$ ) are presented for the transformed data.

A comparison of the fitted GLM with the measured household separation plotted against number of households and household size is shown in Figure 5.6. The GLM was found to explain 83% of the variance in mean household separation within the sample ( $R^2 = 0.83$ ,  $F(4,144) = 169.60$ ,  $p < .001$ ). The full results of the GLM as applied to the compiled data set are presented in Appendix B.

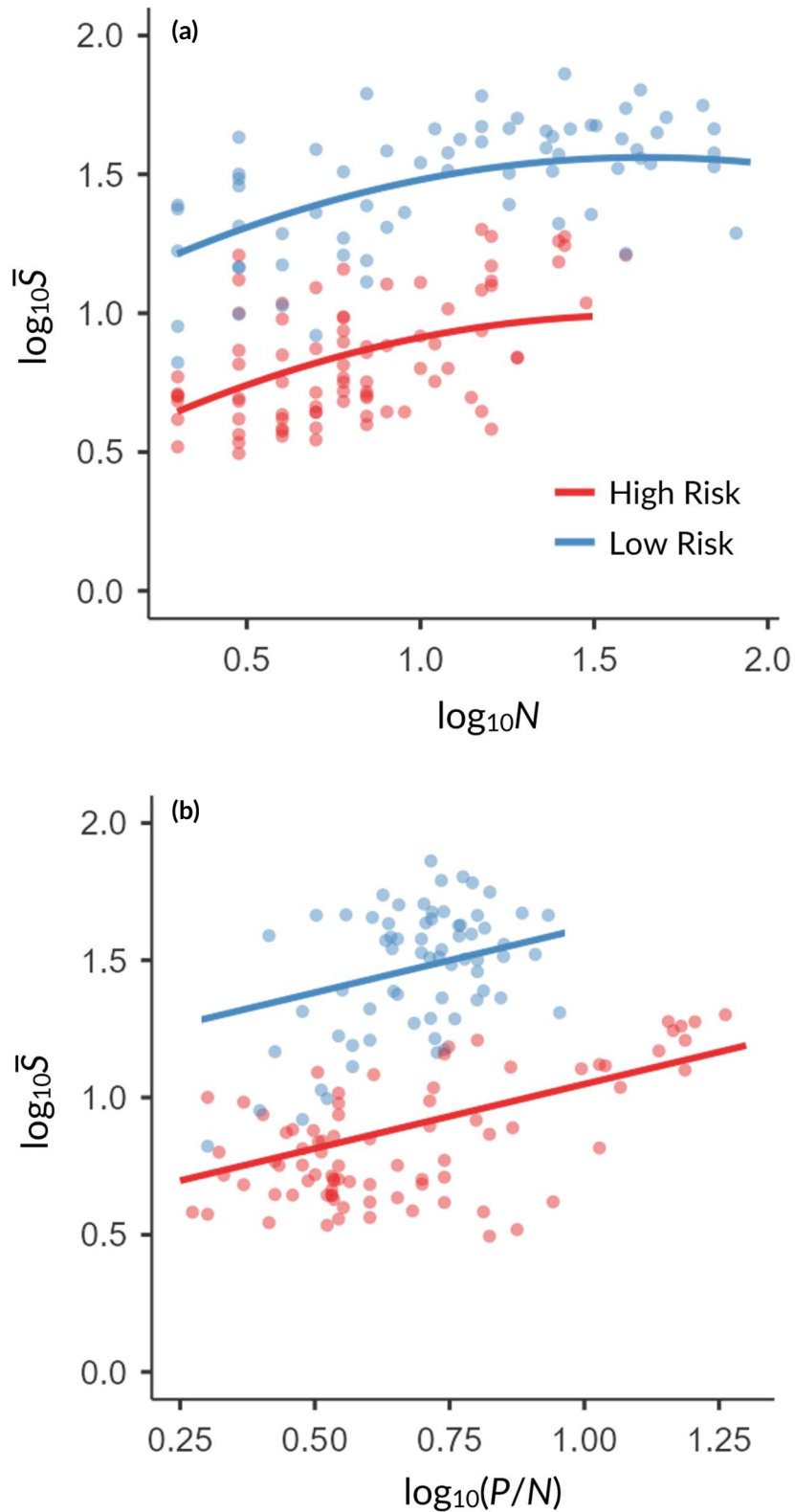


Figure 5.6 – Log-transformed mean household separation ( $\bar{S}$ ) data plotted against: (a) log-transformed number of households ( $N$ ); and (b) log-transformed household size ( $P/N$ ). The estimated mean difference between the ‘low risk’ and ‘high risk’ hunting strategy groups is 0.57 ( $\beta = 1.47, p < .001, SE = 0.03, 95\% \text{ CI } [0.51, 0.63]$ )

GLM analysis found a significant difference in mean household separation between the ‘low risk’ hunting strategy group and ‘high risk’ hunting strategy group ( $F(1,144) = 368.86$ ,  $p < .001$ ,  $\eta_p^2 = 0.72$ ). The estimated differences between log-transformed mean household separation for the ‘low risk’ and ‘high risk’ groups is 0.57 ( $SE = 0.03$ , 95% CI [0.51, 0.63]). Translating this to non-transformed measurements, it is estimated that mean household separation in settlements that rely on ‘low risk’ hunting strategies is approximately 3.72 times greater than the mean household separation in settlements that rely on ‘high risk’ hunting strategies, after adjusting for the effects of both number of households and household size. These findings support the hypothesis that social buffering drives closer household spacing in hunter-gatherer settlements to mitigate the stress associated with the uncertainty inherent to high risk hunting strategies

As expected, mean household size was found to be significantly related to mean household separation ( $F(1,144) = 45.06$ ,  $p < .001$ ,  $\eta_p^2 = 0.24$ ). In good agreement with the expectation that mean household separation scales as the square root of mean household size, the GLM returned an estimated scaling exponent of 0.47 ( $SE = 0.07$ , 95% CI [0.33, 0.61]). These findings support the hypothesis that household separation varies with household size to maintain social homeostasis.

Number of households was also found to be significantly related to mean household separation. Both the linear term ( $F(1,144) = 55.99$ ,  $p < .001$ ,  $\eta_p^2 = 0.28$ ) and quadratic term ( $F(1,144) = 6.03$ ,  $p = .015$ ,  $\eta_p^2 = 0.04$ ) included in the GLM to approximate the relationship between number of households and mean household separation were found to be significant. These findings are consistent with the hypothesis that household separation varies with number of households to counteract the perception of social isolation in smaller communities.

The OLS assumptions of normality and independence of variables were both found to be met. No evidence of multicollinearity was found for hunting strategy risk (VIF = 1.12, Tolerance = 0.90), mean household size (VIF = 1.10, Tolerance = 0.91) or number of households (VIF = 1.22, Tolerance = 0.82). The Shapiro-Wilk test indicates that the residuals were normally distributed ( $W = 0.99$ ,  $p = .804$ ). This finding was confirmed by the Q-Q plot of the quantiles of standardised residuals and theoretical quantiles of the normal distribution, which shows little deviation from the diagonal (Figure 5.7).

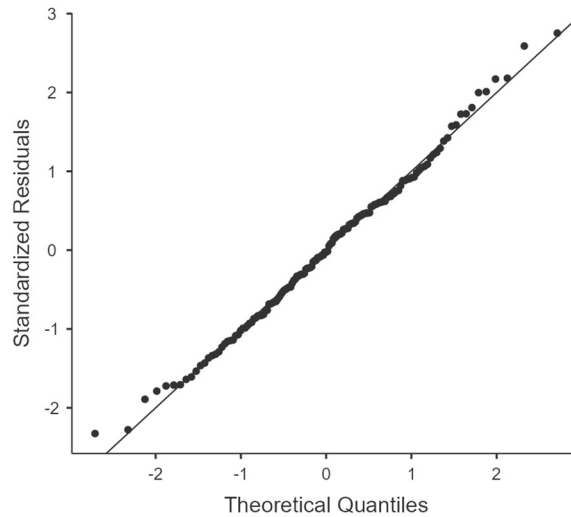


Figure 5.7 – Q-Q plot comparing quantiles of standardised residuals of GLM with theoretical quantiles of the normal distribution

The assumption of homogeneity of residual variance was also found to be met. Levene’s test found no evidence that the variances were significantly unequal ( $F(1,147) = 2.18, p = .142$ ). A plot of the residuals against predicted values for the fitted GLM shows a slight ‘bow tie’ pattern, indicative of some heteroscedasticity (Figure 5.8). This formation indicates smaller variances at central observations compared with observations at the extremes, which may be due to the use of a quadratic polynomial to approximate the expected sigmoidal relationship between household separation and number of households. Nevertheless, any heteroscedasticity is minimal and unlikely to substantially affect the results of the GLM.

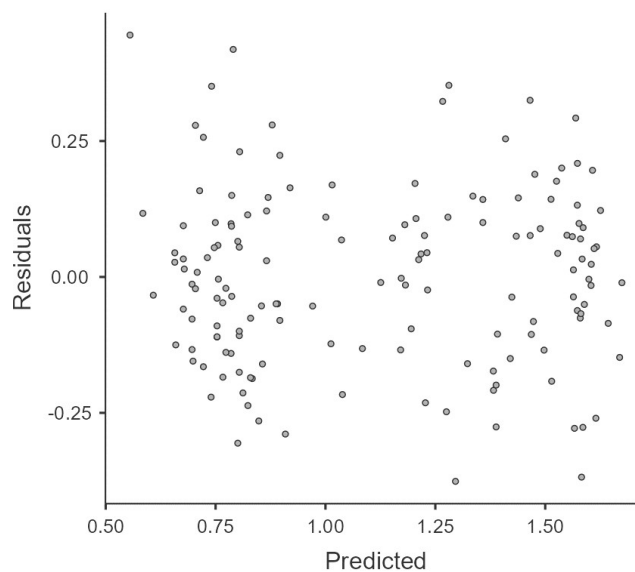


Figure 5.8 – Residuals versus predicted values for fitted GLM

### 5.2.2. Nonlinear Regression Analysis

Nonlinear regression analysis was undertaken to determine if the significant positive relationship between household separation and number of households found by GLM analysis is due to the perception of social isolation in smaller settlements. Specifically, nonlinear regression analysis was applied to determine if the regression model (Formula 4.1) describes the relationship between household separation and number of households.

Nonlinear regression of the entire sample determined the likely presence of outliers in the ‘high risk’ hunting strategy group. The fitted model for the high risk strategy group is shown in Figure 5.9(a). The Shapiro-Wilk test found only weak evidence that the residuals followed a normal distribution ( $W = 0.97, p = .052$ ). A plot of the residuals of regression against number of households shows three potential outliers that could influence the regression (Figure 5.9(b)). For outlier detection, the data was partitioned into two groups at the estimated inflection point of 5.06. A box and violin plot shows the quartiles for each group (Figure 5.9(c)). The three settlements identified in the residual plot exceeded the third quartile plus 1.5 times the interquartile range, meeting the technical definition of outliers.

The three settlements identified as outliers, which are all associated with the lower asymptote, were: A-NE-2 (Efé), I-NP-3 (Efé) and Naonoko Anoko B (Warao). The latter settlement consisted of four substantial (‘permanent’) dwellings, of which only three were occupied (Wilbert 1980). Furthermore, some former residents had left the occupied households. The reported number of households and household size are therefore not representative of the settlement demographics at the time of its construction, which may artificially inflate the value of  $\bar{S}/\sqrt{P/N}$ . The first Efé settlement identified as an outlier, I-NP-3, may be similarly unrepresentative. The recorded household size for I-NP-3 is 2.0, which is lower than average of 3.0 across all settlements occupied by the same group (Efé settlements denoted ‘NP’). The adjustment for household size would be insufficient if the recorded population is not indicative of the population at the time the settlement was laid out. The other Efé settlement, A-NE-2, is identified as ‘abnormal’ owing to tension within the group after the death of a young girl (Fisher 1987, pp. 117, 119). As the identified outliers were all considered potentially unrepresentative, they were removed from the data set for subsequent regression analysis.

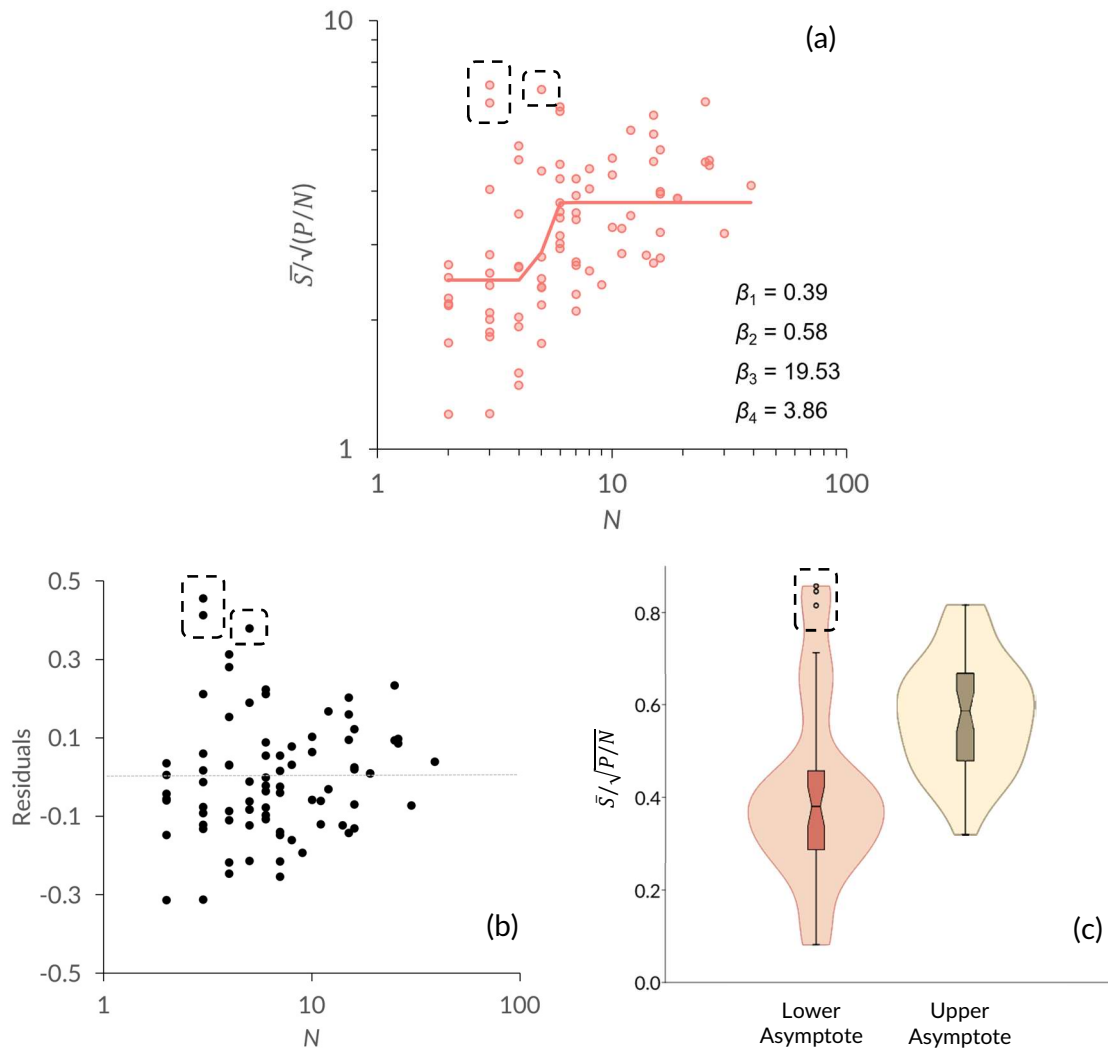


Figure 5.9 – Preliminary regression results for all ‘high risk’ hunting strategy data showing identified outliers (dashed box) on: (a) a plot of the line of best fit against observed data; (b) a scatter plot of the residuals of regression; and (c) a violin-box plot showing distribution of  $(\bar{S}/\sqrt{P/N})$  above and below the estimated inflection point of  $N = 5.06$ .

Nonlinear regression of the data was repeated after removal of the outliers. The estimated parameters and root mean square errors (RMSE) of the fitted regression model are presented in Table 5.1. The upper and lower asymptotes of the regression model are given by  $\beta_1$  and  $\beta_2$ , respectively. The antilogarithms of these parameters are related, but not equal, to  $S_\infty$  and  $S_0$  in Formula 3.9. The inflection point of the fitted model, which is given by  $(\beta_3 / \beta_4)$ , is also presented. The line of best fit and 95% prediction intervals based on the RMSE for each group are shown in Figure 5.10.

Table 5.1 – Results of nonlinear regression

Hunting Strategy	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	Inflection	RMSE
High Risk	0.36	0.58	19.99	3.88	5.15	0.14
Low Risk	0.95	1.23	2.72	0.34	8.09	0.17

The model was found to fit the data well, confirming the sigmoidal relationship between household separation and number of households. The residuals were normally distributed for both the ‘high risk’ ( $W = 0.99, p = .628$ ) and ‘low risk’ ( $W = 0.99, p = .755$ ) hunting strategy groups. The residual plots for both groups appear balanced, with no clear bias that would indicate systematic deviation of the data from the model or heteroscedasticity (Figure 5.11). These findings support the hypothesis that perceived social isolation in smaller settlements predicts closer physical proximity between households.

According to the model, the inflection point of the sigmoidal function corresponds to the number of households at which, on average, the actual and desired number of friendships are equal. The average number of desired friendships per household head can thus be approximated as the inflection point less one (i.e. excluding the household in question) by assuming the constant of proportionality,  $a$ , in Formula 3.9 is approximately equal to 1 at low  $N$ . The estimated inflection point for the ‘high risk’ group occurs at  $N = 5.15$ , while for the ‘low risk’ group the inflection point occurs at  $N = 8.09$ , corresponding to an average number of desired friendships in the range of about 4 to 7. These findings are consistent with the reported range of about 4 to 6 close friendships for people living in modern towns and cities (Dunbar 2018; Gillespie et al. 2015; Solana 1986).

The observed difference in inflection points between the ‘high risk’ and ‘low risk’ hunting strategy groups is consistent with the social buffering hypothesis. Social buffering of stress caused by hunting uncertainty would increase the frequency of social interaction between household pairs that are socially closest. It is considered likely that the concentration of social interaction between those household pairs would reduce their desired number of social connections. The average desired number of social connections for households in the ‘high risk’ group would thus be lower than for the ‘low risk’ group. According to Formula 3.9, this would lower the inflection point for the ‘high risk’ group compared with the ‘low risk’ group.

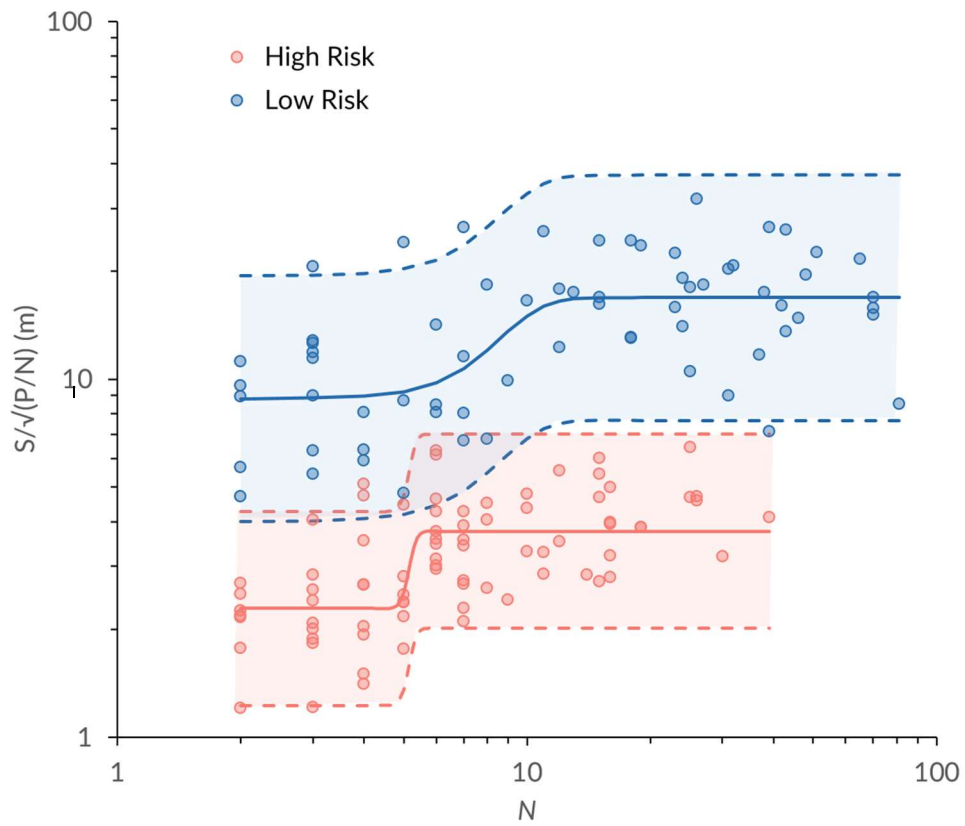


Figure 5.10 – Scatter plot of mean household separation adjusted for household size,  $(\bar{S}/\sqrt{P/N})$  and number of households ( $N$ ) for the ‘low risk’ (excluding outliers) and ‘high risk’ hunting strategy groups showing the lines of best fit (—) and 95% prediction bands (-----) of the sigmoidal model determined by nonlinear regression

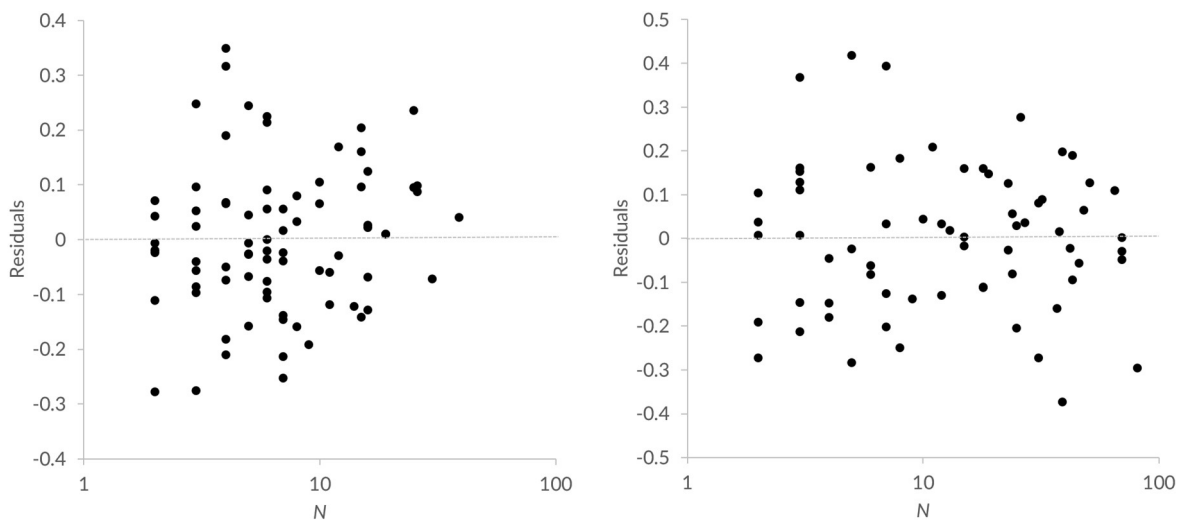


Figure 5.11 – Scatter plots of the residuals of regression for: (a) the ‘high risk’ hunting strategy group (excluding outliers); and (b) the ‘low risk’ hunting strategy group

Further evidence for the social buffering hypothesis is found by analysing the lower and upper asymptotes of the fitted model,  $\beta_1$  and  $\beta_2$ . Both  $\beta_1$  and  $\beta_2$  were found to be higher for the 'low risk' hunting strategy group than for the 'high risk' group, consistent with the findings reported in the preceding section that hunting risk is negatively correlated with household separation. It is also apparent from nonlinear regression analysis that the difference in household separation between the two groups varies with number of households. Taking the antilogarithm of the values of  $\beta_1$  and  $\beta_2$ , the relative difference between the lower and upper asymptotes for the two groups is calculated as:  $(8.91 - 2.29) / (16.98 - 3.90) = 0.50$ . In other words, the effect of the number of households on household separation (after controlling for household size) is approximately halved for the 'high risk' hunting strategy group compared with the 'low risk' group. It is expected that in settlements where 'high risk' hunting strategies are relied on there will be a certain number of household pairs practicing social buffering. That fraction of households will remain in close proximity regardless of the number of households in the settlement. So, the difference between the upper and lower asymptotes is expected to be smaller for the 'high risk' group than the 'low risk' group because a smaller fraction of household pairs will space themselves further apart in larger communities.

# Chapter 6

## DISCUSSION

### 6.1 Spatial Determinants in Hunter-Gatherer Settlements

#### 6.1.1 Evidence for Hypotheses

The purpose of this study was to investigate the determinants of household separation and, by extension, population density in hunter gatherer settlements. For the analysed sample of 149 hunter-gatherer settlements, GLM analysis found that household separation was significantly related to hunting strategy risk, household size and number of households. The observed effects were large for all three variables (as determined by  $\eta_p^2$ ), but the effect of hunting risk on household separation was found to be far greater than the effects of household size and number of households.

The findings of the present study strongly support the hypothesis that physical proximity between households provides ‘social buffering’ of the stress caused by hunting uncertainty (Hypothesis A). GLM analysis found that strategies that provide a low risk source of protein, specifically migration hunting, net fishing, protein gathering or a reliable income, were associated with mean household separations approximately 3.72 times greater than high risk hunting strategies (i.e. individual targeting of low density or low yield prey). Further evidence is provided by nonlinear regression of the modelled relationship between household separation and number of households (Formula 3.9). The relative difference in upper and lower asymptotes of the fitted sigmoidal model was observed to be smaller for the ‘high risk’ group than for the ‘low risk group’. The observed difference suggests that a fraction of household pairs in the ‘high risk’ group maintain close separation regardless of community size, consistent with the hypothesis that the ‘high risk’ group are practicing social buffering. The socially closest fraction of households maintain close physical proximity even in large communities because hunting risk does not change with number of households. The high rate of social interaction among that fraction would also be expected to lower the desired number of social connections as quality of interaction overrides quantity. The result would be the observed lowering of the inflection point for the ‘high risk’ group, as demonstrated in Figure 3.4.

Although inconsistent with the previously proposed ‘risk pooling’ hypothesis (Whitelaw 1983, 1989, 1991; Wiessner 1982), the present findings provide context to the observed correlation between the practice of risk pooling and high population densities in hunter-gatherer settlements. Included within the present data set are various high density settlements whose inhabitants do not practice risk pooling. These include the Haida of Haida Gwaii (MacDonald 1983), who practice ‘pot-latch’ ceremonies rather than the regular redistribution of food (Swanton 1909), and the Warao of Venezuela (Wilbert 1980) who practice a similar form of ritualised annual redistribution of food (Heinen and Ruddle 1974) (Figure 6.1). However, no evidence of the converse situation was found. No low density settlements were identified in which risk pooling was practiced. The Ngatatjara of Western Australia have been cited previously as an example of a group who share meat extensively, but who have low density settlements (Gould and Yellen 1987; Hewlett et al. 2019). But sharing among the Ngatatjara is limited to large game (e.g. kangaroos and emus), which are not integral to their survival or the provision of protein. Their primary source of protein is the goanna, which are quickly found and easily caught (Gould 1967), meeting the definition of ‘protein gathering’ (Stiner and Munro 2002). It is clear that high density settlements can occur in the absence of risk pooling, but on the evidence available it appears that risk pooling is never practiced in low density settlements. This observation is readily explainable by the hypothesis put forward in the present study that risk itself is the cause of high density hunter-gatherer settlements rather than a cultural response to risk (i.e. risk pooling).



Figure 6.1 – Plans of (a) the Haida settlement of Cumshewa, Haida Gwaii, ca. 1830s (after MacDonald 1983); and (b) the Warao settlement of Bure Bureina, Venezuela, 1954 (after Wilbert 1980), showing dwellings as white polygons and other structures as grey polygons.

The social buffering hypothesis presented in the current study also provides context to the observations of Fedurek et al. (2023). They found a reduction of cortisol levels among Hadza men after spending time together, while no significant effect was observed for Hadza women. The concentration of hunting duties among Hadza men means that the uncertainty of hunting is more likely to be a stressor for men than women. The observed reduction in cortisol among men only may therefore be explained by social buffering of the stress associated with that uncertainty.

The findings of the present study also strongly support the hypothesis that household separation is smaller in hunter-gatherer communities with fewer households because increased physical proximity provides increased social interaction, counteracting the perception of social isolation and maintaining social homeostasis (Hypothesis B). The model developed to describe the relationship between household separation and number of households, which was based on the probability perceived social isolation for a given community size, was found to fit the measured data well. Household separation was observed to vary as a sigmoidal function of the number of households after correction for the effect of household size for both the ‘low risk’ and ‘high risk’ groups. Furthermore, the average number of social connections required to avoid perceptions of social isolation was found to range from approximately 4 to 7, consistent with previous studies that have reported a range of about 4 to 6 close friendships among people living in modern towns and cities (Dunbar 2018; Gillespie et al. 2015; Solana 1986).

By contrast, the present findings are inconsistent with the prevailing hypothesis that households space themselves further apart in larger communities because the presence of relative strangers means social stress is greater (Lobo et al. 2022; Whitelaw 1989, 1991). The greatest change in household separation is observed to occur between 5 and 10 households for the ‘low risk’ group and between about 5 and 6 households for the ‘high risk’ group. It is considered unlikely that there would be enough mutual strangers in settlements of this size to warrant avoidance measures. Even in a settlement of 10 households, where the total number of adults may be about 20 (assuming an average of two adults per household), it is expected that all adults would be well known to one another. It is possible that the importance of interaction with strangers for social stress has been overstated (e.g. Whitelaw 1989, pp. 55, 74) and that social stress scales with any variance in social distance, such that physical distance more subtly reflects social distance. If that were the case, the clustering of kin groups within settlements would be observed, which has previously been found in only about 36% of settlements (Whitelaw 1989, Table 7.10). Mean household separation of clustered settlements would therefore be expected

to increase with number of households, while the mean household separation of non-clustered settlements remains unchanged. This is not observed in the present data set, which has a sigmoidal form.

The third hypothesis put forward, that household separation varies with household size to maintain a constant mean rate of social interaction and thereby maintains social homeostasis (Hypothesis C), is also strongly supported by the present findings. GLM analysis found that that household separation scales as the 0.47 power of household size after controlling for the effects of household separation. This is consistent with the modelled relationship between these variables (Formula 3.4), which predicts a scaling exponent of 0.5.

A previous study undertaken by Gould and Yellen (1987) that found no correlation between household separation and household size appears to have suffered from several limitations. The sample size may have been too small for the inherent variance in the data to find a significant effect. Furthermore, the failure to control for number of households as a covariate would have further contributed to the variance.

The findings of the present study therefore provide strong support for each of three proposed determinants of household separation: hunting strategy risk, household size and number of households. They further place into context observations of previous studies, which in several cases provide further support for the proposed hypotheses.

### 6.1.2 An Evolutionary Origin of Space

A question posed at the start of this thesis is ‘why do some hunter-gatherers choose high-density living, while others do not?’ The evidence provided by this study points to the *proximate* cause being the neurobiological benefits and costs of close physical proximity in varying economic and demographic contexts. Physical proximity to social affiliates inhibits the biological stress response to uncertainty through social buffering and maintains social homeostasis by eliminating perceived social isolation as a stressor. Conversely, closer physical proximity is disfavoured in the absence of these stressors because social interaction can itself be a cause of stress. Thus, variance in hunter-gatherer settlement population density is a product of the neurobiological response to the presence or absence of various stressors. As human neurobiology is the product of biological evolution, the *ultimate* cause of varying population densities among hunter-gatherer settlements may be natural selection.

Social homeostasis is likely underpinned by competing selective advantages of social isolation and social crowding. The stress response to perceived social isolation promotes closer physical proximity and therefore greater social interaction. These in turn promote cooperative behaviour (Christiansen and Pedersen 2018; Duffy and Ochs 2009; Kabo et al. 2014; Kraut et al. 1990; Salazar Miranda and Claudel 2021), which is advantageous for survival and reproduction. The stress of loneliness may indirectly facilitate cooperation. The stress of social crowding clearly plays an opposing role. By placing a limit on physical proximity, social crowding stress response may be an evolved mechanism for minimising the costs of social interaction. The relevant costs of social interaction would not be those that are related to the stress response itself. Rather, it would be costs that exist in the absence of the evolved stress response. A clear candidate is the transmission of communicable disease, the rate of which increases with time spent in physical proximity to others (Alirol et al. 2011; Arbel et al. 2022; Li et al. 2018; Sy et al. 2021). The opposing stress responses that maintain social homeostasis may thus be an evolved mechanism for balancing the benefits of cooperation against the costs of disease transmission. The evidence presented in the present study suggests that physical proximity is the behavioural variable by which that balance is maintained.

The evolutionary origins of social buffering have also been considered previously. Social buffering appears to have evolved to reinforce social connections, rather than to simply minimise the negative effects of stress (Wu 2021), and may have contributed to the evolution of social living (Kiyokawa et al. 2018). A distinction between social buffering and perceived social isolation as drivers of sociality is that social buffering promotes preferential social interaction with close social affiliates (Hennessy et al. 2009). The specificity of social buffering suggests that in certain situations a limited number of higher quality social connections may be advantageous. The results of the present study suggest social buffering is of particular relevance in uncertain situations. Animal studies have produced similar findings (e.g. Leshem and Sherman 2006). Social buffering may therefore be an evolved mechanism for addressing uncertainty. An implication of that conclusion is that it is advantageous in unpredictable situations to cooperate with a small number of trusted social affiliates, additional to cooperating with a larger group.

The findings of the present study situate physical proximity within hunter-gatherer settlements in an evolutionary context. The evolutionary answer to why some hunter-gatherers choose high-density living, while others do not is simply that there are selective advantages to varying degrees of physical proximity depending on context.

### 6.1.3 Other Potential Determinants

The combination of hunting strategy risk, household size and number of households was found to collectively explain 83% of the variance in mean household separation within the sample of hunter-gatherer analysed for the present study. A large part of the residual variance in household separation may be due to random variation in human behaviour. However, other possible factors may also be considered.

An additional factor that may affect household separation is inter-household tension. Closer household proximity for social buffering of uncertainty or to reduce loneliness requires a positive relationship between neighbours. Inter-household tensions would likely render both mechanisms ineffective, particularly if they are widespread within the settlement. Internal tensions appear to play a role in the separation of households in one particular settlement included in the data set. During the nonlinear regression analysis undertaken for the present study, the Efé camp denoted 'A-NE-2' was determined to meet the technical definition of an outlier. The mean household separation in A-NE-2 was found to be much larger than other settlements of the same type (i.e. 'high risk' hunting strategy and relatively low number of households), including other Efé settlements. Fisher (1987, pp. 117, 119) acknowledged the 'abnormality' of A-NE-2, ascribing its unusually elongate form and widely spaced dwellings to internal tensions following the death of young girl. Chronic internal tensions would likely result in the breakup of a settlement. Nevertheless, it is plausible that tensions may play a role in determining household separation for some hunter-gatherer settlements.

It is also plausible that environmental constraints play a role in determining household separation in some cases. Dense vegetation has been raised previously as a potential determinant of household separation in hunter-gatherer settlements due to the limitations it places on communication (Fisher and Strickland 1991; Hamilton et al. 2018). Such a constraint would seem plausible only for short term settlements, for which the benefit of clearing the vegetation may not be balanced by the investment of time and labour. An alternative mechanism by which vegetation could constrain household separation is by providing islands of shelter. Bartram et al. (1991, p. 104) report that the spacing of shade trees is a significant contributing factor in the separation of household clusters in among the Kua of Botswana. Thus, it is also possible that vegetation may either increase or decrease household separation, depending on context.

The availability of suitable land for construction of a dwelling or laying beds might also act as an environmental constraint on household separation. Steep or rocky terrain, bodies of water or swamps may limit the extent of larger settlement, while the shelter afforded by caves and rock overhangs may promote closed spacing to avoid exposure to the elements. A potential example of the former is found in the present data set. The Kalaallit settlement of Ûmának in Western Greenland was found to have a mean household separation of 16.38 m, well below the mean for similar settlements (i.e. ‘low risk’ hunting strategy and a relatively high number of households). A plan of Ûmának in 1919 shows its position on a flat area flanked by steep slopes (Figure 6.2(a)). An earlier photograph of the settlement captures the rockiness of the surrounding terrain (Figure 6.2(b)). It is plausible that the steep, rocky terrain surrounding the settlement of Ûmának may have acted as a constraint on household separation.

It is also clear, as mentioned in Chapter 2, that household arrangement within hunter-gatherer settlements is of relevance to certain measures of settlement area and population density. As already discussed, the ring model of household arrangement presented by Wiessner (1974) is an oversimplification. But, as alluded to by Porčić (2012), any deviation from even distribution of households in two dimensions would cause settlement area to scale nonlinearly with population size (or number of households). Batty and co-workers (Batty 1991; 2008; Batty and Kim 1992; Batty et al. 1989; Fotheringham et al. 1989; Longley et al. 1991) have previously described the nonlinear scaling of urban settlement area with number of allotments as fractal, drawing comparisons with the aggregation of particles in physical system. It would be interesting to investigate whether hunter-gatherer settlements also display fractal scaling and whether any differences in fractal dimension exist between hunter-gatherer settlements that practice low and high risk hunting strategies and between those settlements and urban settlements. Such differences may speak to differences in the settlement formation process, similar to the differences in fractal dimension observed between different physical systems (Bushell et al. 2002).

The variables considered in the present study, namely hunting strategy, household size and number of households, were able to account for a large part of the variance in household separation in hunter-gatherer settlements. Nevertheless, it would be useful to extend the current research by investigating the effects of other potential spatial determinants, such as internal group dynamics, environmental constraints and household arrangement, which may either act against or in concert with the aforementioned variables.

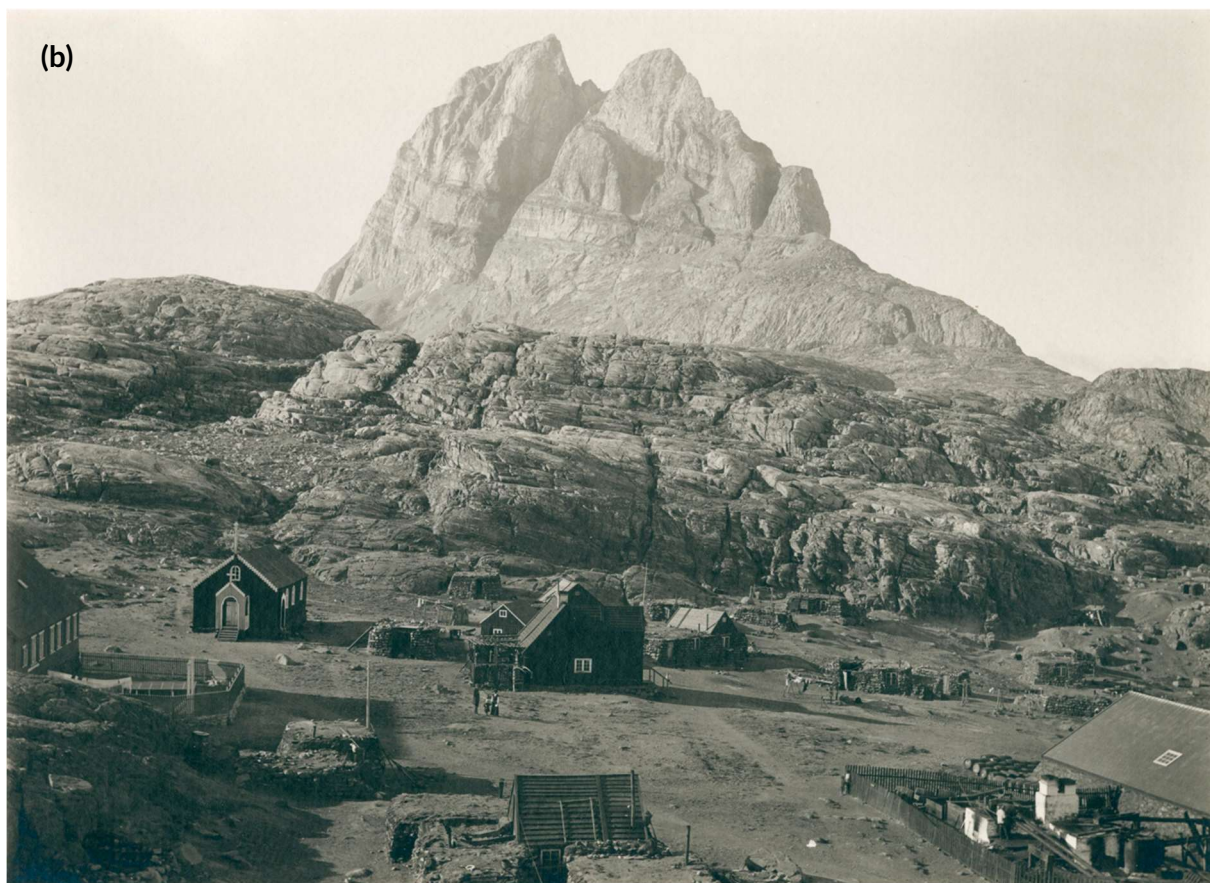
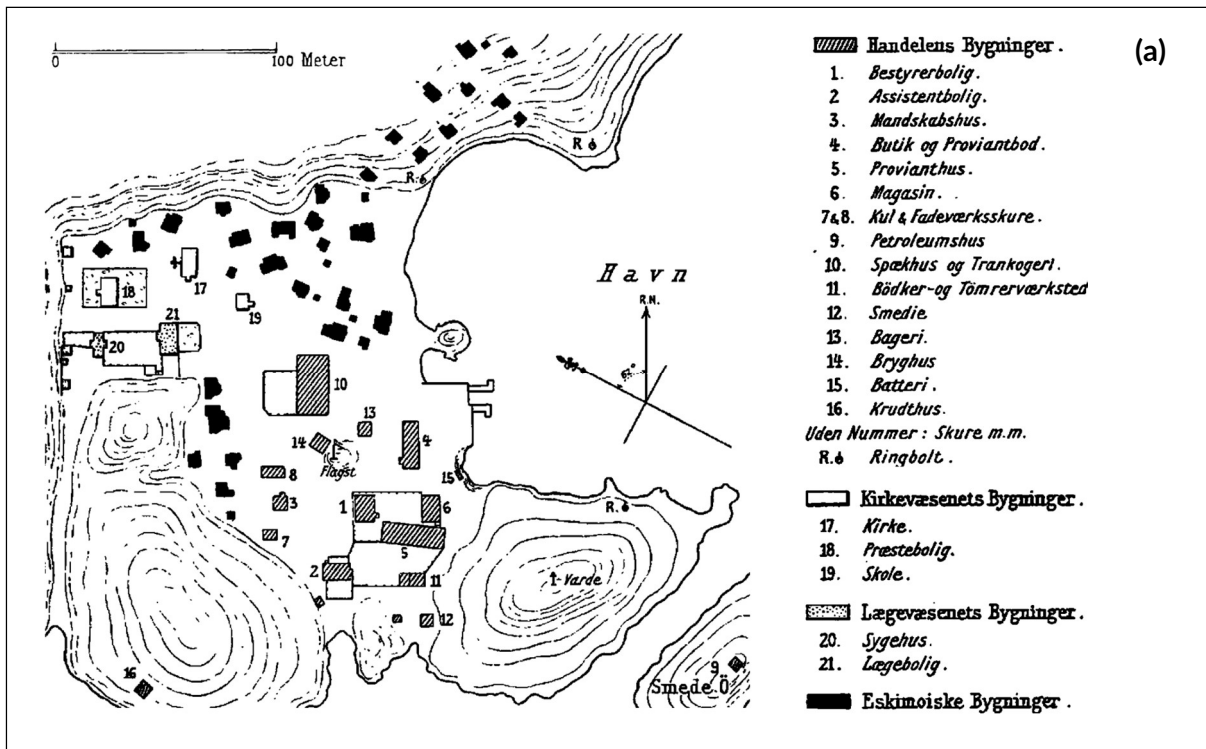


Figure 6.2 – The Kalaallit settlement of Uummannaq (*Umának*), Western Greenland, as represented in: (a) a plan of the settlement as it existed in 1919 (Amdrup et al. 1921); and (b) a photograph of the settlement, ca. 1889-1909, showing the rocky escarpment at its north-eastern edge (National Museum of Denmark)

#### 6.1.4 Limitations of Study

Although the results of the present study clearly support the hypothesised role of neurobiological mechanisms in determining household separation, a number of limitations should be acknowledged.

The main limitation of the present study is the quality of the available data. The settlement plans that were able to be used in the study were recorded with varying degrees of accuracy. The accuracy of plans was checked against satellite imagery if the geographic location was known, but this was possible for only a limited number of settlements. In some cases, the only available population size data for a settlement, which is necessary for calculating mean household size, were estimates made by the primary researcher or observer. This was especially the case for larger settlements, for which it was likely impractical for the observer to undertake a complete survey of the settlement. Fluctuations in population size may have also contributed a degree of error to reported population sizes. The number of people within a settlement at the time of recording may not have been an accurate reflection of the total population size if members were absent (e.g. due to extended hunting trips) or visitors were present. Nevertheless, because the data were taken from a large number of sources, it is likely that any errors due to data quality would be random rather than systematic so are unlikely to significantly bias the results of the study.

A common limitation of studies that utilise ethnographic data to make general predictions about human behaviour is the representativeness of the sample analysed. Unlike previous studies in this area that have opted to increase sample size and the potential expense of data reliability (Lobo et al. 2022; Whitelaw 1989, 1991), the sample size of the present study was limited by the availability of reliable data. The majority of references cited by Whitelaw (1989) were reviewed for the present study, but many were excluded because no population data was provided, settlement plans did not include a scale or the plans were schematic representations only. The sample nevertheless provided cultural and ecological breadth, encompassing 42 distinct cultural contexts, all possible climate zones and nine different vegetation zones. Despite this breadth, several biases do exist within the data set. Certain environmental contexts are better represented than others. In particular, temperate and subtropical climate zones are poorly represented. Additionally, the sample is mostly confined to observations of hunter-gatherer settlements made within the 20<sup>th</sup> century. In almost all cases, the observed hunter-gatherers had previously encountered and often taken up cultural traits not typical of their

‘traditional’ culture. Nevertheless, the hypotheses tested relate to neurobiological mechanisms that are common to all humans. It is not expected that they would vary by environmental or cultural context.

The necessary reliance of the present study on previously recorded data carries with it limitations. These limitations have been minimised for the present study by focusing on data quality rather than data quantity. Furthermore, the universality of the behavioural mechanisms investigated mean that any bias towards certain environmental or cultural contexts. Therefore, the methodological limitations of the study should not detract from its findings or from their broader applicability to hunter-gatherers in general.

## **6.2 Space as an Archaeological Proxy**

A motivation of the present study is the potential for household separation to be used as a proxy for human behaviour when interpreting the archaeological record. Invoking the ethnographic analogy, the present findings provide a sound basis for achieving that goal.

A key requirement for the ethnographic analogy is immanence (Wolverton and Lyman 2000). In other words, the analogy must relate to intrinsic and unchanging properties. The present study has found that significant evidence that social buffering and social homeostasis are likely primary determinants of household separation in hunter-gatherer settlements. As both social buffering and social homeostasis are based in human neurobiology and are therefore expected to be common to all humans the requirement of immanence is satisfied. It can be assumed that the neurobiological response of contemporary hunter-gatherers to stressors is the same as that of *Homo sapiens* throughout history. Social buffering and social homeostasis would have always played the same role in determining household separation. Household separation can therefore, at least in principle, be a reliable indicator of the operation of these neurobiological among past hunter-gatherers.

In order to interpret household separation in an archaeological site, several practicalities would need to be addressed. To measure household separation the locations of households would need to be determined. Various archaeological signals of household locations could be used. Obviously the foundations and other structural remains of dwellings provide the clearest signal of the location of former households (e.g. Schledermann 1971; VanStone 1970). Stone tent rings also provide a clear indicator (e.g. Binford 1991b; Savelle 1987; Wilson and Slobodina 2007). Although they can be caused by natural processes, stone rings found in the same context

as other material of human origin (e.g. lithic debris and faunal remains) can be reliably interpreted as former location of tents. The distribution patterns of debris relative to hearths have also been used to determine the location of dwellings (e.g. Julien 2006; Karlin and Julien 2019). In addition to household location, the population of the settlement would need to be estimated to determine mean household size. Settlement population can be estimated from dwelling floor space, although this is much more reliable for temporary settlements than for permanent settlements (Porčić 2012). Analysis of lithic debitage has also been used to estimate the population of settlement (Karlin and Julien 2019).

The utility of household separation as an archaeological proxy lies mainly in its relationship to hunting risk. Wide household separation indicates a high likelihood of access to abundant, easily caught prey (e.g. migrating herds or sessile animals) or the use of mass capture technology. Mean household separation could be used to observed changes in economic risk across space and time domains, tracking changes in the natural environment and culture. It could be used as a standalone indicator of hunting risk or in a multi-proxy approach to confirm assumptions based on, for example, faunal evidence.

Analysis of household separation may also be useful as a method of error-detection. When employed in a multi-proxy approach, the convergence of household separation and other proxies to a unified outcome provides greater confidence in that interpretation. The failure of proxies to converge may point to flaws in assumptions about the site or incomplete information. For example, if faunal evidence from a site points to a low risk hunting strategy (e.g. domination of the faunal assemblage by a single migratory species), yet close household separation points to a high risk hunting strategy, several possibilities could be considered. One possibility is that mean household separation is underestimated because the full extent of the site has not been excavated. Another possibility is that the number of households is overestimated because the site is a palimpsest. Included in a suite of tests, the use of household separation as a proxy for past human behaviour may provide greater confidence in the interpretation of a site, or aid in both identifying an error of interpretation and determining the cause of that error.

The interpretation of household separation in specific archaeological sites is beyond the scope of the present study. While more work will be required, the present study has shown the feasibility of employing household separation in past hunter-gatherer settlements as a proxy for human behaviour.

### 6.3 A World of Uncertainty

A focus of the present study is the uncertainty of hunting as a trigger of social buffering and closer proximity between hunter-gatherer households. It would be useful to explore the limits of the present findings by considering whether other stressors elicit the same effect on household proximity as hunting risk and whether people who do not rely on hunting and gathering are similarly affected.

Hunting is not the only source of uncertainty or stress for hunter-gatherer households. Environmental change or instability that affects food security more broadly (Burke et al. 2021), the threat of violence from other groups (Allen and Jones 2014) and forced resettlement (Billson 1990; Bishop 1974; Condon 1981; Petersen 1986; Thomas and Thompson 1972; Waldram 1987) are all potential stressors for hunter-gatherers. Further investigation to consider the relationship between these variables and household separation may provide a more complete picture of the spatial determinants in hunter-gatherer settlements.

Forced resettlement may be of particular relevance to contemporary hunter-gatherers. As mentioned in Chapter 1 of this thesis, attempts to resettle hunter-gatherer groups frequently result in a range of societal problems, including intra-group aggression, violence and substance abuse (e.g. Condon 1981; Waldram 1987). These behaviours are known responses to stress (Anthenelli and Grandison 2012; Sprague et al. 2011), which may be the direct result of the resettlement process, the feeling of disempowerment it creates and uncertainty about the future. The resettlement process typically results in the displacement of people into a planned, low-density settlement consisting of widely spaced permanent dwellings (e.g. Waldram 1987). The design of these settlements likely reflects a presumption that low density living is inherently superior to high density living, although in some cases may also be the product of well-meaning attempts to replicate a sparse arrangement of households prior to displacement (e.g. Waldram 1987). But, as shown by the present study, proximity to others and the flexibility to modify that separation are important alleviators of stress. The transplantation of people into a rigid, planned environment may be both a cause of stress and a constraint on the mechanism by which that stress may be relieved. The chronic stress that follows inevitably gives rise to the aforementioned societal problems.

Uncertainty and stress are not confined to hunter-gatherers. It is possible that economic uncertainty also acts as a motivator for closer physical proximity among people who rely on different forms of subsistence. A comparison of the Daasenach pastoralists of southern Ethiopia

and northern Kenya with the Dukha reindeer herders of north-western Mongolia supports this suggestion. Unreliable milk production caused by water insecurity is a source of uncertainty for the Daasenach (Bethancourt et al. 2022), who maintain closely spaced dwellings (Gifford 1977, p. 73) (Figure 6.3(a)). By contrast, the Dukha have widely spaced dwellings and access to reliable water and fodder for their reindeer (O’Brien and Surovell 2017) (Figure 6.3(b)). The neurobiological underpinnings of household separation mean that a similar trend might be observed in urban environments.

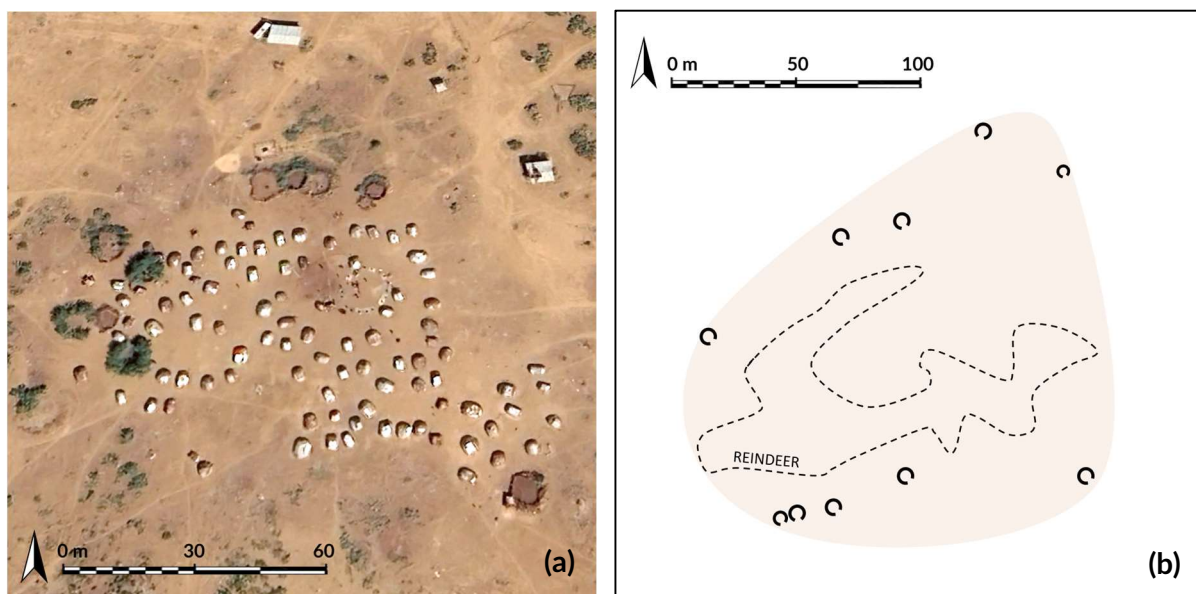


Figure 6.3– Settlements of the: (a) Daasenach pastoralists of southern Ethiopia (Google Earth); and (b) Dukha reindeer herders of north-westerns Mongolia (after O’Brien and Surovell 2017). A comparison of these pastoralist communities shows a correlation between food security and greater household separation, as also observed for the hunter-gatherer groups of the present study.

Extension of the present findings to urban settlements has further implications. Fletcher (2004) has previously observed that the outpacing of material change by social change may result in the built environment becoming increasingly maladapted to social context (see also Longhurst 2015; Thoeming 2018). In settlements where household separation is an adaptation to economic context, changes to that context could give rise to the material-social ‘dissonance’ described by Fletcher. That dissonance may have significant consequences for the inhabitants of a settlement. Settlements constrained by natural or artificial barriers (e.g. the city walls of pre- and early modern European cities) may become increasingly stressful environments as the population grows and density increases. On the other hand, low density settlements, which are suited to contexts of relatively economic certainty, may become increasingly stressful for their

inhabitants in the face of economic decline. The wide spacing of households would inhibit the stress-reducing effects of social buffering, leading to chronic stress and social problems like those mentioned in the preceding Section. As noted by Fletcher (2004, p. 111), '[maladapted] material could adversely affect viable social life... [and] might restrict the maximum span of time over which a community can persist'. Fletcher (2019) further observes a particular vulnerability of low density cities to collapse and abandonment, while compact cities display greater resilience and continuity. The absence of an important mechanism for relieving the stress on individuals in times of economic uncertainty (i.e. the social buffering effect provided by close physical proximity to social affiliates) may be the cause of that vulnerability.

The findings of the present study clearly have implications beyond the internal dynamics of hunter-gatherer settlements. They raise questions about the social and individual impact of displacing people, whether they are hunter-gatherers forced from their traditional lands, public housing tenants or private renters forced to seek new accommodation or house-owners forced to sell their property because of compulsory acquisition. Under what circumstances can the inevitable stress to the individuals involved be justified and how can that stress be managed if displacement is unavoidable? Can buildings and urban areas be designed that are sympathetic to the social needs of their inhabitants, particularly those under economic stress? It is the hope of the author that the findings of the present study prompts further research that considers these questions and ultimately informs public policy and urban design.

## Chapter 6

# CONCLUSION

It has long been recognised that the spatial characteristics of past hunter-gatherer settlements may provide insights into the lives of their inhabitants. Yet, despite various hypotheses, observations of widely varying population density and separation of households between hunter-gatherer settlements have not been well-explained. The present study considered the three potential predictors of household separation in hunter-gatherers settlements were considered in the present study: number of households, household size and hunting strategy. Each was hypothesised to be related to household separation via the human neurobiological phenomena of either social buffering (the inhibition of stress by physical proximity to social affiliates) or social homeostasis (the modification of social behaviour to minimise the opposing stresses of social crowding and loneliness). Hunting strategy was hypothesised to influence household separation by triggering a social buffering response where the adopted strategy has a high risk of failure and is therefore likely to be a source of stress due to uncertainty. Variance in the number of households and mean household size between settlements was hypothesised to be accompanied by variance in household separation to achieve a consistent, optimal encounter rate between individuals and therefore maintain social homeostasis.

Analysis of the ethnographic and archaeological data set compiled for the study provided strong support for the proposed hypotheses. General linear model analysis showed a significant positive correlation between household separation and each of the three variables, providing strong support for the hypothesised role of social homeostasis and social buffering as determinants of household separation. Furthermore, the predicted relationships between household separation and both number of households and household size, as determined by mathematically modelling, were well-supported by regression analysis. Although the availability and quality of data was limited, the findings of the study were nevertheless conclusive. In summary, the results of the present study are consistent with the proposition that household separation and, by extension, population density in hunter-gatherer settlements are determined in large part by the human neurobiological response to the stresses of uncertainty, social crowding and loneliness.

The present findings have implications for the archaeological interpretation of hunter-gatherer settlement sites. The strong support for neurobiological mechanisms being the underlying driver of variance in household separation provides a sound basis for invoking the ethnographic analogy. Since human neurobiology is a relative constant, it can be assumed that cotemporary hunter-gatherers behave the same way in response to uncertainty, social crowding and loneliness as hunter-gatherers in the distant past. Household separation in the archaeological record can thus be interpreted as being a product of the same processes as observed among contemporary hunter-gatherers. Resolving the practicalities of applying the present findings to the interpretation of archaeological sites provides an avenue for future research.

The present findings also have implications for the study of human settlements more generally. As human neurobiology is a relative constant, the findings of the present study may be relevant to all human settlements, not just those created by hunter-gatherers. Social homeostasis and social buffering may play a role in determining the form of contemporary urban settlements and those of past agricultural societies. Extending the present work beyond hunter-gatherers is a further avenue for future research.

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## Appendix A

### SETTLEMENT DATA

Cultural Group Country Ecological Zone References	Settlement	Year	P	N	$\bar{S}$ (m)	HS
!KUNG Botswana Tropical Shrubland  (Brooks et al. 1984; Gould and Yellen 1987; Lee 1979; Yellen 1977)	≠Tum ≠Toa 4	1968	24	7	5.0	H
	//Gakwe ≠Dwa 2	1968	24	7	5.1	H
	//Gakwe ≠Dwa I	1968	24	7	7.2	H
	≠Tum ≠Toa 3	1968	21	4	10.8	H
	Shum !Kau 3	1968	19	6	5.2	H
	Shum !Kau 2	1968	17	5	4.4	H
	N!abesha	1968	17	5	4.6	H
	N/on/oni <sup>1</sup> Toa 2	1968	17	5	4.4	H
	≠Tum ≠Toa 5	1968	17	5	5.2	H
	N/on/oni ≠Toa 1	1967	14	4	3.6	H
	Hwanasi	1968	12	3	3.7	H
	N!abesha	1968	12	3	4.2	H
	Shum !Kau 1	1968	12	3	4.8	H
	≠Tum ≠Toa 3	1968	11	3	4.9	H
	/Tanagaba	1968	11	2	4.1	H
	≠Tum ≠Toa 2	1968	11	2	5.1	H
	N/on/oni ≠Toa 1	1968	11	2	5.9	H
	N/on/oni ≠Toa 1	1967	10	2	4.8	H
	≠Tum ≠Toa 1	1968	10	2	5.0	H
	≠Tum ≠Toa 1	1968	7	2	5.0	H
DBC-18	1968 - 1969	38	15	8.7	H	
ACHÉ Paraguay	Tobatiry	1932	35	4	4.2	H

<b>Cultural Group</b> <b>Country</b> <b>Ecological Zone</b> <b>References</b>	<b>Settlement</b>	<b>Year</b>	<b>P</b>	<b>N</b>	<b><math>\bar{S}</math> (m)</b>	<b>HS</b>
Tropical Moist Forest (Vellard 1934)	Arroyo Pora	1932	15	2	3.3	H
AKA Rep. Congo Tropical Rainforest  (Kitanishi 1994, 1995, 1998, 2000)	Village Camp	1992	81	11	7.8	H
	M Group, Period 5	1992	62	19	6.9	H
	M Group, Period 6	1992	61	19	6.9	H
	B Group	1995	43	14	5.0	H
AKWE-SHAVANTE Brazil Tropical Moist Forest  (Flowers 1983; Maybury-Lewis 1967)	Sao Marcos	1964	350	30	10.9	H
	Sao Domingos	1958	220	16	14.8	H
	Simoes Lopes	1962	175	16	13.0	H
ALYAWARRE Australia Tropical Desert  (Denham nd., 2015; O'Connell 1987; O'Connell and Hawkes 1981, 1984)	Gurlanda A	1971	167	32	47.3	L
	Bendaijerum Ridge	1974	142	23	39.4	L
	Gurlanda B	1971	93	23	45.3	L
	Gurlanda A	1971	86	19	50.3	L
	Bendaijerum Flat	1971	76	13	42.3	L
	Angungera	1971	54	12	37.8	L
	Angungera	1971	35	8	38.4	L
BAKA Cameroon Tropical Rainforest  (Gallois and Duda 2016; Kitanishi 2000; Yasuoka 2014)	Settlement 2	1993 - 1994	63	10	8.3	H
	Settlement 3	1993 - 1994	61	15	12.1	H
BASARWA Botswana Tropical Shrubland  (Kent 1991; Kent and Vierich 1989)	Site 2	1976 -1978	31	6	7.9	H
	Site 8	1976 -1978	14	5	7.5	H
	Site 1	1976 -1978	8	4	3.8	H
BIRHOR India	Sijhua	1955	40	15	4.4	H

<b>Cultural Group Country Ecological Zone References</b>	<b>Settlement</b>	<b>Year</b>	<b>P</b>	<b>N</b>	<b><math>\bar{S}</math> (m)</b>	<b>HS</b>
Tropical Moist Forest  (Sen and Sen 1955; Williams 1974)						
BORORO Brazil Tropical Moist Forest  (Lévi-Strauss 1936)	Kejara	1936	140	25	15.3	H
COPPER INUIT Canada Polar  (Usher 1965)	Coppermine (Kugluktuk)	1963	250	48	44.7	L
	Holman (Ulukhaktok )	1963	115	15	47.0	L
CREE (MISTISSINI) Canada Coniferous Forest  (Rogers 1973; Rogers & Rogers 1959)	Fall Camp	1953	13	4	10.6	L
CREE (WESTERN) Canada Tundra Woodland  (Waldram 1987)	Fish Camp	ca. 1975	135	26	72.7	L
DENE (CHIPEWYAN) Canada Coniferous Forest  (Irimoto 1979, 1981a, 1981b; Jarvenpa 1975)	Patuanak	1971	434	65	56.0	L
	Wollaston Lake	1976	349	70	37.8	L
	Winter Camp zuzaze	1975 - 1976	8	3	14.7	L
	Gabriel be nue-1	1975	29	6	18.6	L
	Gabriel be nue-2	1975	22	4	14.9	L
	Øai nu-2	1975	16	3	14.6	L
DENE (WILLOW LAKE) Canada Coniferous Forest  (Janes 1983, 1988)	Willow Lake Camp	1975	31	7	24.4	L
EFÉ DR Congo Tropical Rainforest	A-NB-3	1984 - 1985	33	11	5.7	H
	A-NT-1	1984 - 1985	30	16	3.8	H

Cultural Group Country Ecological Zone References	Settlement	Year	P	N	$\bar{S}$ (m)	HS
(Fisher 1987; Fisher and Strickland 1989)	A-NB-4 / I-NB-1	1984 - 1985	30	9	4.4	H
	A-NB-1	1984 - 1985	24	7	4.3	H
	A-NP-5	1984 - 1985	23	8	7.6	H
	A-NR-2 / I-NR-1	1984 - 1985	23	8	4.4	H
	A-NP-7 / I-NP-1	1984 - 1985	22	7	7.6	H
	A-NG-1	1984 - 1985	21	10	6.3	H
	A-NE-5 / I-NE-1	1984 - 1985	21	6	5.6	H
	A-NP-7 / I-NP-1	1984 - 1985	21	6	8.6	H
	A-NG-3	1984 - 1985	20	3	7.3	H
	A-NG-5	1984 - 1985	19	7	5.7	H
	A-NE-6	1984 - 1985	18	6	6.5	H
	I-NP-2	1984 - 1985	18	4	5.7	H
	A-NB-2	1984 - 1985	16	6	5.8	H
	A-NE-2	1984 - 1985	16	5	12.4	H
	A-NG-4	1984 - 1985	15	7	5.2	H
	A-NP-1	1984 - 1985	14	6	9.6	H
	A-NP-6	1984 - 1985	14	6	4.8	H
	A-NP-3	1984 - 1985	14	4	9.5	H
	A-NG-2	1984 - 1985	13	5	3.5	H
	A-NR-1	1984 - 1985	10	3	3.4	H
I-NP-3	1984 - 1985	6	3	10.0	H	
G/WI Botswana	N/utscha Village	1976	42	12	10.4	H

Cultural Group Country Ecological Zone References	Settlement	Year	P	N	$\bar{S}$ (m)	HS
Tropical Shrubland  (Hold 1980)						
HADZA Tanzania Tropical Shrubland  (Hawkes et al. 1991; O'Connell et al. 1991)	Umbea B	1986	39	12	6.3	H
HAIDA Canada Temperate Mountain System  (Dawson 1880; Macdonald 1983, 1989; Orchard 2007)	Skidegate (Ski-de-gates)	1836 - 1841	600	39	16.2	H
	Chaatl (Kow-welth)	1836 - 1841	417	26	18.9	H
	Skedans (Skee-dans)	1836 - 1841	380	26	17.5	H
	Tanu (Cloo)	1836 - 1841	378	25	18.2	H
	Kaisun (Kish-a-win)	1836 - 1841	274	15	20.0	H
	Ninstints (Quee-ah)	1836 - 1841	246	16	12.6	H
	Cumshewa (Cum-sha-was)	1836 - 1841	229	16	18.9	H
HARE (KAWCHOTTINE) Canada Boreal Tundra Woodland  (Hara 1980)	Fort Good Hope	1962	349	70	33.7	L
IGLULINGMIUT Canada Polar  [Mathiassen 1928)	Iglulik	1922	73	10	12.9	H
INUGHUIT Greenland Polar  (Adler 1979; Malaurie 1982)	Siorapaluk	1974	98	15	43.2	L
	Qeqertat	1974	49	9	46.3	L
IÑUPIAT (NUNAMIUT) USA (Alaska) Boreal Tundra Woodland  (Amsden 1977; Binford 1978b, 1991b)	Anaktuvuk Pass	1969	122	24	24.6	L
	Amalgamation Site - Tulugak Lake	1949	65	18	61.7	L
	Ingstad Site - Tulugak Lake	1949	64	18	46.1	L
	Tulugak Lake	1949	38	7	23.0	L

Cultural Group Country Ecological Zone References	Settlement	Year	P	N	$\bar{S}$ (m)	HS
	Schoolteacher Site	1969	35	11	31.7	L
	Bear Site	1948	35	5	28.7	L
	Immanik	1949	19	3	30.5	L
	Kakinya-Rulland	1948	19	3	24.5	L
	Immanik	1948	17	3	34.6	L
	Bear Site	1948	13	2	38.8	L
IÑUPIAT (TIKIĠAĠMIUT) USA (Alaska) Polar  (Larsen and Rainey 1948)	Point Hope (Tikiġaq)	1941	250	46	16.4	L
KALAALLIT Greenland Polar  (Amdrup et al. 1921)	Jakobshavn	1919	246	42	22.7	L
	Umanak	1919	206	39	46.1	L
	Pröven	1919	196	31	47.5	L
	Egesminde	1919	171	27	32.5	L
	Upernivik	1919	170	31	31.9	L
	Ritenbenk	1919	129	24	60.6	L
	Söndre Upernivik	1919	108	18	54.7	L
	Christianshaab	1919	93	15	3.8	H
KIVALLIRMIUT Canada Polar  (Vallee 1962)	Baker Lake	1959	165	39	4.0	H
KUA Botswana Tropical Shrubland  (Bartram 1993; Bartram et al. 1991; Hitchcock 1982; Vierich 1981)	Kunahajina A	1986	26	4	7.1	H
	Khwee	1978	25	7	34.8	L
	Kunahajina B	1986	16	4	15.5	L

<b>Cultural Group Country Ecological Zone References</b>	<b>Settlement</b>	<b>Year</b>	<b>P</b>	<b>N</b>	<b><math>\bar{S}</math> (m)</b>	<b>HS</b>
KUNWINJKU Australia Tropical Dry Forest  (Altman 1987)	Momego (Mumeka)	1980	44	10	13.0	L
	Gukapangga	1980	26	7	16.2	L
	Manbulgardi	1980	26	7	8.3	L
	Gurorr	1980	24	6	21.0	L
	Mimanyar	1980	15	5	32.6	L
KWAKIUTL Canada Temperate Mountain System  (Rohner and Rohner 1970)	Gilford Island	1962	100	25	9.7	H
LABRADOR INUIT Canada Boreal Tundra Woodland  (Sillitoe 1979, 1981)	Railroads Fishing Camp	1970	85	12	32.3	L
MIKEA Madagascar Tropical Shrubland  (Tucker 2000, 2004, 2019)	Behisatse	1998	31	6	19.4	L
MRABRI Thailand Tropical Moist Forest  (Boeles 1963; Velder 1963)	Doi Thong	1963	31	6	36.1	L
MULTIPLE (ARNHEM LAND) Australia Tropical Dry Forest  (Hiatt 1965)	Maningrida	1960	420	81	42.5	L
MULTIPLE (DENE, METTIS) Canada Boreal Tundra Woodland  (Weir 1967)	Fort Franklin (Déljñę)	1965	305	43	19.3	L
	Fort Norman (Tulita)	1965	224	38	37.3	L
NETSILIK Canada Polar  (Balicki 1968, 1970; Savelle 1987)	Sheriff Harbour	1831	23	4	38.9	L

Cultural Group Country Ecological Zone References	Settlement	Year	P	N	$\bar{S}$ (m)	HS
NGATATJARA Australia Subtropical Desert  (Gould 1967, 1977, 1980; Gould and Yellen 1987)	Wanampi Well	1966	107	25	9.9	L
	Tikatika	1966	13	5	20.6	L
	Partjar	1966	10	3	3.9	H
	Pulykara	1970	9	3	3.1	H
NUKAK Columbia Tropical Rainforest  (Politis 1996, 2007)	Rainy Season Camp 1	1992	24	5	4.3	H
	Rainy Season Camp 2	1995	20	3	63.6	L
	Rainy Season Camp 3	1992	18	4	23.8	L
OJIBWA (ROUND LAKE) Canada Boreal Tundra Woodland  (Rogers 1962)	Round Lake (Weagamow)	1958	256	43	33.2	L
	Donnelly River Winter Camp	1958	9	2	43.0	L
PINTUPI Australia Tropical Desert  (Gargett and Hayden 1991; Gould 1967; Nicholson and Cane 1991; Spurling and Hayden 1984)	Papunya	1971	300	37	16.8	L
	Nabulabanda (Camps 3 -5)	1950s	13	3	9.0	L
	Nabulabanda (Camps 1 and 2)	1940s	7	2	6.6	L
	Walu	1940s	5	2	41.4	L
	Ngaru	1940s	4	2	23.1	L
QUEBEC INUIT (TAQAGMIUT) Canada Polar  (Graburn 1964, 1969)	Sugluk (Salluit)	1959	257	51	50.7	L
TUNUMIIT Greenland Polar  (Zavatti 1965)	Angmagssailk (Tasiilaq)	1961	600	70	46.1	L
WARAO Venezuela Tropical Moist Forest  (Wilbert 1980, 1994)	Yaruara Akoho	1954	79	8	12.7	H
	Hanoko Buroho	1954	33	6	14.4	H
	Bure Bureina	1954	32	3	6.6	H

Cultural Group Country Ecological Zone References	Settlement	Year	<i>P</i>	<i>N</i>	$\bar{S}$ (m)	HS
	Naonoko Anoko A	1954	32	3	13.2	H
	Naonoko Anoko B	1954	19	3	16.2	H
YU'PIK USA (Alaska) Polar  (VanStone 1970)	Akulivikchuk	1884	72	8	20.4	L

NOTE: *P* = settlement population; *N* = number of households;  $\bar{S}$  = mean household separation; HS = hunting strategy;  
H = high risk, L = low risk

## **Appendix B**

### **GLM RESULTS**

Table B1 – Results of GLM analysis of variance (ANOVA)

Measure	df	F	p	$\eta_p^2$
Model	4	169.60	<.001	0.83
Hunting Strategy	1	368.86	<.001	0.72
$\log_{10}(P/N)$	1	45.06	<.001	0.24
$\log_{10}(N)$	1	15.98	<.001	0.10
$\log_{10}(N)^2$	1	6.03	0.015	0.04
Residuals	144			
Total	148			

NOTE: df = degrees of freedom; F = F-value; p = p-value;  $\eta_p$  = partial eta squared;

Table B2 – Results of GLM ordinary least squares (OLS) regression

Effect	Estimate	Standard Error	95% Confidence Interval	
			Lower	Upper
Intercept	0.44	0.09	0.27	0.61
Low Risk – High Risk	0.63	0.16	0.32	0.94
$\log_{10}(P/N)$	0.47	0.07	0.33	0.61
$\log_{10}(N)$	0.57	0.03	0.51	0.63
$\log_{10}(N)^2$	-0.19	0.08	-0.35	-0.04