Computational approaches to the study of post-marital residence

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Abstract

Post-marital residence is the location taken by a couple after marriage. It is often a cultural practice, a choice based on tradition. Through its effect on family and family structure, post-marital residence influences important concepts and practices such as inheritance of property, status of men and women, initiation rites and tracing of descent. Due to its long-reaching effects and the fact that it is relatively easy to observe, through a short discussion with informant or by collecting information about marriages, post-marital residence has become an important subject of study for many anthropologists.

In the past, post-marital residence was predominantly explored through association studies. However, factors influencing post-marital residence often exhibit unclear causative direction. This makes their study using association analyses difficult.

This thesis will explore post-marital residence using three different computational methods: an evolutionary approach based on language trees; a data-mining approach that finds clusters of societies in an ethnographic database; and an agent-based model of warfare-induced residence change. These three methods enable exploration of post-marital residence from significantly different angles, which enables me to describe a much more complex and balanced picture. I find no evidence for the existence of global patterns of residence change. In fact, even language groups with similar demographic histories differ significantly in their patterns of residence evolution. However, I find strong evidence for the existence of more localized patterns. Based on data that describe societal properties such as the prevalent type of subsistence, sex taboos or type of housing, societies can be clustered into groups, with some groups being almost exclusively formed by societies with a single type of residence. Finally, I find that while warfare is able to induce a change of residence, it does this only when a significant portion of the society is under warfare pressure. However, warfare can also be a catalyst when another factor influencing residence change is present.

My results suggest that more localized patterns should be explored. Based on the grouping of societies identified in this work, one should not assume that because two societies have the same residence state that similar factors must be in play. In fact, a multitude of factors could induce change into a specific residence state under different conditions. Thus, the factors for residence change should be explored on a case-by-case basis and societies with similar histories and pressures should be grouped together and investigated instead. Societies where the change of residence was induced by warfare could be one such group. Results from the agent-based model can help to specify the exact conditions required.

Computational-based approaches enable new and interesting points of view on classical anthropological problems. However, they are limited by the existence of data and a functional knowledge of societies and cultures. These are often lacking, at least in a programatically accessible form. Thus, developing better and more accessible databases and knowledge banks with a mechanistic description of cultural concepts should be a primary future focus for anthropology.

Taken together, the results of the three approaches shown in this thesis form a strong statement regarding how various factors influence a change of post-marital residence. This provides a proof of concept of benefits for tacking classical anthropology questions with computational tools. It will hopefully work as an invitation for collaboration between the two research areas.

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1. Introduction

Post-marital residence is the location of residence taken by a newly-wed pair after marriage. While this is often a physical residence, i.e., specific house or building, it is more generally a location based on proximity of the pair's respective families; among migrating hunter-gatherers, such as Aboriginal Australians, this takes the form of a migrating campsite. However, the post-marital residence is also a cultural practice, a traditionally taken residence. This custom gives rise to varying family structures: a family that can be centred around a female line (females are local, while their husbands have to move in from different villages), a male line or given a form where an extended family does not exist. Through its effect on family and family structure, the traditionally taken post-marital residence creates the leading structure of societies. Post-marital residence is not fixed: communities can and do change their preferences over time, and the aim of this thesis is to contribute methodologies that can investigate the reasons for this computationally.

Directly or indirectly, post-marital residence influences, and is influenced by, such important concepts and practices as sex division of labour (male vs female contributions to subsistence) (Hart, 2001), the inheritance of property (Zhang, 2008), the status of men and women (Adams, 1983) and even sexual practices (Mattison, 2011). It also influences mythology and initiation rites (Owen, 1965) through its effect on another cultural practice: the tracing of descent (Murdock, 1949). Due to its long-reaching effect and the fact that it is relatively easy to observe, the choice of post-marital residence became an important subject of study in both contemporary and extinct pre-literate and literate societies. Finally, because post-marital residence practices create specific genetic patterns through the distribution of lineages (Oota et al., 2001), it has become a useful proxy to estimate population history through DNA data (Guillot et al., 2016).

1.1 Motivation

Although post-marital residence can be classified by many different terms with definitions differing from author to author, in this work, I will predominantly use only the most common terms and definitions. In **matrilocality**, a newly-wed couple resides with or near the wife's family. Under **patrilocality**, the newly-wed couple resides with or near the husband's family. Two additional terms are also of close interest: **ambilocality** and **neolocality**, although they are not the immediate focus of this work. Under **ambilocality** or **bilocality**, there is no preference for post-marital residence. More precisely, the residence with husband's and wife's family is taken with similar frequency. Finally, under **neolocal** post-marital residence, a couple prefers a new location altogether (this is typical in modern societies) (see Figure 1.1). For a more detailed exploration of residence classification, see section 1.6.

Distribution of these four states of post-marital residence varies greatly, with some residences being more common in particular groups of people. When the residence frequency is inspected globally, some residences are overwhelmingly more common than other residences. For example, in the Ethnographic Atlas, the majority of societies are patrilocal (63%) with the second most common residence, matrilocality, lagging far behind (13%) (see Figure 1.2). This huge imbalance in the frequency of adopted residence

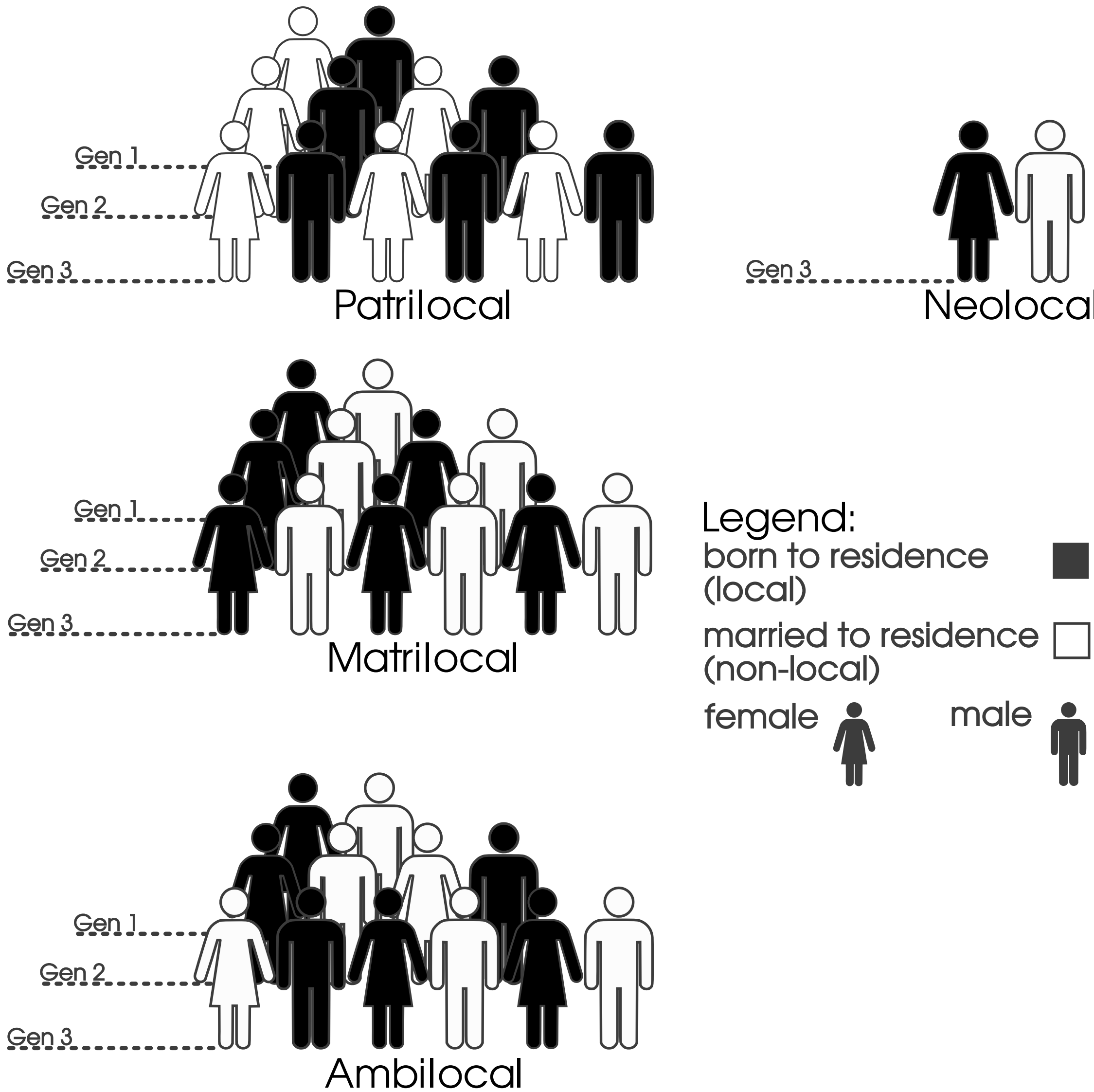

Figure 1.1: Visualisation of primary types of post-marital residence and their effect on the creation of extended families.

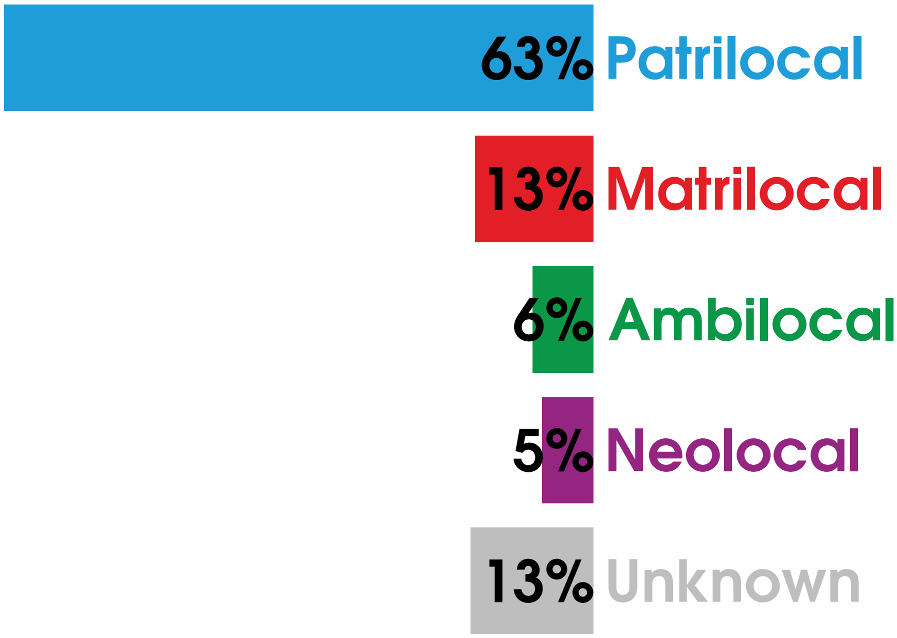

Figure 1.2: Residence frequency in the Ethnographic Atlas. The frequency of four major residences in the Ethnographic Atlas, data obtained from D-place (Kirby et al., 2016).

must have some cause and functional differences between residences were explored to find factors influencing the adoption of a particular state.

Most importantly, the post-marital residence is not static. In time, as the society changes and evolves, the preferred post-marital residence state does change as well. This change can be rapid, such as during the clash of civilisations in the colonial and post-colonial period (Hiatt, 1984; Korotayev, 2003; Bates, 2010; Starn, 2011), or slower, caused by internal pressures (Murdock, 1949; Ember, 1967; Divale, 1984; Zhang, 2008). And while we have some ideas, often related to economic conditions, the precise effect of many responsible factors is, however, yet to be determined.

Societies are commonly divided along functional divisions, often based on the major means of obtaining subsistence and a general style of life, such as hunter-gatherers, horticulturalists or pastoralists and a general pattern of post-marital residence is prescribed to these classes: pastoralists are patrilocal, horticulturalists matrilocal and hunter-gatherers ambilocal. These, however, did not produce strict rules, merely tendencies and even these were often inaccurate, with many exemptions, and in the case of hunter-gatherers, some even questioned if the concept of post-marital residence is appropriate at all (Kelly, 1995). This led to a more detailed exploration of factors associated with post-marital residence. However, the lack of detailed anthropological data makes a chronological understanding of cultural change complicated. Due to this, the research of post-marital residence have to rely on indirect means, more often a cross-cultural comparison across different cultures, but in these cultures, the post-marital residence might work in a different functional context, as a structure that was adopted due to different cultural pressures. Without an ability to perform direct experimental research, standard scientific methods used in anthropology, such as correlation, are unable to disentangle causal relationship between a large number of environmental and cultural variables and post-marital residence.

Despite these problems, a number of factors were suggested to play a major role in the transitions of post-marital residence, the most prominent of them are the sex-based division of labour and warfare (Murdock, 1949), both of these factors are strongly associated with a dominance of one sex (in the case of sex division of labour, the sex with higher contribution to subsistence) and produce a remarkable changes in society and along these factors, two theories were formulated: the warfare theory of matrilocality (Ember and Ember, 1971), where the division of labour and the pattern of warfare determine the post-marital residence, and the migration theory of matrilocality (Divale, 1974), where the warfare is caused by migration and the transition to matrilocality is an adaptive choice that enables the survival of the society.

Given that the standard methods used have been unable to disentangle the causal relationship between the environmental and cultural variables and post-marital residence, new methods are required.

1.1.1 Aim

The aim of this work is to explore global and local patterns, and factors influencing post-marital residence change using modern computational methods to understand the evolution of post-marital residence.

To do this, I will explore the anthropological literature on this topic, gather ethnographic accounts and previously collected datasets, and then explore these datasets using modern analytical and modelling tools. Specifically, I will use language tree-based analysis and a data-mining of an anthropological database to understand the global patterns of residence evolution. To explore the local patterns, I will build an agent-based model that simulates artificial communities and the interactions between them, as well as pressures that cause communities to switch their post-marital residence state.

1.2 History of post-marital residence research

1.2.1 Association studies

Academic interest in post-marital residence began at the very end of the 19th century and was deeply interconnected with the study of kinship. Key terms for post-marital residence: matrilocality and patrilocality, were coined by Thomas (1906) (see Barnes, 1960 for the usage of these terms), although interest in post-marital residence as different dispersal of males and females during a marriage is even older (Tylor, 1889). Unfortunately, a discussion of post-marital residence was overshadowed by a focus on matriarchy and patriarchy, with the idea that matriarchy (and thus matrilocal and matrilineal society) is some primitive state of existence (Thomas, 1906). This was disproved when it was discovered that some matrilocal and matrilineal societies have in fact higher social complexity than some patrilocal patrilineal societies (Schneider, 1961). Furthermore, the existence of matriarchy was questioned: "*. . . most of the so-called matriarchal, i.e., woman-ruled, societies show this condition. Under such circumstances, the wife derives her power from the backing of her own male relatives, which prevents the exercise of physical dominance by the husband.*" (Linton, 1936).

The first proposed factor that determined, or at least influenced, post-marital residence, was the division of labour by sex (Lippert and Murdock, 1931; Linton, 1936). The sex with a higher economic impact from its labour would thus predict residence. While this theory was popular (Murdock, 1949; Service, 1962; Ember and Ember, 1971; Pasternak et al., 1997; Ember, 2011), it was statistically supported only within North America (Driver, 1956; Driver and Massey, 1957) and rejected when a global sample was studied (Brown, 1970; Ember and Ember, 1971; Divale, 1974), probably due to rather abnormally large proportion of hunter-gatherers, and especially so-called *complex* hunter-gatherers (hunter-gatherers with complex social structure and high population density thanks to abundant fishing or hunting food source), in the North American sample. While not supported by data on a global sample, division of labour remained a popular factor and was often included with other factors in some form.

Since higher economic yields increase social status in a relationship, a variation or generalization of this theory was proposed: anything that increases the relative status of one sex will tend to centralize its residence and lineage (Murdock, 1949), such as political integration, slavery, polygyny, movable property (e.g., cattle) and warfare, all favouring patrilocal residence. While some matrilocal societies have higher social complexity than equivalent patrilocal societies, there was a lack of matrilocal societies among pre-industrial state societies. The more a society is organised around states, the less it tends to be matrilocal. One reason might be that structures created by matrilocal residence are more complex and can solve various inner conflicts, so matrilocal societies tend to be more peaceful, while patrilocal societies tend to suffer from internal conflict (Ember and Ember, 1971; Ember, 1974; Divale, 1974, 1984). Thus, patrilocal societies might be pressured to create novel structures, independent of kinship, to stabilize themselves and reduce inner conflict.

Warfare became another factor that gained popularity as an explanation for the adoption of a certain residence type. However, although the increased frequency of warfare was attributed to societies with patrilocal residence, several well-known head-hunting societies were matrilocal: Ibans of Borneo (Otterbein, 1977), Jivaro of Eastern Ecuador and Peru (Hawkes, 1981) and Amazonian Munducucu (Jones, 2011). It turned out that there is a difference in the effect of internal warfare (warfare between villages or groups of the same community) and external warfare (warfare between two culturally unrelated communities). This was simultaneously picked up by Ember and Ember (1971) and Divale (1974). However, they formulated their theories with different causal directions. According to Ember's *Warfare Theory of Matrilocality* (Ember and Ember, 1971) a society with purely external warfare and matridominant division of labour would be matrilocal, while in other cases (some internal warfare or purely external warfare with patridominant division of labour), society will be patrilocal. According to this theory, warfare caused, together with the division of labour, a change of residence. On the other hand, Divale's *Migration Theory of Matrilocality* (Divale, 1974) suggested that at first, a community migrates to a new environment or is invaded by another community and there, due to external warfare, is forced into an adaptive change towards matrilocality to stop internal warfare and to increase its chance of survival. From there Divale's theory continues in a similar spirit to Murdock's Main Sequence Theory (Murdock, 1949) with a switch from patrilineal to matrilineal descent. Then a new ecological equilibrium is reached by either destruction of one or the other community or by general depopulation. After that, the society will switch to patrilocal residence and then later to patrilineal descent as well. Both of these theories became relatively popular, but also a target of critique (Ember, 1974; Hawkes, 1981; Korotayev, 2003; Marck and Bostoen, 2011; Jones, 2011; Ember, 2011).

Another factor, polygyny, a situation when a man has more than one wife, is as complex as warfare. There is not a single form of polygyny, but two functionally different types: sororal polygyny, where a man marries two or more sisters, and non-sororal polygyny, where a man marries two unrelated women. Sororal polygyny is connected with matrilocality and sisters usually live in the same house, while non-sororal polygyny is associated with patrilocality and both women often live in different houses (Murdock, 1949). While sororal polygyny probably does not influence a transition towards matrilocality, the same does not apply to transition to patrilocality with non-sororal polygyny (Divale, 1984). If a man, married matrilocally, is able to acquire another wife, through status, male-controlled wealth, wife-capture or a female slave, he will create a patrilocal residence inside his original wife's matrilocal one (Murdock, 1949). This can lead to either dissolution of matrilocal residence or stratification of society into elite families (such as the family of a village chief, headman or big man) marrying patrilocally in an otherwise matrilocal society (Divale, 1974). In time, patrilocal marriage will be associated with status by the members of the community and, without factors keeping society in matrilocal residence, in time more and more men will marry patrilocally and thus non-sororal polygyny will lead to a dissolution of matrilocal residence.

While slavery seems to be connected to patrilocality (Murdock, 1949; Ember and Ember, 1971), it does not seem to be widely discussed, unlike pastoralism (Murdock, 1949; Aberle, 1961; Ember and Ember, 1971), which is also connected with patrilocality. On the surface, pastoralism and slavery are very similar: both are forms of movable property (unlike immovable, i.e., agricultural land) that has to be actively guarded (in the case of cattle/sheep/goats against being stolen, in the case of slaves, against rebellion/escape). However, except in extreme cases, while a pastoral style of life often forms the main form of subsistence, in the case of slavery it is often an additional way of obtaining wealth on top of an existing type of subsistence. In other words, while communities often depend on cattle, they, except in extreme cases, do not depend on slaves. Thus the effect of pastoralism is more pronounced.

Finally, a male absence was suggested as a factor that could turn patrilocal residences into matrilocal ones (Harris, 1997). If husbands are absent from home for a long time, on trade, fishing or raiding expedition, wives stay at home and have to rely on female support groups, which are more easily formed around kin groups, i.e., around sisters rather than husband's brothers' wives. However, this effect seems to be at least partially connected to the division of labour, since absent men cannot provide enough sustenance.

Outside of matrilocal and patrilocal residence, a change to ambilocality seems to be related to a depopulation event (Service, 1962; Ember and Ember, 1971; Ensor, 2011) or small group size in general, typical for hunter-gatherer societies (Kelly, 1995; Scelza, 2011). The ability to choose residence enables the choice of the best location from an economic perspective and helps balance the male to female ratio resulting from a small number of births.

1.2.2 New modelling perspectives

Most of the previously mentioned research on post-marital residence was based on association studies and a great deal of anthropological, ethnographic and sociological knowledge. However, human societies are complex, and association studies do not recover causal relationships but, as the name implies, associations. Thus, while two researchers might have agreed on the importance of certain factors and both found the same factors relevant in their studies, they might have disagreed on what is an effect of residence and what is a cause, like in the case of the *Warfare Theory of Matrilocality* and the *Migration Theory of Matrilocality* (see Divale, 1984; Ember, 2011) where both authors agreed on an association of warfare with residence, but disagreed on its causal relationship. More recently, association studies almost disappeared or were much more complex, and new models or modelling perspectives appeared. With them came a refinement of previous theories or an appearance of new factors that might influence the adoption of post-marital residence.

Division of labour was revisited again and with success, it was discovered that, similarly to warfare and polygyny, the effect of division of labour is also not linear (Korotayev, 2001, 2003), and while it is true that patridominant division of labour is associated with patrilocality, highly matridominant labour is associated with patrilocality and polygyny, since in that case, it is very advantageous for a man to take control of several women to benefit from their labour. It was also newly reconsidered from a more economic-based perspective (Zhang, 2008; Little and Malina, 2010; Kramer and Greaves, 2011; Jones, 2011), and while such a perspective and relative gain and loss by either gender was discussed before (e.g. Hart, 2001), it was now formally defined and studied using a game theory approach with a gain/loss matrix (Ji et al., 2016).

Similarly to this economic perspective, the residence was connected with parental investment and a new factor was proposed: the certainty of paternity (Alexander, 1974; Greene, 1978; Flinn, 1981; Hartung, 1981; Ensor, 2011). Under this theory, it might be more advantageous for a man to invest in his sister's sons and not his own if he is highly uncertain about the paternity of his children. In that case, he would share potentially a higher amount of DNA with his sister's children than his own. However, it seems that certainty of paternity needs to be exceptionally small, from 0.33 (Alexander, 1974) to 0.268 (Greene, 1978), while real values range from 0.981 in high paternity confidence societies to 0.702 in low paternity confidence societies (Anderson, 2006).

To solve the so-called Galton's problem (e.g., Korotayev and Munck, 2003), that two societies might have similar social institutions because of common descent or cultural diffusion and not through independent development, Mace et al. (1994) suggested the use of phylogenetic trees, graphs where branching represents the evolution of genes, species, languages or in this case, cultures (see Figure 1.3). Since a phylogeny of cultures is not known, language trees were used instead. Usage of language trees has several advantages: languages evolve in similar ways to DNA (Cavalli-Sforza, 1997) and thus methods developed for estimating DNA trees, with modifications that respect evolution of languages, can be used

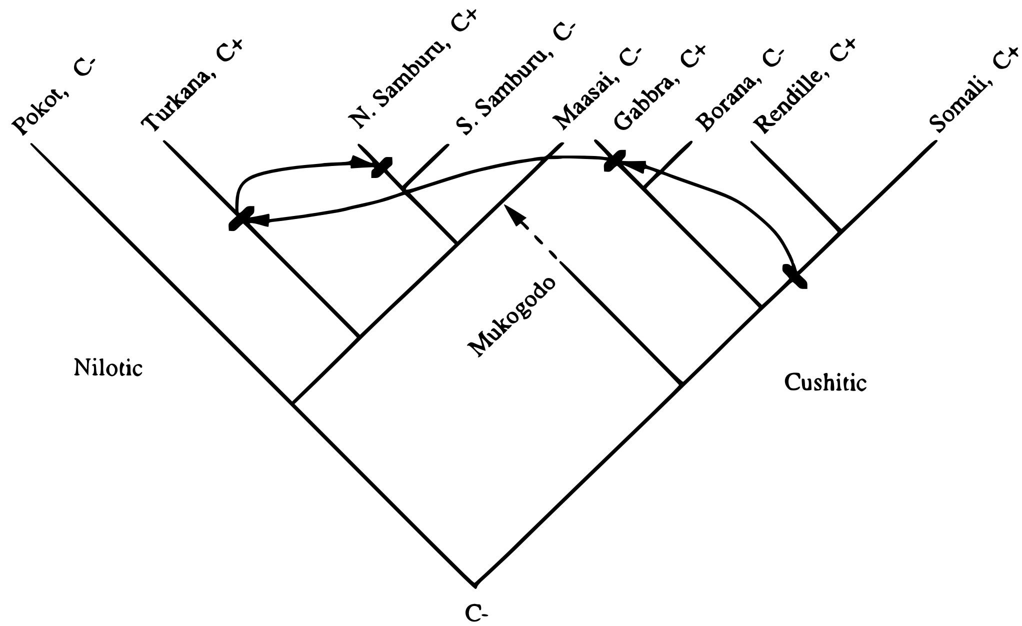

Figure 1.3: An example of a phylogenetic approach used in cultural anthropology. A language phylogeny of nine Kenyan cultures. Note that branch lengths do not represent time. Marked traits $C+$ and $C-$ show presence and absence of camel-herding. Black bars show possible events of independent adoption and black arrows a possible horizontal transmission (i.e., cultural diffusion) of camel-herding. The existence of camel herding in Rendile and Somali can be explained by their shared ancestry, rather than independent adoption of camel-herding. From Mace et al. (1994).

(in fact, DNA and language comparison methods share similar roots, see Anttila 1989). Additionally, the data required for construction of language trees have been collected for more than century in the form of *Swadesh lists*, lists of words, often body parts, that does not change often (resistant to sudden language changes and horizontal transfers); and finally, there is a strong correlation between residence and language, since both are passed through family (Cavalli-Sforza and Feldman, 1981).

With this tool, the relationship between pastoralism and residence was revisited (Holden et al., 2003) and, at least among the Bantu people in South Africa, confirmed that the adoption of cattle drives the loss of matriliny. Mapping residence on language trees enables us to reconstruct the evolution of residence, something that was not possible before. This was applied to reconstruct the evolution of post-marital residence in the Austronesian language family (Jordan and Mace, 2007; Jordan et al., 2009; Fortunato and Jordan, 2010), the Indo-European language family (Fortunato and Jordan, 2010) and the Bantu language family (Opie et al., 2014). All these works also tried to test the relationship between residence and descent as suggested by the *Main Sequence Theory* (Murdock, 1949), according to which the change in residence is followed by the change in respective descent (i.e., from patrilocal patrilineal society into matrilocal patrilineal and then matrilocal matrilineal). However, it seems that this theory does not generally hold. An attempt to compare cross-cultural patterns in the evolution of these language families was performed (see Chapter 2). In total, five language families were analysed: Austronesian, Bantu, Indo-European, Pama-Nyungan and Uto-Aztecan, but no common pattern, except the common tendency to switch to patrilocality, was observed.

While the post-marital residence puzzle has not been solved, notable progress has been made. The synthesis of modern more formal mathematical methods with deep knowledge and a detail-oriented approach to the past opens doors to new progress. However, even after more than 100 years of research, the question of what causes the change of residence, especially between patrilocality and matrilocality, remains unresolved.

1.3 Principal theories of post-marital residence change

In the previous section, I outlined the history of post-marital residence research and various factors that could determine post-marital residence: division of labour, slavery, polygyny, pastoral style of life, male-absence, the certainty of paternity, economic loss and gain, and depopulation/low population. In this section, I would like to concentrate on two theories connecting warfare with residence, the *Warfare Theory of Matrilocality* (Ember and Ember, 1971) and the *Migration Theory of Matrilocality* (Divale, 1974, 1984). Both are complex theories covering a multitude of mentioned factors directly or indirectly.

Both theories are built on the importance of warfare, a process that can have multidimensional effects on society. Warfare as a factor that could be responsible for change of a post-marital residence, was first noted by Murdock (1949), as a general effect that increases male status. Interestingly, there was no objection or test required to associate males and warfare (and violence in general). This association feels strangely natural to us and hardly anyone would even question this relationship. It is supported cross-culturally: males do monopolize warfare, weapons and violence (Divale and Harris, 1976)[1]. Note that warfare here is defined as any conflict between two societies or villages. Limiting warfare to full-scale warfare makes its presence dependent on population density and social organisation (i.e., clans, tribes, nations) and thus seemingly absent in societies with low-population density and a low level of organisation, such as simple hunter-gatherers (Kelly, 1995). Merging this warfare with what is often called *feuding* makes warfare present in most societies, regardless of their population density (Ember and Ember, 1971; Divale, 1974).

It was Otterbein and Otterbein (1965) who first noticed the relationship between warfare, residence, polygyny, division of labour and fraternal interest groups. Another important finding was that matrilocal societies are often more internally peaceful (Van Velzen and Van Wetering, 1960). It is hard to wage war against your neighbour if their soldiers are your sons and your soldiers their sons (i.e., the nonexistence of fraternal interest groups). Still, even in matrilocal society, authority is held by men, but by brothers instead of husbands (Schneider, 1961). This, in fact, makes descent and decision-making in conflict an element that perhaps leads to a certain instability of matrilocal residence.

1.3.1 Warfare Theory of Matrilocality

While Otterbein and Otterbein (1965) first noticed the relationship between warfare and residence, it was Ember and Ember (1971) who suggested a direct link between a lack of internal warfare and matrilocality. As noted by Murdock (1949), if warfare enhances the status of males, then societies with more frequent warfare should be patrilocal, but this was not supported by data (Ember and Ember, 1971). However, if the type of warfare was split, as hinted at by Schneider (1961) in his description of structural differences between patrilocal and matrilocal residence, into internal (infighting between villages) and external (fighting between two groups of different culture or tribe), then the type of warfare, together with division of labour, can predict residence (Ember and Ember, 1971). Ember's theory is as follows: the patridominant division of labour is the default type. However, if warfare disrupts male labour, female labour will start dominating. This is more likely among farmers than among hunters or pastoralists. Then, if society fights in purely external warfare (and thus has no infighting), there is no reason to keep patrilineally localized males close and thus economic considerations will be more important (i.e., keeping more productive daughters at home) and society becomes matrilocal. If, however, there is still local infighting, and thus a need to keep one's related males close for protection,

[1] This might not be so strange from a purely biological point of view, testosterone, a male sex hormone, is responsible for increased muscle and bone density, aggression and risk-taking (Ronay and Von Hippel, 2010)

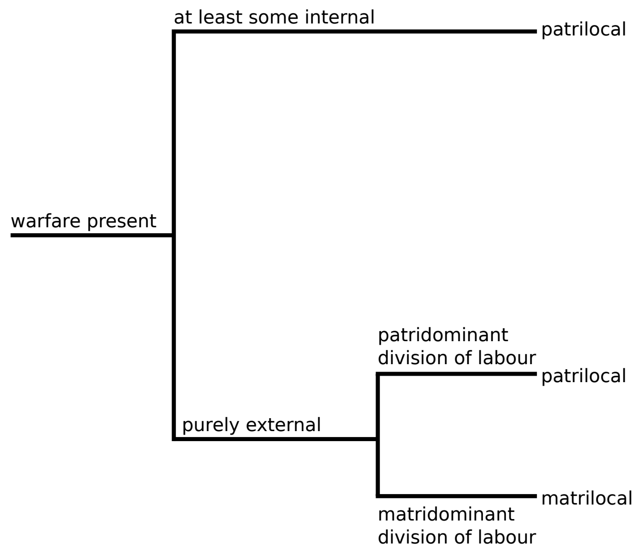

Figure 1.4: Relationship between warfare and post-marital residence as proposed by Ember and Ember (1971). Matrilocality will arise only when warfare is purely external and labour is matridominant, either due to economic conditions or due to warfare interfering with male contributions to sustenance.

or if the warfare does not disrupt male labour, e.g., is waged in a time when little work needs to be done, then society will be patrilocal (see Figure 1.4).

1.3.2 Migration Theory of Matrilocality

A rival theory was proposed by Divale (1974), who expanded it in his later work (Divale, 1984). Inspired both by previous discoveries (Otterbein and Otterbein, 1965; Ember and Ember, 1971) and his earlier research on warfare, Divale noticed connections between change of residence (or in fact, a rather drastic change of society) and migration, or more generally, a drastic change of condition, such as an expansion of a population into a new, already-occupied environment, or a coming of Europeans into a new world, where diseases, modern weapons and the political presence of Europeans themselves significantly distorted an established political and environmental climate. And thus, almost as a response to Ember and Ember (1971), Divale formulated his own theory (Divale, 1974) stating that when a pre-state society migrates, due to overpopulation, new technology or method of subsistence, or due to European colonial behaviour, to a region already inhabited by a society with a similar level of organisation, it causes a disequilibrium between the people and environment, either a lack of land, water or available food resources available for both populations. A new equilibrium can be established by the destruction of the original inhabitants, newcomers or general depopulation and thus, given a level of organisation, an adaptive response from both societies is external warfare. In this situation, Divale suggests that the adoption of matrilocality is an adaptive response to this situation, since matrilocality will break fraternal interest groups and stop internal warfare, a step required for the survival of society. Divale supports this theory with two examples: Mundurucu, a native Brazilian tribe (Murphy, 1956, 1957, 1960), and Osage, a North American tribe (Bailey, 1971) and a strong positive correlation between migration, residence and external warfare.

Later, Divale (1984) refined his theory, adding a better explanation for change towards the matrilocal residence and describing change back to patrilocality, in a process which integrated Murdock's *Main Sequence (Kinship) Theory* (Murdock, 1949), according to that change in descent follows after a change in residence. At first, a (patrilocal patrilineal) community is forced to migrate into an already occupied

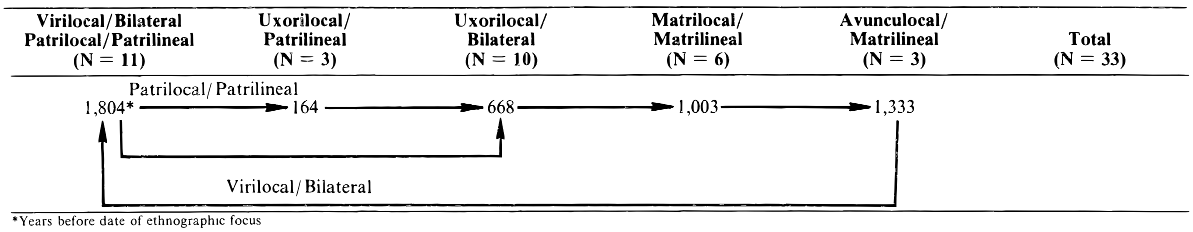

Figure 1.5: The progression of residence pattern with average dates of past migration. N is a number of societies in the sample. From Divale (1984).

environment. Stress from lack of resources will result in warfare between the societies. In this refined theory, only peripheral villages, villages that are closer to the enemy and thus have higher warfare mortality, will change towards matrilocality, in an attempt to increase the number of warriors the village has to prevent its destruction. Other villages will adopt matrilocality as they will perceive the "*internal peace and harmony*" of matrilocal villages. This will result in a matrilocal patrilineal society. After some time, as per *Main Sequence Theory*, patrilineal descent groups will break down and the community will become bilateral (descent traced through both mother and father) and then matrilineal. When an equilibrium is reached and the pressure caused by external warfare decreases, males will try to use their dominance to gain authority over their residence (by first not leaving their natal villages, matrilocal matrilineal societies tend to be endogamous (Divale, 1974)), giving rise to first avunculocal and then patrilocal society, which in time will break matrilineal descent and turn first into a patrilocal, bilineal or ambilineal, society and then a patrilocal, patrilineal society. According to Divale's findings, this cycle should take on average 1804 years (see Figure 1.5).

1.3.3 Comparison and critique

Both theories tried to explain the relationship between warfare and residence. According to Ember (1974), both theories are similar, but postulate different causal directions. While, according to Ember's theory, warfare (together with labour) cause residence, according to Divale's first formulation, the (matrilocal) residence prevents internal warfare. However, further speculations of both authors in their later work makes this less clear, since Divale significantly refined his theory in his following work and provided a more predictive scenario where a switch to matrilocality is caused by warfare (warfare losses) and Ember's attempt to reconcile Divale's finding (Ember, 2011) speculated that communities might be more successful at migrating and surviving if they first switch to matrilocality, which seems to be against her former idea that warfare causes residence change.

Both theories have been criticized, and while Divale's theory was subject to criticism more often, it seems that it was also more often discussed (Ember, 1974; Korotayev, 2003; Marck and Bostoen, 2011; Jones, 2011). One of the major critiques of the first formulation of Divale's theory was his vague explanation of why villages adopt matrilocal residence. In his first formulation, it was to stop internal warfare. While this problem was partially solved in his second formulation for villages with increased warfare mortality, he again used a perceived "*internal peace and harmony*"[2] as a reason to switch to matrilocality for all the other villages without increased warfare mortality. Another point of criticism was migration itself. According to Ember (1974) and Korotayev (2003), communities with internal warfare would have a hard time migrating. Ember (1974) also adds that even Divale's own data says that half of the migrating societies that migrated within the past 500 years were patrilocal. While Korotayev (2003) offers a similar critique, he reluctantly agrees with some of the points: he argues that

[2] An almost Lamarckian idea. It implies an organised change; the village would not benefit from these matrilocal advantages until a significant portion of villages marry matrilocally for one or more generations. Whether or not can human culture evolve in Lamarckian way is, however, an open question.

internal peace must be a prerequisite for a migration, that long-distance migration of several bands has to be organised, that organised migration is the subject of study by both Ember and Divale and that such organisation would bring internal peace. I however disagree with him on the point that such organised migration was implied by Ember and Divale, since several neighbouring villages might decide to migrate independently as they are subjected to the same pressures. He also points out that the prevalence of migrating matrilocal communities might be due to a greater success of the matrilocal community in waging warfare, due to a lack of internal warfare and greater access to warriors (brothers and husbands), while the patrilocal communities go extinct. But this is in agreement with Divale's formulation, where he suggests that a switch to matrilocality is an adaptation to external warfare.

1.3.4 Relationships to other theories

While both authors chose warfare, they both assumed different effects of warfare. According to Ember, warfare masked a division of labour and thus it is the division of labour, in the absence of internal warfare (need to protect against neighbours) that drives the choice of residence. Divale's theory on the other hand presumed a relatively direct effect of warfare: increased warfare losses in villages at the periphery caused a need to replace warriors to save them from destruction. In this situation, fathers would be forced to persuade their sons-in-law to come and live with them and protect them, which is not outside the realm of possibility (Zhang, 2008), especially since in pre-state societies, the sex ratio is usually in favour of males (Divale and Harris, 1976), and so such fathers would have access to a number of unmarried low-status males willing to accept this in exchange for a wife or two (in the case of sororal polygyny). Thus Divale's theory is in fact a "warfare theory of matrilocality". However, Korotayev (2003) mentions that another factor can be masked by this relationship, male absence (Harris, 1997), since purely external war often means a long absence of males from their villages. When males are absent from their villages, it usually interferes with their contribution to subsistence, and when it does not, as in the case of pastoral societies, then the residence is often patrilocal (Ember and Ember, 1971).

Male absence and warfare losses interfere with another factor, paternity certainty. If a widow marries again, children from her first marriage would almost surely not be from her present husband, as was common for Iroquois (Brown, 1975; Martin and Voorhies, 1975), where males were often away hunting, trading and fighting. Thus even if the paternity certainty factor by itself is not strong enough, in practice it is often compounded with warfare, division of labour and male absence.

Finally, Jones (2011) points out the similarity with the *Meta-ethnic frontier theory of state formation* (Turchin, 2003, 2006, 2009), according to which states develop along ethnic borders to gain specific identity, while according to Divale, matrilocality is adopted along such borders if the population is small enough. Jones suggests this matricentric social organisation might form one type of demic (i.e., population) expansion (the other being a segmentation of patrilineages) and thus, while not being a *more primitive stage of existence*, it might certainly be a *phase* of existence during demic expansions, such as Austronesian expansion in Southeast Asia and Oceania, Bantu expansion in Central and South Africa and Na-Dene expansion in North America.

1.4 Difficulties in post-marital residence research

There are two major hurdles that stand in the way of attempts to solve the question of how post-marital residence evolves and, in fact, cultural evolution as a whole. The first, and probably the most prominent one, is the lack of data for major historical processes. Often, data quality is poor and patchy and/or its reliability is dubious or the classification in databases in unclear. The second problem is the complexity of cultural evolution.

1.4.1 Data quality and acquisition

Patchy data are the result of the nature of historical processes, and while some societies have left us with a number of historical documents, they often describe political figures, famous battles or religion, rather than the everyday life of common people. If society did not possess writing, we often have to rely on descriptions by other civilizations (such as the Greeks or Romans) or archaeological evidence, and while post-marital residence can be partially determined from the shape and size of a living area of household (Divale, 1977), the finer details, as well as information on related factors, are lost.

During an age of colonisation, the local authority often had little understanding of, or interest in, preserving native populations and their style of life. Thus, even through explorers, priests or even ethnographers provides detailed notes on the life of natives, their further study would be often impossible, as they were either assimilated into colonial culture (forcibly or willingly) or killed, a fate of many tribes in both Americas or Australia (Starn, 2011; Bates, 2010).

Where historical documents are present, they must be carefully evaluated, since they were often not written by people trained in anthropology, but by explorers or priests, lacking the training to properly document and classify native society. Even in a situation when trained anthropologists were present and lived in a native society for an extended period of time, they might have misinterpreted or misrepresented some facts. Such an example is Napoleon Chagnon, who documented Amazonian Yanomamo, and classified their society as highly war-like, although it might have been his presence, iron tools that he gave as gifts and protection that he offered with his shotgun, that made the Yanomamo more warlike (Ferguson, 1995). Another infamous example is Margaret Mead's *Coming of age in Samoa* (Mead et al., 1943). In this book, Mead described a free sexual culture of young Samoan girls, where flirting or even sexual intercourse was not unusual among teenage girls. Derek Freeman however accused her of projecting her own ideology, misinterpreting her data and even believing lies of teenage girls (Freeman et al., 1983). According to Freeman, who studied and lived among Samoans, Mead could not even speak the local language properly, as evidenced by many spelling errors in her work. However, it was pointed out that the differences between data collected by Mead and Freeman could be explained by difference in location (both studied different part of Samoa), time (40 years later, during which time Samoa adopted Christianity) as well as perspective (where Mead talked predominantly with young females, Freeman was often closer to village chiefs). And while Mead might have made a lot of errors in her research (Orans, 1996), Freeman style of critique was rather unusual (Marshall, 1993) and in his critique, he often misinterpreted and cherrypicked Mead's data (Shankman, 2009). Still, Goodenough (1956) presents an example where even when scientists did their best to collect and interpret data, their classifications of post-marital residence might differ.

1.4.2 Complexity of cultural evolution

Even relatively simple societies are already very complex systems, as demonstrated by the number of factors that could be responsible for changes of post-marital residence. Since residence forms a central structure by forming a relationship network, it is influenced by, and influences, many factors. A related problem to complexity, in the absence of data, is the causality of effects. Due to the patchy structure of data and their complex nature, it is often impossible to estimate a causal direction. As again demonstrated by post-marital residence, either residence causes patterns of warfare, or warfare causes a change of residence. Alternatively, change in the residence might have been caused by the absence of males or absence of males caused a change in the division of labour and this caused change of residence. Or it was frequent warfare that caused a prolonged absence of males, which caused a change in residence, and change in the division of labour is just an effect of the absence of males that are not connected to the change of residence and thus the absence of males serves as a hidden variable. However, due to the absence of data from a number of different time-points, to prove a causal relationship, data from different cultures in a different stage of existence needs to be used (Divale, 1984), which complicates the matter, since different cultures have different histories, structures of society, and ecology.

1.5 Modelling human societies

Mathematical models are a description of a system using mathematical language. In contrast to verbally specified models, mathematical models offer a more precise description of causes and effects, explicit rules and also the size of the expected effect. They are also a great tool against narratives (Guillot and Cox, 2016), since if we think that certain factors are relevant, then the model should produce observable behaviour, and by explicitly weighting the probability of each scenario or parameter value (i.e., calculating likelihoods and comparing them using the likelihood ratio test, if the models are nested, or using Akaike/Bayesian/deviance information criterion).

The first models that described human populations were probably Malthusian growth, an exponential model of growth where the population is not bound by the environment or available resources (Malthus, 1798), and logistic growth, where the population was bounded by the environment and available resources, a *capacity of the environment* (Verhulst, 1845). Nowadays, models of human population are widely used in economic (Bonabeau, 2002), sociology (study of human behaviour on social media: Gilbert and Karahalios, 2009, research on sexual networks: Bearman et al., 2004), and even biology and anthropology (especially population movement: Liu et al., 2006; Lansing et al., 2011, or evolution of collaboration: Axelrod, 1997), while mathematical models describing cultural evolution, outside language, are still relatively uncommon (Creanza et al., 2017).

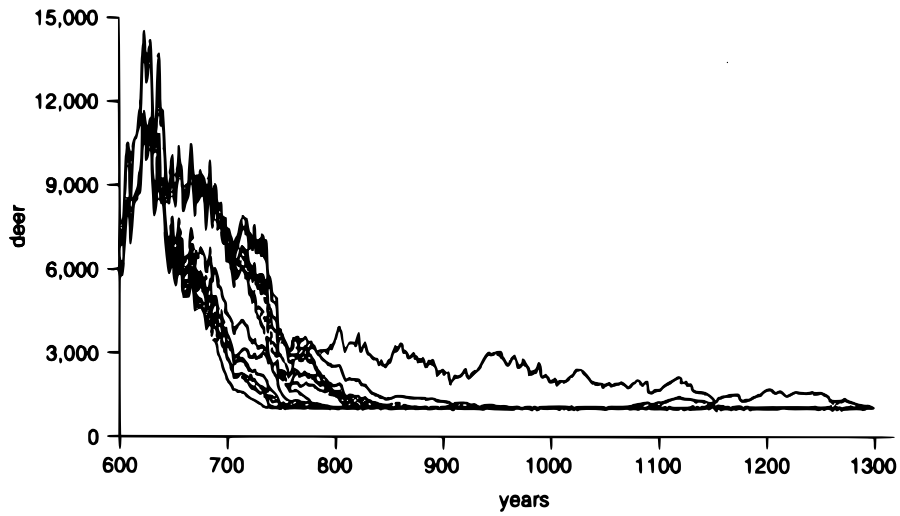

Figure 1.6: The deer population in the Mesa Verde region from 16 runs of an agent-based model. While the population peaked at around 14 000 deer, they quickly became overhunted, forcing local Puebloans to adopt a new source of protein, possibly a domesticated turkey. From Kohler et al. (2008)

1.5.1 Examples

Village Ecodynamic Project (VEC)

Around 2002, a group of archaeologists, geologists, geographers and computer scientists formed the Village Ecodynamic Project, a project that studies ancient sites of ancient Puebloans located in the south of the USA using various mathematical modelling techniques and using archaeological, geographical and ecological data to inform these models. This spawned a wide range of interesting publications, ranging from investigation of the relationship between warfare and population density (Kohler et al., 2009), a consumption and renewal of firewood, which suggests that it might be one of the limiting resources in the region (Johnson et al., 2005), simulation of the effect of food exchange networks on the population during drought (Crabtree, 2015) and the estimation of population density through archaeological data, such as tree rings, amount of pottery found and the number and size of residences (Ortman et al., 2007). The Village Ecodynamic Project is truly a unique project, studying a single, although significant, area through a vast number of different models and in particular, utilising a significant amount of archaeological evidence to inform their models, which is rather unusual.

Rise and fall of empires

Peter Turchin, an ecologist turned historian, is applying mathematical modelling to historical processes, aiming to explain general patterns in history. With an interest in the development of states (Turchin, 2003, 2006, 2009), Turchin and colleagues are trying to explain the rise and fall of empires through warfare, technology and interaction between settled farmers and nomadic pastoralists. Turchin tried to explain a cyclical effect of warfare as an effect of population density, with warfare intensity lagging behind (Turchin, 2003; Turchin and Korotayev, 2006). This relationship enables warfare to increase even when the population is decreasing, in which case warfare continues due to an act of revenge, and thus populations will be significantly depleted or even go extinct. Another interesting example is his spatially explicit simulation of technological development (Turchin et al., 2013).

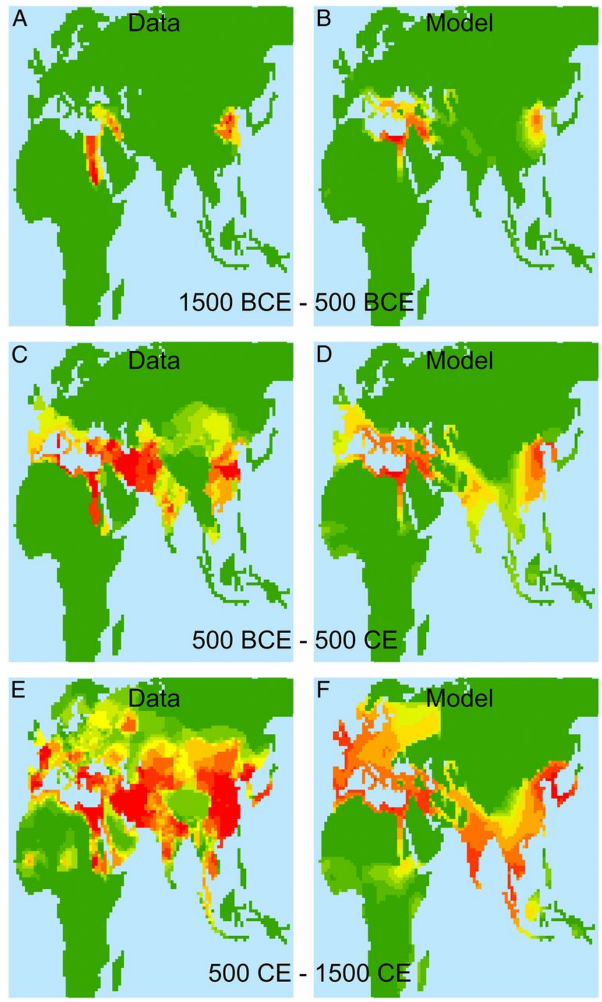

Figure 1.7: Turchin et al.'s 2013 model of formation of empires. Comparison between data (A, C, and E) and prediction (B, D, and F) for three historical eras. Colour coding shows frequency of empires over time and repeated runs. Red shows frequent empires, yellow less common and green an absence of states. From Turchin et al. (2013)

Ten years ago, Turchin's work was covered in a number of popular science media, his attitude to modelling history was compared to Hari Seldon's Psychohistory, a fictional science from Foundation by Isaac Asimov (unfortunately, the name Psychohistory was already taken, so Turchin named his new journal Cliodynamics). However, many criticism came upon his head since his first models were relatively simple (Spinney, 2012), usually, population models derived from biology, which ignored the great complexity of human culture and his emphasis on cycles might have reminded some of the Hegel and Marx spiral theory of human development. Only time will prove if they were right or wrong, but some of Turchin's later research shows interesting developments.

Moralizing high gods

Another approach to cultural modelling is represented by the group around Russell D. Gray. Language evolution and phylogenetic analysis is at the centre of interest of this group (Dunn et al., 2011), but not due to languages themselves, but because language trees carry information about the demographic history of human populations (Gray and Atkinson, 2003) and are useful in the research of cultural evolution (Greenhill et al., 2009; Gray et al., 2010). Using these methods, various facets of cultural evolution can be researched, such as the evolution of complexity (Currie et al., 2010) or the effect of high moralising gods (Watts et al., 2015). Through these methods and extension of the Ethnographic Atlas named *D-place*[3], this group continues in the tradition established by Murdock and others, extending their approach with new datasets and modern computational approaches.

1.5.2 Agent-based modelling

An agent-based model (ABM) is a class of models that utilises a large number of agents, actors or individuals, each behaving individually. Through interactions between the agents, ABMs are used to identify emergent behaviours and thus even a simple ABM with a few rules is a complex system. ABMs have several significant advantages (see e.g. Bonabeau, 2002, for discussion):

- a complex behaviour of agents can be implemented and modified relatively easily, giving a great flexibility
- where a lot of other types of model struggle to represent a spatial dimension, this comes naturally to agent-based models
- through their individual-based form, they are ideal for the representation of individual humans, which makes building rules and interpretation of result more convenient

However, some of the strengths of ABMs create weaknesses. The flexibility of ABMs makes their validation, comparison to real data or just processing their results a complicated task. First of all, as with real systems, the output of ABMs is summarized in the form of summary statistics and the choice of summary statistics must well represent the dimensionality of the system. Due to a large number of possible behaviours and complex parameter interactions, a great range of parameters needs to be explored. However, more complex ABMs have often significant computing cost. Finally, while the acomparison of summary statistics from model and summary statistics from real data can be done with techniques such as Approximate Bayesian Computation (Tavaré et al., 1997), ABMs are often not complex enough to represent real data well and the computing cost of more complex ABMs prevents this. Instead of model fitting, ABMs are usually used to explore mechanisms and effects of individual decisions (Matthews et al., 2007). Despite these caveats, a well-constructed ABM allows the interactions between variables to be evaluated, and models of complex interacting agents to be constructed with relatively low research cost.

Agent-based models in Anthropology

Agent-based modelling in social sciences have a long tradition. One of the first ABMs simulated was Schelling (1971) segregation model. Using this model author challenged the notion that the segregated communities are the result of prejudice and instead showed how this can be an effect of agents wanting just a few neighbours similar to them. This model wasn't even a computer model, instead, the author manually repositioned coins according to a simple set of rules. Another famous example involves a model of hunter-gatherers decision making (Mithen, 1987, 1988). In this model, hunter-gatherers can choose to pursue particular resources based on their previous encounters or information obtained from their kin. However, over-hunting particular resource depletes it and decrease the probability of successfully encountering it. The agents have to thus adopt a particular strategy of pursuing certain resources to maximize their yields. In time ABMs gained on popularity and publication such as *Growing artificial societies* (Epstein and Axtell, 1996) provided a general guide to building artificial societies.

[3] accessible at `https://d-place.org`

Another breakthrough came with an introduction of two models simulating the Anasazi communities, the Village model described above (Kohler et al., 2000) and the Long House Valley model (Axtell et al., 2002). Both models utilized detailed information about the landscape and simulated a soil degradation to simulate ancient Puebloan population in Southwest of U.S.A. Both of these models not only showed how to utilize a large amount of detailed archaeological information but were able to present results in an easily approachable format.

According to Sun et al. (2016) ABMs can be divided into two types, complex data-driven models relying an extensive demographical or geographical information, such as soil erosion (Barton et al., 2010; Kolm and Smith, 2012, e.g.,). A famous trendsetter was the Village Ecodynamic Project mentioned in the previous section (for review see A. et al. 2012). For example, Balbo et al. (2014) simulate the interaction between monsoons and population dynamics in the Gujarat province of Northwest India. Three groups of entities are simulated: climate (precipitation patterns), environment (ground model and resources) and agents (hunter-gatherers) that interact with the environment. The environment is simulated as a lattice with data obtained from Landsat satellite imagery. The climate is simulated from historical precipitation data from the period 1871 to 2008. Interaction between ground and climate models set up the overall biomass available for groups hunter-gatherers and their size was then observed. The model of diffusion of human cultures with the spread of farming from Lemmen and Gronenborn (2018) does not utilize satellite imagery, but the geographic region, Europe in this case, was divided into regions based on their net primary productivity derived from climate, rainfall and latitude. The model then simulates populations with evolving technology, economic diversity and agriculture. In these cases, the results are often directly comparable to archaeological records.

The other models mentioned by Sun et al. (2016) are “toy” models. They do not rely on any extensive information and have often much simpler structure as they simulate only the specific part of the problem and do not try to closely replicate reality. Instead, they are used as a tool to understand some underlying principles that arise from the interaction of several rules. A good example of this type of models is the above-mentioned segregation model Schelling (1971), but these model do not need to be so simple. For example, the model of complexity of tribal polities (Gavrilets et al., 2010) simulates hexagonal grid with communities that can wage warfare and subdue each other, getting control over defeated opponents. However, losing war or death of leader can cause subdued communities to rebel and gain freedom. Authors then describe a cyclical pattern of the rising complexity of polities followed by their dissolution when factors such as the ability to store resources or unequal yields are present. Another example might be a model of out of Africa expansion described by Hölzchen et al. (2016). A detailed environment is still simulated, it is, however, randomly generated and instead of comparing the model outputs to real archaeological data, authors are trying to understand the way human population might spread based on the preference of different ecological niches that are distributed in the environment and the presence of various geographical or ecological barriers.

ABMs in Anthropology are well established field with a high-quality journal JASSS[4], while also being regularly published in other classical anthropological journals. However, ABMs was not yet used to explore the evolution of post-marital residence.

1.6 Classification of post-marital residences

The basic and most general classification of post-marital residence (PMR) is into four states: matrilocality, patrilocality, ambi- or bilocality and neolocality as described in section 1.1. Apart from those four, avunculocality, a type of residence where a pair resides with or near a husband’s matrilineal uncle, is often added to form 5 common residence rules. However, these are very generalized classifications. Human behaviour is incredibly complex and there are many variants and forms of each PMR and various authors considered different aspects to be more or less important, so a range of other schemes classifications

[4] `jasss.soc.surrey.ac.uk/`

emerged. By exploring them we will better understand the concept of post-marital residence. This is immensely important during data collection, when a careful interpretation of ethnographies is required (as is done in Chapter 2), model development (Chapter 4) and interpretation of results from analyses. For example, Murdock (1949), in his *Social Structure*, distinguishes six different residence types:

Matrilocal residence "If custom requires the groom to leave his parental home and live with his bride, either in the house of her parents or in a dwelling nearby, the rule of residence is called *matrilocal*." (Murdock, 1949, page 16)

Patrilocal residence "If, on the other hand, the bride regularly removes to or near the parental home of the groom, residence is said to be *patrilocal*." (Murdock, 1949, p16)

Bilocal residence "Some societies permit a married couple to live with or near the parents of either spouse, in which case such factors as the relative wealth or status of the two families or the personal preferences of the parties to the union are likely to determine whether they will choose to reside matrilocally or patrilocally. The rule of residence in such cases is termed *bilocal*." (Murdock, 1949, p16)

Neolocal "When a newly wedded couple, as in our own society, establishes a domicile independent of the location of the parental home of either partner, and perhaps even at considerable distance from both, residence may be called *neolocal*." (Murdock, 1949, p16)

Avunculocal residence "A fifth alternative, which we shall term *avunculocal* residence, prevails in a few societies which prescribe that a married couple shall reside with or near a maternal uncle of the groom rather than with the parents of either spouse or in a separate home of their own." (Murdock, 1949, p17)

Matri-Patrilocal "The Dobuans of Melanesia reveal a special combination of matrilocal and avunculocal residence whereby the two rules alternate with one another, periodically, throughout the married life of a couple. A more frequent compromise consists in requiring matrilocal residence for an initial period, usually for a year or until the birth of the first child, to be followed by permanent patrilocal residence. For this combination, which is really only a special variant of patrilocal residence, we propose the term *matri-patrilocal* as preferable to 'intermediate' or 'transitional' residence." (Murdock, 1949, p17)

However, later in his *Ethnographic Atlas* (Murdock, 1967), a database of cultures, Murdock distinguishes 10 different types of residence:

Patrilocal Newly-wed pair resides with or near the husband's patrilineal kin.

Virilocal Like patrilocal, but patrilineal kin groups are absent.

Matrilocal Newly-wed pair reside with or near the husband's matrilineal kin.

Uxorilocal Like matrilocal, but matrilineal kin groups are absent.

Avunculocal Newly-wed pair resides with or near husband's maternal uncle.

Bilocal (Ambilocal) Newly-wed pair resides with or near either husband's or wife's family according to their choice.

Matrilocal-Avunculocal option Like bilocal, but the choice is limited to matrilocal and avunculocal residence.

Avunculocal-Virilocal option Like bilocal, but the choice is limited to avunculocal or virilocal residence.

Neolocal Newly-wed pair establishes a new independent residence away from both husband's and wife's families.

Duolocal Both husband and wife remain separated, living in their original residences.

It is important to note that patrilocality and virilocality or matrilocality and uxorilocality do not differ in the type of residence that is taken after marriage. What differs is the existence or nonexistence of a specific kin-group. Those are created by tracing descent through the male line (patrilineal), female line (matrilineal), both (bilineal) or choice of mother's or father's lineage (ambilineal) – so-called descent rules. Thus, if we define patrilocal residence as a residence with or near a husband's family or kin and matrilocal residence as a residence with or near a wife's family or kin, then Murdock's definition of patrilocal, virilocal, matrilocal and uxorilocal will be as follows:

Patrilocal per Murdock patrilocal residence and patrilineal descent

Virilocal per Murdock patrilocal residence but not patrilineal descent

Matrilocal per Murdock matrilocal residence and matrilineal descent

Uxorilocal per Murdock matrilocal residence but not matrilineal descent

Thus, this description partially describes descent rules as well. However, this distinction is not kept in literature and usage of patrilocality/virilocality and matrilocality/uxorilocality is mostly dependent on the author's personal preferences.

Sometimes, two authors use the same name for residence with different meanings. For example, Kramer and Greaves (2011) classify Venezuelan hunter-gatherers Pumé into 4 distinct types of residences: virilocal, uxorilocal, neolocal and natalocal. In this case however, natalocality was used in the meaning of natal village, irrespective of with which kin pair newly-weds established their residence, since the study examined the dispersal of both males and females across different villages. However, other sources use natalocal (or natolocal) as a name for duolocality or its variant (Fox, 1979; Huber and Breedlove, 2007; Mattison, 2016). Similarly, ambilocal or bilocal residence is sometimes used for situations where a pair periodically alternate between both patri- and matrilocal residence (Barnes, 1960), the non-alternating meaning as per Murdock's definition is then assigned to the other from this pair. Probably the least-used term is utrolocal residence (Freeman, 1955), a special case of ambilocal residence where several children of both sexes bring their partners to their parent's residence. It is used almost uniquely for the Ibans of Borneo.

Another type of residence that is mentioned by Murdock (1949) is matri-patrilocal. This residence type starts as matrilocal, but after some time (usually a year or after the first child is born) it switches to patrilocality. In the Ethnographic Atlas (Murdock, 1967) Murdock decided to distinguish between residence in the first year of marriage and after the first year altogether. However, in the overwhelming majority of cases in collected samples in Ethnographic Atlas, the residence is either not different from later years (in 1003 cases) or matrilocal (in 204 cases from total 1243 sampled societies with known values), which shows the relevancy of the special cases in the form of matri-patrilocal residence.

1.6.1 Conceptual problems in classification

These terminology issues should not pose any significant problem if, during re-examination of a text or data source, each author's definitions are used and then transformed properly. However, a more conceptual problem arises during the examination of ethnographies, a problem that might have a significant effect on data collection and thus data quality. As Barnes (1960) notes, there is a distinction between residence rules and the actual residence that is taken. For example, if we limit ourselves to matrilocal and patrilocal marriages and exclude special cases like avunculocal, duolocal marriages or alternating bilocal marriage, we can write these residence rules:

Patrilocal rule where most marriages are patrilocal

Ambilocal rule where patrilocal and matrilocal marriages occur in similar proportion

Matrilocal rule where most marriages are matrilocal

We get three residence rules, however there were only two underlying marriage residence types. Thus if a researcher recorded a number of marriages per period of time, they would have to infer a residence rule from realized marriages.

Further confusion can arise when this inferred marriage rule is confronted with traditional residence. For example, imagine a society where the traditional residence is patrilocal. However, due to economic pressure, i.e., due to lack of farmland, a significant portion of males are marrying matrilocally to a daughter (only child) who would inherit her father's field. In this situation, if an informant was questioned for a traditionally taken residence, the result would be a patrilocal society. However, if an ethnographer instead collected data for a longer period of time, they might conclude that the society is ambilocal. This shows a possible problem that might arise when a conclusion about residence rules is made during a short period of time or when historical records are examined. This demonstrates the conceptual difference between a traditional residence, what I call here an inferred residence, and an actual residence taken after marriage by a pair, all which are called by the same term "post-marital residence".

1.6.2 Definitions used in this work

In this work, unless stated otherwise, I will consider only four residence states: matrilocal, patrilocal, ambilocal and neolocal residence. I understand these residences as majority rules, i.e., the most common residence in these cases are: matrilocal, patrilocal, matrilocal and patrilocal with similar frequency, and neolocal residence.

1.7 Content of this work

In this chapter (Chapter 1), I have explored a history of post-marital residence research to get a deeper understanding of all factors, thoughts and theories that were explored during the past 150 years of anthropological inquiries and I had inspected more deeply several popular theories of post-marital residence, namely the *Warfare Theory of Matrilocality* (Ember and Ember, 1971) and the *Migration Theory of Matrilocality* (Divale, 1974) which will be a target of deeper interest in following chapters. I have also explored successful examples of different approaches to computer modelling in anthropology with a special emphasis on ABM model.

I have then explored different classifications of post-marital residence to gain a better understanding what is being classified. Human behaviour varies greatly even inside a single society, and with a cross-cultural comparison, great care needs to be taken to analyse and distinguish individual aspects of societies. Different authors have different points of view on the classification of expressed behaviour and this will also show in the data. By exploring these classifications I have revealed possible problems and intricacies with the post-marital residence classification that could prove to be important in following chapters when the results of analyses are being interpreted.

Chapter 2 reconstructs post-marital residence evolution by simulating its evolution backward on language trees. This is performed for five different language groups to investigate the patterns of residence evolution and ask whether there is a global pattern, such as if different language groups share a similar pattern of evolution or if ambilocality serves as a transitional state between patri and matrilocality. This chapter was published as *Post-marital residence patterns show lineage-specific evolution* in Evolution and Human Behaviour (Moravec et al., 2019)

Chapter 3 utilises data-mining techniques to describe the structure of data in the Ethnographic Atlas, a major anthropological database. This is done to better describe and understand the relationships between societies, their properties, such as hunting or sex differences, and post-marital residence. Existence of a small number of clusters with different residences would mean that the old division into hunter-gatherers, horticulturalists and pastoralists is not sufficient, especially to describe groups with shared post-marital residence pattern and that the post-marital residence can exist in a different functional context. The clusters gained from the analysis were then investigated with respect to several important variables that determine the major forms of societies: sedentary status, type of agriculture, main source of subsistence and population density. These patterns were then compared to the cluster residence distribution.

Chapter 4 builds an agent-based model of residence change based on the *Warfare Theory of Matrilocality* and the *Migration Theory of Matrilocality*. This chapter describes these theories from a modelling point of view, analyses their plausibility and unify them under a common framework. This unified theory is then transforms into an agent-based model which is then evaluated. This chapter was published as *Warfare induces post-marital residence change* in Journal of Theoretical Biology (Moravec et al., 2018).

Chapter 5 explores possible extensions of the model from chapter 4 that would result in a more detailed simulation. The chapter also includes discussion and description of various modelling decisions required to represent various aspects of the model original model.

Chapter 6 then summarizes the results from previous chapters and comments on the state of current post-marital residence research. The chapter concludes with some ideas and suggestions for future investigations.

This work is not meant to provide the conclusive evidence of dynamics or factors influencing post-marital residence change. It should be seen as a computational investigation of post-marital residence with new methods and an attempt to discover previously unseen or unrecognised patterns and so provide a different point of view on commonly discussed theories of residence change.

2. Simulation of Post-Marital Residence on Language Trees

2.1 Preamble

One of the major problems of the study of post-marital residence and cultural evolution in general is a lack of data on a time-progression of immaterial culture, except when the changes in native culture were both documented and induced by colonising European settlers (Divale, 1984). In biology, a similar problem was solved using phylogenetic trees, graphs showing evolutionary relationships, usually inferred from DNA. The inferred tree can then be used to simulate the evolution of other traits, be it discrete (Pagel, 1994) or continuous (Pagel, 1999). A similar methodology was suggested for cultural evolution, a phylogenetic tree reconstructed from languages (Mace et al., 1994; Mace and Holden, 2005). Evolution of languages shares a lot of commonalities with the evolution of DNA (Cavalli-Sforza and Feldman, 1981; Cavalli-Sforza, 1997) and thus well-understood methods can be used (Pagel, 2009). More importantly, the most commonly used data source, the Swadesh list (Swadesh, 1952) offers several significant advantages. Swadesh (Swadesh, 1952) chose words that form a core of vocabulary, are not related to environment or technology and are present in all languages (Embleton, 1986). They are also remarkably stable, which makes the estimation of ancestral branching events possible (Pagel, 2009). Given that both language and culture are primarily transmitted through family (Mace et al., 1994), language trees can be used as a proxy for the branching and evolution of cultures, and evolution of a cultural trait can be simulated on that tree, especially where both language and cultural trait of interest are transmitted vertically through family, rather than horizontally by adoption from other cultures (see Gray and Watts, 2017).

This chapter was published as *Post-marital residence patterns show lineage-specific evolution* (Moravec et al., 2018)

2.1.1 Author contributions

The primary study design, simulation of post-marital residence on language trees, followed previously published work (Jordan and Mace, 2007; Jordan et al., 2009; Fortunato and Jordan, 2010; Opie et al., 2014), all follow-up comparative analyses, their design and interpretation, were performed by me as well as the majority of text with heavy contributions of M.P.C. and S.M., the PhD supervisors. Text was then revisited after comments from other authors.

In the paper, the author contributions are as follows: **J.C.M.**, Q.A., S.J.G., R.G., S.M. and M.P.C. designed the study, Q.A., C.B., S.J.G., R.M.R. and R.G. provided data, **J.C.M.** performed analyses, and **J.C.M.**, Q.A., C.B., S.J.G., F.M.J., R.M.R., R.G., S.M. and M.P.C. wrote the manuscript.

2.1.2 Aim

Simulation of post-marital residence on language trees was done previously for the Austronesian (Jordan and Mace, 2007; Jordan et al., 2009; Fortunato and Jordan, 2010), Indo-European (Fortunato and Jordan, 2010) and Bantu (Opie et al., 2014) language families. However, each language tree was estimated in isolation. The only attempt to compare two language families and their patterns of post-marital residence evolution were by Fortunato and Jordan (2010), where an attempt to compare Indo-European and Austronesian results was made, but normalizing rates to one arbitrary rate and then comparing those normalized rates seems to ignore the mathematical interpretation of rates. This chapter aimed to correct this, gather a larger sample of language families covering a significant part of the world, estimate their pattern of post-marital residence evolution and perform a cross-cultural comparison by comparing individual patterns of residence change across trees. In total, five language trees were analysed and compared: Austronesian (South East Asia and Oceania), Bantu (Central and South Africa), Indo-European (Europe and Asia), Pama-Nyungan (Australia) and Uto-Aztecan (North America).

2.1.3 Methods

To simulate the evolution of residence states on a given language tree we have used the same methodology that is used to estimate a phylogeny from DNA (Pagel, 1994), utilizing Felsenstein's tree likelihood (Felsenstein, 1981). The difference is that when using a language tree, the topology and branch lengths are known and do not need to be co-estimated, which would be impossible since residence is only a single symbol (residence state), while DNA data is usually in thousands (nucleotide bases). The method works by simulating the evolution of residence along a branch using a rate matrix. The rate matrix specifies the rates of transitions from one residence state to another. This, together with the length of a branch, gives a probability vector of the society being in a particular residence state after the evolutionary time, represented by the length of a branch. Using this, we can calculate the probability distribution of all represented residences for each node on a language tree given the particular residence matrix, and calculate the likelihood of the tree, a probability that we will observe the estimated evolution of residence for a given rate matrix. By comparing these likelihoods, one can find the most probable scenario and thus the most probable rate matrix, an underlying pattern or rule for post-marital residence evolution.

Comparison of rate matrices

Rates can be directly compared if they share the same time scale. By estimating rates on language trees where branch length represents lexical evolution, the estimated rates are per lexical change, a changed amount of words per collected cognate lexicon. Under this assumption, we can compare rates of residence change between language trees and thus compare how residence evolves with respect to changes in languages.

One way to compare the pattern of change is to try to fit the rate matrix to the tree and data. Additionally, we can decompose the rate matrix Q into the modified rate matrix Q', $E(Q') = 1$, and the rate of change μ, $Q = \mu Q'$. This way we can compare both Q', a pattern of change, and μ, speed of changes, separately. See the paper for a more detailed description of all used methods.

2.1.4 Results

There was no apparent common pattern found among the studied language families. Both the direction and the magnitude of rates were significantly different in each language tree. This was further confirmed by fitting the rate matrix and modified rate matrix estimated on other datasets to the tree and residence of each dataset. The only rate matrix that fitted well in different datasets was the modified Austronesian rate matrix with the Uto-Aztecan dataset.

2.1.5 Discussion

While non-existence of a common pattern between language families is not that surprising, as the prevailing theories suggest that residence is more dependent on local ecological conditions, such as female-dominated agriculture, male-dominated hunting or herding (Ember, 1967; Ember and Ember, 1971; Divale, 1984; Korotayev, 2003; Ember, 2011), some of the finer details are a bit unexpected or further confirm patterns that were suggested in previous studies (Jordan et al., 2009; Fortunato and Jordan, 2010; Opie et al., 2014). We could not observe any direction of residence change as suggested by Divale (1984) (i.e., patrilocal → matrilocal → ambilocal → patrilocal). Another unexpected result is that language groups that experienced a big agricultural expansion (Bantu, Indo-European and Uto-Aztecan) showed a significantly different pattern, both in the speed and direction of residence evolution.

Evolutionary time

We used branch-time in lexical changes, which hinders some interpretations regarding rate or number of changes of post-marital residence. If branch-time was in real-time instead of lexical time, i.e., if dated trees were used, this would make interpretation much easier, we could talk about time in the natural sense instead of the less-understandable and more abstract *evolutionary time*. This would have numerous advantages, for example, if Divale's time-sequence (Figure 1.5) would be confirmed by analysis, we could directly compare his time with the one estimated from trees. However, dated trees were not used for several reasons detailed below, from scientific to technical.

One of the major axioms of the analysis is that culture can be represented by a tree and that the language trees represent relatively accurate evolution of cultures. While not in agreement with other authors, tying branch-time into the evolutionary time of the underlying process is one less assumption than assuming that the evolution of post-marital residences is independent of the underlying branching process. In other words, using lexical time instead of real-time is more parsimonious. Additionally, the same type of trees (with branch-time in lexical changes) was used in previous studies and since this work aimed to summarize and compare patterns from trees studied previously, it was important to use the same type of data (or in fact, exactly the same data) for validation of results.

As for technical problems, there were two. First of all, data collection was the most time-intensive process and we were not able to collect dated-trees for all datasets. Additionally, one of the collected dated-trees showed erratic behaviour and thus had to be rebuilt without dating. In this tree, while the total branch lengths in a real-time were on a realistic scale (around 10^3 years), the total branch lengths in an evolutionary-time were at least three magnitudes different from the total branch lengths of all other trees. The other technical problem was with the magnitude of rates estimated on dated trees. In the preliminary analysis, the rate of change for dated and non-dated trees was on a similar scale. This is however impossible since the branch-time differed by several magnitudes (10^3). This would imply that even on a relatively short branch of a dated tree, given its magnitude and relatively high rate of change, a large number of residence changes would take place, which contrasts with the relatively conservative estimates in the ethnographic literature, such as 2 in 1333 years according to Divale (1984). Closer inspection would be required to find out if this pattern is due to a bug in the software used, a wrong prior or if it is a true pattern estimated from the data.

Use of mean rate matrix during the comparison between language trees

While comparing rate matrices between language trees, we did not use a full posterior distribution of rate matrices. While it would be better to compare the full distribution, this was not possible for technical reasons: the software BayesTraits (Meade and Pagel, 2014) does not support fitting trees to the Bayesian MCMC sample and I was not able to reproduce the calculated likelihood values from BayesTraits. After personal inquiry, the author of software promised to investigate this matter, but even after providing a repeatable example, the problem was not solved to this date. This is the reason why mean matrix, obtained by averaging all rates from the posterior distribution, was used instead.

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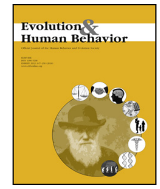

Post-marital residence patterns show lineage-specific evolution

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A B S T R A C T

Where a newly-married couple lives, termed post-marital residence, varies cross-culturally and changes over time. While many factors have been proposed as drivers of this change, among them general features of human societies like warfare, migration and gendered division of subsistence labour, little is known about whether changes in residence patterns exhibit global regularities. Here, we study ethnographic observations of post-marital residence in societies from five large language families (Austronesian, Bantu, Indo-European, Pama-Nyungan and Uto-Aztecan), encompassing 371 ethnolinguistic groups ranging widely in local ecologies and lifeways, and covering over half the world's population and geographical area. We apply Bayesian comparative methods to test the hypothesis that post-marital residence patterns have evolved in similar ways across different geographical regions. By reconstructing past post-marital residence states, we compare transition rates and models of evolution across groups, while integrating the historical descent relationships of human societies. We find that each language family possesses its own best fitting model, demonstrating that the mode and pace of post-marital residence evolution is lineage-specific rather than global.

1. Introduction

The decision about who will leave home after marriage and who will stay – post-marital residence – influences social structures in important ways, including inheritance of property (Agarwal, 1988; Leacock, 1955), household size (Divale, 1977; Ember, 1973), types of marriage, and broader family structure (Divale & Harris, 1976). From an evolutionary perspective, investment in grand-children hinges on factors including co-residence (Sear & Mace, 2008), and differential movements of men and women on marriage even impact genetic variability in sex-specific DNA (Guillot et al., 2016; Lansing et al., 2017).

Post-marital residence states vary widely, but in ethnographically-attested societies worldwide, the most common residence pattern is *patrilocality* (Murdock, 1967), where women move to live with the family of their husband. Nonetheless, other residence practices are also common, the most frequent of which are *matrilocality*, where women remain with their natal community, while men move; *ambilocality*, where a newly-wed couple lives with the family of either the husband or wife; and *neolocality*, where the couple establishes a new residence separate from their respective families.

Importantly, the social norms of post-marital residence that individuals and societies follow – their 'residence rules' – are not static, but change over time. Residence is heavily co-articulated with other aspects of descent, marriage and kinship, but residence itself has commonly been viewed as one of the key driving forces of broader social structure (Murdock, 1949). Consequently, explanations for transitions in post-marital residence tend to focus mostly on external factors, and a number of theories have been proposed to explain when and why residence patterns change. These factors typically invoke major cultural disruptors; behaviours that are sufficiently common globally that they might be expected to influence residence dynamics in universal ways, such as gender-biased division of subsistence labour (Ember & Ember, 1971; Lippert & Murdock, 1931), warfare (Ember &

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Ember, 1971) and migration (Divale, 1974). Conversely, individual choices – of people and communities (Ly et al., 2018) – also play a role in creating these new cultural norms. Here, we set out to explore which of these views is most supported by the data.

There are multiple reasons why a community might adopt a new post-marital residence rule; for instance, ecological changes or technological developments (including transitions to agricultural, pastoral (Aberle, 1961) or wage-labour (Ember, 1967; Zhang, 2008) lifestyles) often change the gender-productivity balance (Brown, 1970), and communities may come to favour the more economically beneficial sex (Ember & Ember, 1971; Lippert & Murdock, 1931; Murdock, 1949). Modelling has suggested that these changes in residence can be evolutionarily stable (Ji et al., 2016).

Warfare can also drive post-marital residence change: war with external parties often disrupts male labour, while feuding within a community can encourage related men to cluster together for protection (Ember, 1974; Ember & Ember, 1971). Villages at war could have high death rates and thus may switch to matrilocal residence, replenishing losses by attracting men from allied villages that are not at war (Divale, 1974, 1984).

It has been suggested that matrilocal societies are more peaceful (Van Velzen & Van Wetering, 1960), with matrilocal bands perhaps acting as a frontier-advancing structure (Jones, 2011). Feuding is common in patrilocal societies (Divale, 1974, 1984; Ember & Ember, 1971; Otterbein & Otterbein, 1965), forcing them to develop explicit peacemaking mechanisms and enacting political integration to reduce infighting. This in turn links patrilocal residence with the increasing political complexity of societies (Ember & Ember, 1971; Murdock, 1949), thus presupposing a global trend towards patrilocality with the rise of polities and states. Ambilocality has been considered to be an adaptive social configuration, especially for forager or hunter-gatherer groups, who rely on a broad resource base (Marlowe, 2004) or are affected by resource instability (Kelly, 1995). While most hunter-gatherers seem to be classified as patrilocal (Ember, 1978) due to their culturally preferred residence, this might contrast with their actual social flexibility.

Finally, human behavioural ecologists have drawn attention to context-specific inclusive fitness considerations that, in aggregate, may shape community-level norms of residence (Kramer & Greaves, 2011; Marlowe, 2004; Scelza & Bliege-Bird, 2008; Wood & Marlowe, 2011). It has been proposed that paternity uncertainty influences post-marital residence (Greene, 1978; Hartung, 1981), where men in situations of high uncertainty may preferentially choose to invest in their sister's children rather than their own. Disentangling inclusive fitness effects on residence from those on descent and inheritance is difficult (Holden & Mace, 2003; Mattison, 2011). Furthermore, the costs and benefits of particular residence norms may vary by the investing sex and over the course of individuals' lives (Wood & Marlowe, 2011). The extent to which such context-specific, individual-level, adaptive forces might scale up, or be generalisable, across different human groups, and thus influence macroevolutionary patterns, is still a topic of investigation.

Generic factors can affect any society. For instance, while particular instances of warfare or migration are geographically restricted, their general trends are often truly global, especially since many geographically-widespread language families have spread through demographic expansions into previously settled regions. Divale (1984, 1974) suggests that while many drivers of residence change appear essentially stochastic, they exhibit cycles of change (for instance, from patrilocal, to matrilocal, to avunculocal and back to patrilocal residence), with each residence change providing the drivers for its successor.

Regardless of the exact causes of residence change, identifying transitions in post-marital residence remains challenging, as they are often hard to observe on a human time scale and leave few direct traces in the archaeological record. While early studies of residence patterns relied on relatively underpowered association tests and correlations methods aim to explicitly model the evolution of post-marital residence through time. By using language trees as a proxy for historical relationships between cultures (Mace & Pagel, 1994), modern phylogenetic comparative approaches can infer ancestral post-marital residence states statistically against a background of phylogenetic divergence within language families (Currie, 2013). Past residence states, and the rates at which societies have transitioned between those different states, can therefore be reconstructed from the present distribution of post-marital residence states using a continuous-time Markov chain within a Bayesian statistical framework (Pagel, Meade, & Barker, 2004).

However, developing methods to analyse patterns across, rather than within, language trees has proven challenging, and to date the evolution of post-marital residence has only been studied using phylogenetic comparative methods – separately – in three language families: Austronesian (Jordan, Gray, Greenhill, & Mace, 2009), Bantu (Opie, Shultz, Atkinson, Currie, & Mace, 2014) and Indo-European (Fortunato, 2011; Fortunato & Jordan, 2010). Now, however, newly available language phylogenies and improved cross-cultural analyses afford an opportunity to undertake the largest investigation of cultural evolution in post-marital residence across multiple language families.

Here, we model transitions in post-marital residence across five language phylogenies, with the aim of testing the hypothesis that a globally common set of processes has governed changes in post-marital residence states. If the processes implied by these theories of residence change operate universally, we would expect to observe similar patterns of residence evolution globally. The alternative is that individual transitions are instead driven primarily by local factors.

2. Materials and methods

2.1. Language trees and post-marital residence data

For cross-cultural comparison of post-marital residence evolution, language families were chosen according to their size and the availability of sufficient linguistic cognate data, resulting in five language families being studied: Austronesian, Bantu, Indo-European, Pama-Nyungan, and Uto-Aztecan. Post-marital residence has previously been analysed individually for the Austronesian (Jordan et al., 2009), Bantu (Opie et al., 2014) and Indo-European (Fortunato, 2011; Fortunato & Jordan, 2010) language families, whose phylogenies and post-marital residence state encodings were obtained from the authors.

For the Uto-Aztecan and Pama-Nyungan language families, a literature search was performed to determine the primary social norm of post-marital residence for each language community (see Supplementary material for details). The Uto-Aztecan language tree was obtained from Ross and colleagues (Ross et al., in preparation), while Pama-Nyungan language data were obtained from the Chirila database (Bowern, 2016) and re-analysed with BayesPhylogenies v 1.1 (Pagel & Meade, 2004) running for 10^7 generations using the *m1p* model, in which cognates are lost and gained at the same rate. Trees were pruned to contain only languages with known residence states. Due to the absence of calibration points, chronological trees were not obtainable for all language families, and tree branches were scaled by the number of cognate substitutions. A posterior tree sample ($500 < n < 1000$) was used for all language families, with variation dictated by the availability of posterior samples for published trees. A summary of residence states observed for each language family is given in Supplementary Table 1. Schematics of the distribution of residence states in the five trees are presented in Fig. 1.

2.2. Transition rates

Some authors (Divale, 1974, 1984; Murdock, 1949) suggest that there may be strong directionality in post-marital residence transitions and thus that some transitions may not occur at all or only at much

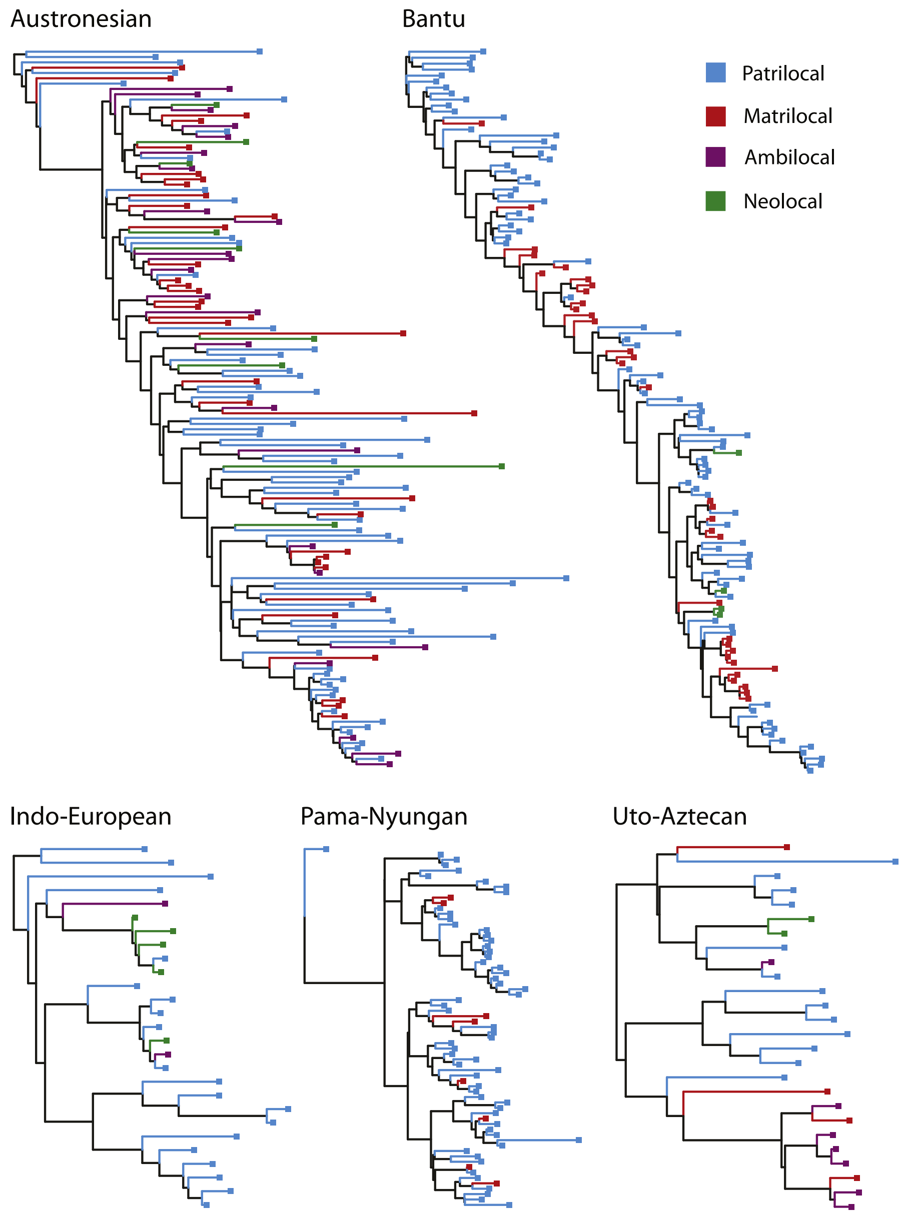

Fig. 1. Ethnographic observations of post-marital residence states mapped on to five language trees: Austronesian, Bantu, Indo-European, Pama-Nyungan, and Uto-Aztecan. Terminal branches are coloured according to the main post-marital residence state recorded for each society. Branch lengths of each maximum clade credibility tree are drawn proportional to the number of observed lexical substitutions. To show the residence states clearly, trees are not drawn to the same scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Monte Carlo (RJ-MCMC) was explicitly chosen to fully explore the complex model space. This method aims to reduce the number of parameters by dynamically setting some to zero, or grouping them under a single governing parameter (e.g., setting all transitions to a single universal rate). Importantly, RJ-MCMC can explicitly test the level of evidence for different patterns and directions of post-marital residence change, which is a feature we exploit below.

BayesTraits v 2 (Pagel & Meade, 2006) was used to calculate the transition rates. Five independent trials of MCMC, each with 10^8 steps, were performed for each language family with a sampling frequency of 10^4 and an exponential prior for the frequency of residence transitions exp(λ). λ was distributed according to the hyperprior $\frac{1}{\lambda} \sim U(0, 200)$ for all datasets except Pama-Nyungan, for which the hyperprior was defined as $\frac{1}{\lambda} \sim U(0, 400)$. These values were chosen from initial maximum likelihood estimates. The convergence of the MCMC runs was explored using convergence tests implemented in the R package coda v 0.18-1 (Plummer, Best, Cowles, & Vines, 2006), and posterior distributions were inspected and summarized using R v 3.3.2 (R Core Team, 2018).

To determine whether each language family has its own mode of evolution, we tested each tree to ascertain whether the transition matrix from any other tree was as good a fit or better to its data. To do so, we calculated the likelihoods of observed residence states for a particular language family tree given the rate matrices of each other language family. From these likelihoods, Bayes factors were calculated by comparing the fit of the original rate matrix with rate matrices estimated from all of the other datasets in pairwise fashion. These values indicate whether the likelihoods are significantly different.

Table 1
Rates of transitions between post-marital residence states. Means and 95% credible intervals are reported (rounded to the nearest integer); dashes indicate transition states that are not observed in a given language tree. Note that zeros were removed from each distribution and are reported separately (see Supplementary Table 2).

	Austronesian		Bantu		Indo-European		Pama-Nyungan		Uto-Aztecan	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Ambi → Matri	123	(10; 292)	–	–	–	–	–	–	28	(2; 72)
Ambi → Neo	106	(10; 267)	–	–	47	(0; 185)	–	–	26	(2; 70)
Ambi → Patri	101	(8; 220)	–	–	55	(0; 235)	–	–	25	(2; 57)
Matri → Ambi	122	(18; 283)	–	–	–	–	–	–	32	(2; 79)
Matri → Neo	66	(6; 218)	3	(1; 6)	–	–	–	–	30	(2; 78)
Matri → Patri	78	(8; 201)	4	(1; 12)	–	–	286	(1; 801)	27	(2; 71)
Neo → Ambi	117	(9; 292)	–	–	48	(0; 188)	–	–	31	(2; 78)
Neo → Matri	110	(9; 295)	10	(1; 51)	–	–	–	–	30	(2; 77)
Neo → Patri	114	(9; 291)	13	(1; 76)	55	(0; 258)	–	–	27	(2; 69)
Patri → Ambi	47	(7; 129)	–	–	38	(0; 185)	–	–	16	(1; 40)
Patri → Matri	63	(6; 172)	3	(1; 5)	–	–	45	(1; 131)	15	(1; 42)
Patri → Neo	27	(5; 71)	2	(0; 5)	83	(0; 334)	–	–	13	(1; 34)
Mean	89		6		54		165		25	

2.3. Simulations

To place rates in a more easily interpretable context, we simulated the number of residence changes on each language tree as defined by its unique transition matrix. Following Huelsenbeck and colleagues (Huelsenbeck, Nielsen, & Bollback, 2003) and using the R package phytools v 0.5-64 (Revell, 2012), 5000 SIMMAP simulations of residence evolution were run using the mean rate transition matrices for each tree. Step-by-step transitions between pairs of states with respect to branch lengths on the maximum clade credibility tree were inferred using the rate matrix Q, as estimated by BayesTraits. Transitions were generated by first drawing time from an exponential distribution according to the diagonal elements of the matrix, followed by choosing the type of transition with probability proportional to its rate. The probability of transitioning from residence state s_i to state s_j is defined as $\Pr(s_i \rightarrow s_j) = {q_{ij}}/{\sum_{k \neq i} q_{ik}}$, where q_{ij} is the rate of switching from state i to j. In other words, probabilities were normalized by the rate of change from the current state s_i to any other state. Estimates of the time to each transition were sampled from an exponential distribution parametrized by the negative of this normalization factor, and samples were drawn until the branch length was reached. To save computation time, instead of sampling from the posterior distribution of the rate matrix calculated by BayesTraits, the posterior distribution was summarized by the mean rate matrix Q, which accounts for zero values in the RJ-MCMC. The total number of simulated transitions in each language family was then normalized by the number of language substitutions (i.e., the total branch length of each tree).

2.4. Scaling dynamics

To test how post-marital residence evolves relative to language branch lengths, a scaling parameter κ (Pagel, 1999) was added to the length of tree branches, such that $t_{\text{new}} = t_{\text{old}}^{\kappa}$. If $\kappa \approx 1$, then the branch length reflects the evolution of post-marital residence, while $\kappa > 1$ or < 1 indicate that longer branches are scaled more than shorter branches. At the extreme, $\kappa = 0$ would suggest that there is no relationship with branch length, and thus post-marital residence would evolve independently of the branches on which changes are observed to occur (i.e., cultural change would be independent of linguistic change).

3. Results

Our analysis focuses on five language families where data are sufficient to explore the evolution of post-marital residence: the previously reported Austronesian (Island Southeast Asia and the Pacific), Bantu data for Uto-Aztecan (Western USA and Mesoamerica) and Pama-Nyungan (Australia) (for a overview of residence states in these datasets, see Supplementary Table 1). Cumulatively, these languages cover over half the world's population and geographical area (see Supplementary Fig. 1). Several of these language families have been associated with Neolithic farming expansions, and they include communities that currently are, or were until very recently, farmers, foragers or pastoralists, with a geographic range from the tropics to temperate regions, and from islands to continents.

We assigned ethnographically observed states of residence pattern norms to contemporary ethnolinguistic groups (Fig. 1). To begin, we tested whether language trees with branches scaled by cognate changes are appropriate for analysing post-marital residence. Branch lengths reflect observed language change and are a proxy for evolutionary time. We rescaled branches using Pagel's κ (Pagel, 1999) to measure the extent to which the observed branch lengths can be rescaled without changing the variability in residence patterns. This simple metric scales all branch lengths by raising them to the same exponent, κ. A value of κ close to zero would suggest that a model with all branches the same length would fit the residence data better; a value close to one provides justification for the current model; while higher values of κ make the tree more star-like, which would mean that the branches effectively have independent random lengths. While inferred κ values (Supplementary Table 9) have large credibility intervals, they strongly centre around 1, supporting the hypothesis that language trees with branches delimited in shared cognates provide a robust basis for inferring post-marital residence change.

From the trees (Fig. 1), it is clear that residence patterns vary widely, even among groups that speak closely related languages. Even a cursory examination suggests great variation in the underlying processes; for instance, not all residence states are found in every language family. Estimated rates of transitions between residence states also indicate differences between language families (Table 1, Supplementary Table 2), with comparatively little change in Bantu in contrast to frequent change in Pama-Nyungan.

Fig. 2 further suggests that patterns of residence change differ between language families. To explicitly test this, we fitted the estimated mean rate matrix for a given tree to every other tree and calculated the likelihood of the fit to the observed residence data. In each case, the tree's own rate matrix fitted significantly better than the rate matrix from any other language family (see Supplementary Tables 3 and 4).

The best statistical support for residence transitions in the language trees occurs from patrilocality to matrilocality, and back. The Uto-Aztecan tree is interesting because there is strong evidence against most directions of residence change (Supplementary Table 2). A benefit of RJ-MCMC, as mentioned previously, is that all directions of change are

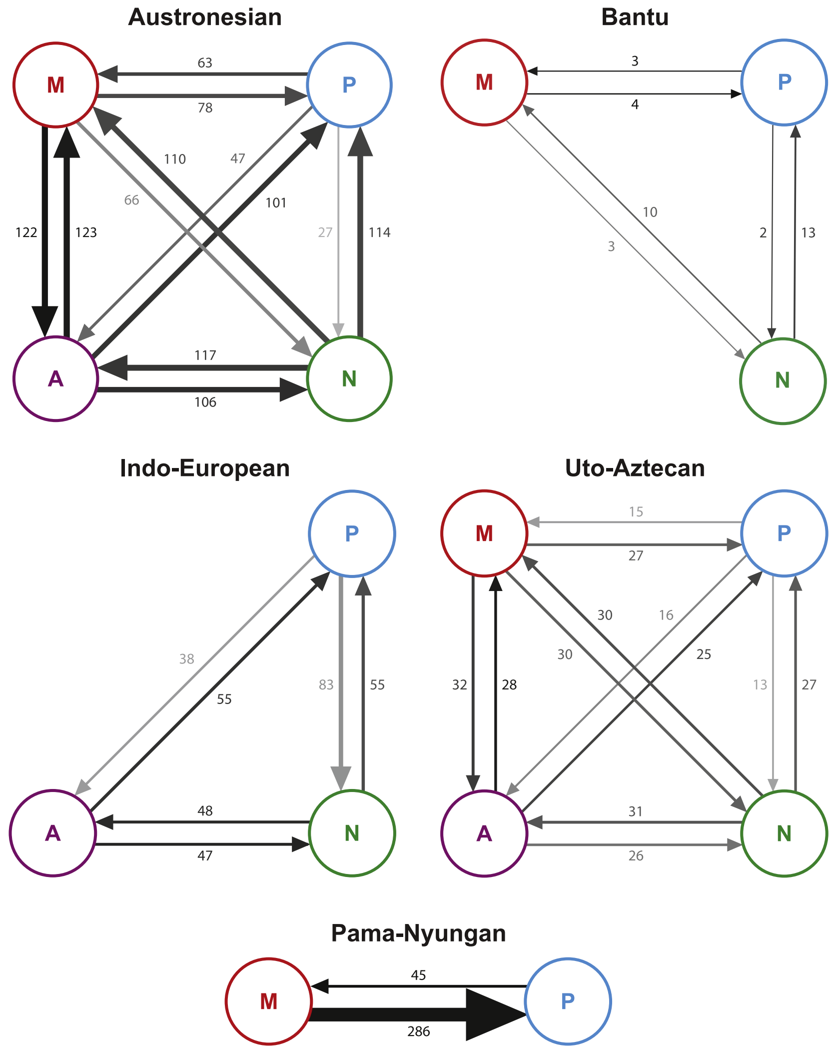

Fig. 2. Graphs showing transition rates between post-marital residence states for each language family. M, matrilocality; P, patrilocality; A, ambilocality; N, neolocality. Arrow weights indicate mean transition rates inferred from the analysis (with values shown adjacent), while shading indicates how frequently the rate is inferred to be zero (lighter shades indicate less certainty). Node colours indicate post-marital residence states, as in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tested explicitly in our models.

SIMMAP (Huelsenbeck et al., 2003) simulations of residence transitions using the observed rate matrices provide additional insight into patterns of change (Supplementary Table 5). In all datasets except Bantu and Uto-Aztecan, several transitions are typically seen to occur along each individual branch. Bantu and Uto-Aztecan are exceptions because estimated rates of residence evolution are low and the number of languages in the tree is small, respectively.

To place these values within a more intuitive conceptual framework, we can make 'back of the envelope' estimates of how these changes map on to the approximate time depth of each language family (Supplementary Table 6). If we assume that the families studied here (or the parts of them represented in the trees) are somewhere around 4000 to 7000 years old, post-marital residence transitions seem to have occurred once along any given lineage every ~425 years in the Austronesian and Indo-European trees and every ~1280 years in the Bantu tree (see Supplementary material). The similar estimates for the Austronesian and Indo-European language families are striking, given that they differ in many key aspects, such as age, magnitude of residence rates and amount of language change. However, the less well-studied Pama-Nyungan and Uto-Aztecan language families give a wider range of values (Supplementary Table 6). More rapid changes in residence in the Pama-Nyungan family might be explained by the fast demographic spread of the language family through Australia, quickly colonizing a wide range of ecological regions (Bouckaert, Atkinson, & Bowern, 2018), as well as the social flexibility of indigenous Australian groups, as evidenced by the rapid spread of 'section' kinship systems (Dousset, 2005).

Across all the trees, there is a tendency for patrilocality to be the most common and persistent state, both from the perspective of simulated transition rates and the time spent in each residence state. 64% of communities are patrilocal, and unlike matrilocality, ambilocality or neolocality, patrilocality appears in all five language trees. The importance of this residence state can be measured by comparing estimated transitions to and from each residence state (Supplementary Table 7), with patrilocality acting as a culturally favoured state (Ji et al., 2016).

Patrilocal residence may stabilize a set of social-structural axes by centralizing both authority and the inheritance of property; for instance, in many matrilocal and/or matrilineal societies, women's brothers still act as heads of household over many decisions (Divale & Harris, 1976; Richards, 1950; Schlegel, 1972; Schneider, 1961). This apparent conflict between descent and decision power was termed the *matrilineal puzzle* by Audrey Richards (1950) (reviewed by Mattison, 2011). However, this does not mean that matrilocality is necessarily unstable or non-favoured (see review by Mattison, 2016), as it is still the second most common state in the Austronesian and Bantu trees. Transitions from matrilocality to patrilocality, and back, and the generally low frequency of ambilocality, suggest that the primary role of ambilocality is not simply as an intermediate state. While ambilocality can occur when the frequency of patrilocal and matrilocal marriages is similar (see Murdock, 1949 and Goodenough, 1956 for field examples), our analyses predominantly support the role of ambilocality as a separate functional state with its own dynamics.

As with transition rates, exploring post-marital residence change through time using SIMMAP simulations (here measured in terms of language change) suggests that patrilocality is cumulatively the most common state, found almost 90% of the time in Pama-Nyungan to around half the time in Austronesian and Uto-Aztecan (Supplementary Table 8). Matrilocality is the next most common residence state, but does not occur at all in the Indo-European family. Neolocality also occurs reasonably often, but the length of time spent in this state is usually short. The exception is Indo-European, where societies are estimated to have spent 23% of their time practising neolocality, which is comparable to the time spent in ambilocal or matrilocal residence in other language families. An unusually high rate of switching is observed from patrilocality to neolocality in Indo-European (Table 1), in line with findings that suggest a special role for neolocality as an alternative residence strategy in Indo-European prehistory (Fortunato, 2011).

Other cultural dynamics unique to particular language families are observed. For instance, transition rates are inferred robustly for Bantu, but are relatively infrequent, as is clear by visual inspection of the tree (Fig. 1). This suggests that there were surprisingly few switches between residence states compared to the other language families in our dataset, which is especially interesting as the Bantu tree is relatively large (here, 120 languages), and yet using SIMMAP simulations parameterized on the transition rate matrix, only 20–36 transitions between residence states were inferred, compared to 255–351 transitions in the Austronesian tree (134 languages). The Austronesian tree also shows evidence for all twelve possible transitions between the four residence states, a property it shares only with the much smaller Uto-Aztecan tree (25 languages). At the other extreme, the Pama-Nyungan tree only exhibits two residence states, patrilocality and matrilocality. However, in contrast to the Bantu tree, a very fast rate of residence change was estimated for Pama-Nyungan, even though relatively few transitions appear on visual inspection of the tree (Fig. 1).

4. Discussion

The analyses presented here represent a new design for tests of evolutionary and cross-cultural hypotheses using cultural phylogenetic methods. Examining the dynamics of post-marital residence in five language families has been made possible by nearly two decades of innovation in the study of language variation via phylogenetic modelling (Gray, Drummond, & Greenhill, 2009; Gray & Jordan, 2000; Grollemund et al., 2015; Kolipakam et al., 2018). This approach is further enabled by recent moves to make these language trees, as well as cultural and environmental datasets that map to the relevant ethnolinguistic groups, openly available via resources such as D-PLACE (Kirby et al., 2016). When hypotheses speak to the evolution of human behaviour as a whole, we urge other researchers to test their ideas across multiple language families. Phylogenetic methods circumvent old qualms about Galton's Problem (e.g., Korotayev & Munck, 2003; Mace & Pagel, 1994; Ross & Homer, 1976), and when these modern computational approaches are combined with spatial and environmental data to inform our understanding of the processes that drive cultural evolution.

In the specific context of post-marital residence, transitions between residence states have been associated with many different factors, such as intense warfare (Divale, 1974, 1984; Ember & Ember, 1971), prolonged male absence (Ember, 2011; Korotayev, 2003; Murdock, 1949), sudden depopulation (Ember, 2011, 1967; Murdock, 1949), changing economic conditions (Ember, 1967; Murdock, 1949), new technological developments (Ember, 1967; Murdock, 1949), inclusive fitness considerations such as paternity certainty and kin altruism (Shenk & Mattison, 2011), post-colonial contact (Ember, 1967; Korotayev, 2003), and even the spread of new dominant cultural practices, like religions (Fortunato & Archetti, 2010; Goody, 1983). However, the most influential theories for macro-evolutionary patterns have emphasized warfare (Ember & Ember, 1971), migration (Divale, 1974) and changes in the gender-based division of subsistence labour (Ember & Ember, 1971; Lippert & Murdock, 1931; Murdock, 1949), all of which are commonly observed globally. As with previous studies that have used phylogenetic comparative methods (Fortunato & Jordan, 2010; Jordan et al., 2009; Opie et al., 2014), we do not attempt to model these putative causal factors directly, but instead employ a probabilistic model that treats transitions in post-marital residence states as a stochastic process with many possible causes. We recognize, however, that not all transitions were necessarily independent; for example, contact with Papuan groups was likely an ongoing driver of the switch to patrilocality among Austronesian-speaking groups (Jordan et al., 2009), and Christianity changed the nature and form of family structures in Europe (Goody, 1983), crossing deep relationships in the Indo-European language tree. Both speak to contact-induced versus internally-driven change. The patterns of post-marital residence that we observe likely represent the cumulative outcome of many interlinked processes, and detailed coevolutionary testing has the potential to tease many of these factors apart in the future.

Overall, our results provide strong evidence that each language family has its own unique dynamics of post-marital residence change, providing little support for the view that common factors have driven similar processes of change in residence states globally. Instead, the evolution of societies seems to be dominated more by local causes, potentially including common factors acting within locally specific contexts. This is especially apparent from estimates of transition rates, presence/absence of residence states and different patterns of robustly inferred rates, all of which vary widely among the language families. Even groups with similar historical trajectories, such as the rapid agriculturally-driven expansions of Bantu and Austronesian speakers, show very different past and modern patterns of post-marital residence. These findings echo the lineage-specific patterns observed for linguistic structural features, such as word order (Dunn, Greenhill, Levinson, & Gray, 2011). Far from arguing for global commonality in the processes underlying post-marital residence change, these results lend support to the idea that a suite of causal factors, many perhaps local in origin, have driven past shifts in post-marital residence.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.evolhumbehav.2018.06.002.

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Supplementary Materials

Data and code availability

Data and code necessary to perform simulations can be found at `https://github.com/J-Moravec/pmr_language_simulation`

Data collection

To ensure the coding was as consistent as possible across trees, we recoded some states in the Bantu tree (Opie et al., 2014) to make them equivalent to the coding for the other language families. This involved changes to just four language groups with neolocal residence states. Three groups (Doko, Tonga and Luchazi) were originally classified as optionally neolocal, but ethnographic records suggest that they are better considered patrilocal. One language (Kinga) was assigned as neolocal, but we were unable to verify this state using independent sources and thus removed it from the analysis.

Post-marital residence data for Pama-Nyungan and Uto-Aztecan (Supplementary Dataset 1) were obtained from a large number of ethnographic sources (referenced in the dataset). As sources often do not mention post-marital residence directly, residence states were inferred from a combination of evidence referring to marriage practices, lineages, husband/wife dominance, house ownership and similar topics. For example, the following sentence is a strong indicator of patrilocal residence, without explicitly mentioning that term: "When the girl was old enough to be married, her father accompanied by his brother, took her to her future husband's camp, and left her there with him" (Howitt, 1996 [1904], p. 198). In a small number of cases, sources did not agree on the same residence state. In these instances, more recent and/or more authoritative sources were preferred. Residence states are naturally less certain for languages that have fewer ethnographic sources, a common theme for many Pama-Nyungan groups.

Individual vs societal states

In interpreting the literature, we have taken care to recognize that the term 'post-marital residence' can stand for two things, realized post-marital residence (the individual decisions of specific newly-weds) and a culture-wide practice (the traditional residence location). Both are seen in the literature (cf. Goodenough, 1956). For instance, the residence of a society might be classified by an ethnographer based on the frequency of realized post-marital residence (e.g., based on tabulated marriages in past years), since not all members of a society necessarily follow the primary post-marital rule (Korotayev, 2003), which can sometimes lead to complex realized residence patterns (Kramer & Greaves, 2011; Wood & Marlowe, 2011). At other times, the cultural ideal, or norm, as reported by informants is used. The latter does not necessarily take local or recent conditions into account, and may on occasion differ from realized post-marital residence at the time of the survey (see Howitt, 1996 [1904], p. 774). However, the former is much less common in the literature and idealized practices do likely reflect genuine existing or older traditions.

An additional problem is caused by the disruption of local conditions, most notably during the colonial era. This is again especially evident in the Pama-Nyungan dataset, where aboriginal Australians were often moved into camps and missions without regard to their original life styles, residence rules or even tribal affiliation (Hiatt, 1984). Depending on the presence of early records, information on traditional post-marital residence states can either be limited or lost.

Effect of the number of states on the magnitude of rates

In Jordan et al. (2009), the Austronesian dataset was encoded as matrilocal and patrilocal only, with ambilocal residence indicated via a 'polymorphic' or mixed strategy. Comparing the two-state analysis of that study with our four-state analysis, it is important to note that differences in estimated transition rates are not necessarily caused by small differences in the data, but could instead be a methodological artifact caused by using different numbers of residence states. This might especially be the case if one classified state masks the presence of another, such as if neolocal societies are defined by an ethnographer as patrilocal. This is because the estimated time of a transition from the current state is given by the diagonal elements of the rate matrix Q, $\text{Exp}(-q_{ii})$, which are the sum of all other elements in the same row, $-q_{ii} = \sum_{k \neq i} q_{ik}$. Thus, if the time spent in a given state is unchanged, but additional transitions from that state are possible, their magnitude will be smaller. A similar effect may be acting in the Pama-Nyungan dataset, where the smaller number of residence states observed could be biasing towards higher mean rates of post-marital residence evolution. Conversely, if previously unobserved transitions are now observed, this would decrease the time spent in a state, increasing q_{ii} and thus increasing the magnitude of rates.

Ancestral state reconstruction

For four of the language families, the ancestral residence state at the root of the tree could not be inferred robustly. The exception is Bantu, for which there is strong evidence that the ancestral residence state was patrilocality (Supplementary Table 10). For Uto-Aztecan and Indo-European, the posterior distributions of ancestral states (Supplementary Figure 2) are strongly multimodal with relatively well-defined peaks, suggesting different, but statistically unresolvable, scenarios for the deep evolution of post-marital residence in these language families.

Simulations

RJ MCMC and Bayes Factor

We used Reversible Jump Markov Chain Monte Carlo (RJ MCMC) to test whether some rates could be set to zero, thus indicating that the respective transitions did not occur. To calculate significance from the posterior densities using Bayes Factors, we first needed to calculate the prior probabilities of rates being set to zero by chance alone.

RJ MCMC samples from all possible models are given by a specific parametrization of the rate matrix Q. Rates could either share the same parameter class (e.g., in a two rate matrix, if $r_{12} = r_{21}$, both parameters share the same parameter class and are thus governed by a single parameter), or are set to zero (e.g.,

$r_{12} = 0$). The total number of models $M(n)$ for n rates can be calculated as all possible categorizations of models under all possible parameter classes, given by the Bell number $B(i)$, and all possible combinations of choosing which rates are non-zero:

$$M(n) = \sum_{i=1}^{n} \binom{n}{i} B(i) \tag{1}$$

This excludes the scenario in which all rates are set to zero, as such a model is not permitted. If we choose specific rates to be zero, we reduce the total number of rates by one, and thus there are $M(n-1)$ models where one specific rate is zero. This gives the prior probability that one specific rate is zero:

$$\Pr(r_{ij} = 0) = \frac{M(n-1)}{M(n)} \tag{2}$$

For $n = 2$, 6 and 12 (as observed in this study), this gives prior probabilities of 0.25, 0.23 and 0.15, which together with posterior probability values from Supplementary Table 2 and the Bayes Factor table from Kass & Raftery (1995) were used to calculate statistical significance (see Supplementary Table 2).

Estimating years between transitions

While our analysis is not performed on dated trees and thus direct time estimates between transitions are not available, it is possible to provide rough estimates by using the approximate age of language families (or the parts of them represented in the trees, see Supplementary Table 6). The maximum distance from root to tip represents the maximum amount of language change during the existence of the language family. Dividing the approximate age of the language family by this number and calculating the average number of residence changes per language change (from Supplementary Table 5), we can obtain a rough lower bound estimate of time per residence change:

$$\text{time per residence change} = \frac{\text{age of family}}{\text{tree height} \times \text{transitions per language change}} \tag{3}$$

This value should be treated as an average time between residence changes, which in turn result from stochastic processes. For example, the large time between residence changes in the Uto-Aztecan language family simply indicates that few changes are expected along any given branch. Dated trees would be preferable, but as these are not available, the rough estimates presented here should be interpreted with caution.

Calculation of the flow matrix

Flow is a ratio of all transition rates going into a given state versus all transition rates from that state. For example, if q_{ap} is the transition rate from ambilocality (a) to patrilocality (p), with similar rate nomenclature for other states, then the flow ratio for patrilocality is $\frac{q_{ap}+q_{mp}+q_{np}}{q_{pa}+q_{pm}+q_{pn}}$, or equivalently, $\frac{q_{ap}+q_{mp}+q_{np}}{q_{pp}}$. The estimated time to a transition is exponentially distributed with the rate as a parameter, $\mathrm{Exp(q_{ij})}$. The sum of rates, which gives the minimum time to the first transition (whichever transition that might be) is also exponentially distributed, $\mathrm{Exp}(\sum \mathrm{q_{ij}})$. This means that the flow of patrilocality can essentially be interpreted as

$$\frac{\text{rate of change } \textit{to} \text{ patrilocality}}{\text{rate of change } \textit{from} \text{ patrilocality}} \tag{4}$$

For example, in the case of the Uto-Aztecan tree, this means that flow into patrilocality is almost five times larger than the flow from patrilocality. Equivalently, transformed into a statement of time, $E\left[\mathrm{Exp}(\lambda)\right] = \frac{1}{\lambda}$, which means that the waiting time for a change from patrilocality is six times larger than the waiting time for change to patrilocality.

Test of agreement between language and residence evolution

We used the κ parameter (Pagel, 1999) to test the relationship between branch lengths and residence transitions. Since branches represent the extent of change in language cognates, this parameter indirectly measures the relationship between the evolution of language and the evolution of post-marital residence states. κ scales all tree branches, such that $t_{\mathrm{new}} = t_{\mathrm{old}}^{\kappa}$. If $\kappa \approx 1$, then language evolution reflects the evolution of post-marital residence (and vice versa). However, if $\kappa \neq 1$, rescaling of branches is necessary to explain the association. We ran the same BayesTraits analysis as specified in the Methods, but also estimating the κ parameter. Estimated values are summarized in Supplementary Table 9. Values of κ are distributed near 1, with no general trend for larger or smaller values. Bayes Factors calculated for the model without κ versus the model with κ (Supplementary Table 11) confirm that there is little evidence for $\kappa \neq 1$. Following the parsimony principle (i.e., penalizing addition of parameters), the simpler model without κ is preferred.

Comparison of rate matrices

To explicitly compare the fit of rate matrix Q_j with the fit of the original rate matrix Q_i, we first calculate the probability of obtaining data D_i under the respective rate matrices given the topology T_i; i.e., the likelihoods $\Pr(D_i|Q_j, T_i)$ and $\Pr(D_i|Q_i, T_i)$ (see Supplementary Table 3). From these likelihoods, Bayes Factors are calculated as:

$$\frac{\Pr(D_i|Q_j, T_i)}{\Pr(D_i|Q_i, T_i)} = \frac{\Pr(Q_j|D_i T_i)\Pr(Q_i)}{\Pr(Q_i|D_i T_i)\Pr(Q_j)} \tag{5}$$

Under the assumption that all rate matrices have the same prior probability; i.e., $\Pr(Q_i) = \Pr(Q_j)$, the Bayes factor is equal to the proportion of likelihoods (see Supplementary Table 4).

Transformation of rate matrices

To address the possibility that the rate matrices might share a similar pattern (i.e., directionality), but differ in the rate of overall residence change, we transformed rate matrix Q into overall transition rate μ and transformed rate matrix Q': $Q = \mu Q'$.

Since the transformed rate matrix Q' has expected number of transitions one (i.e., $\pi\,\mathrm{tr}(Q') = 1$, where π is the stationary distribution of the given rate matrix), the overall rate is thus dependent only on μ, and both μ and Q' can be used for comparisons between datasets (see Supplementary Table 12). This approach was used to compare the fit of each rate matrix to the residence and tree data of the other datasets, where the rate matrix Q' was multiplied by the overall mutation rate μ from the original dataset (see Supplementary Table 13 and Supplementary Table 14).

Supplementary Table 1: Summary of recorded post-marital residence states.

	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan	Total
ambilocality	23	–	2	–	7	32
matrilocality	36	34	–	8	4	82
neolocality	9	4	5	–	2	20
patrilocality	66	82	19	58	12	237
Total	134	120	26	66	25	371

Supplementary Table 2: Probability of rates being assigned as zero, thus suggesting that the transition does not occur. Dashes indicate transition states that are not observed in a given language tree.

	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
ambi →matri	*0.04	–	–	–	*0.04
ambi →neo	0.14	–	0.10	–	†0.56
ambi →patri	0.18	–	0.17	–	0.27
matri→ambi	*0.02	–	–	–	0.23
matri→neo	†0.67	†0.61	–	–	†0.44
matri→patri	0.31	**0.00	–	*0.02	†0.44
neo →ambi	0.20	–	0.13	–	†0.38
neo →matri	0.29	0.44	–	–	†0.35
neo →patri	0.27	0.24	0.33	–	†0.42
patri →ambi	†0.48	–	†0.82	–	†0.67
patri →matri	0.26	*0.05	–	**0.00	††0.82
patri →neo	††0.94	0.23	†0.76	–	††0.86

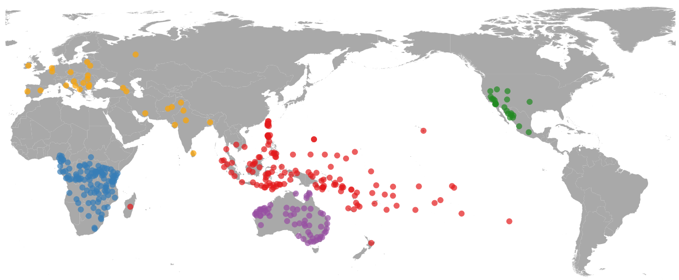
The significance of the posterior probability differs depending on the number of rates. Significance was interpreted according to Kass & Raftery (1995). See Supplementary Material text for information on how priors were calculated.

* significant positive support

** strong positive support

† significant negative support

†† strong negative support



Supplementary Figure 1: Geographical distribution of sampled languages: Austronesian (red), Bantu (blue), Indo-European (yellow), Pama-Nyungan (purple) and Uto-Aztecan (green). The geographical locations of languages are plotted according to Glottolog 3.0 (`http://glottolog.org`).

Supplementary Table 3: Comparison of the fit of each estimated mean transition rate matrix to observed post-marital residence states and trees for the other language families. The transition rate matrix estimated from one dataset was fitted to the tree and residence data for the other datasets to obtain a likelihood. All likelihoods are presented as natural logarithms.

	Rate matrix				
Dataset	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
Austronesian	−155	$-\infty$	$-\infty$	$-\infty$	−172
Bantu	−115	−65	$-\infty$	$-\infty$	−95
Indo-European	−30	$-\infty$	−21	$-\infty$	−24
Pama-Nyungan	−52	−33	$-\infty$	−25	−39
Uto-Aztecan	−31	$-\infty$	$-\infty$	$-\infty$	−25

Supplementary Table 4: Level of evidence for the rate matrix specific to each language family compared to rate matrices estimated from different language families. The transition rate matrix estimated from one language family was fitted to the tree and residence states of each other language family. Bayes Factors were calculated to determine the fit relative to the original rate matrix, with reported values interpreted according to Kass & Raftery (1995).

	Rate matrix				
Dataset	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
Austronesian	–	†††∞	†††∞	†††∞	†††33
Bantu	†††99	–	†††∞	†††∞	†††60
Indo-European	†††19	†††∞	–	†††∞	†6
Pama-Nyungan	†††55	†††17	†††∞	–	†††29
Uto-Aztecan	†††12	†††∞	†††∞	†††∞	–

† significant negative support
†† strong negative support
††† very strong negative support
∞ – the probability of obtaining the observed data under this rate matrix is zero

Supplementary Table 5: Simulated transitions by language family. Mean and 95% credible intervals for all transitions obtained from 2000 SIMMAP simulations of post-marital residence evolution on the maximum clade credibility tree for each language family. The total number of simulations is also shown normalized for the number of language substitutions (i.e., the total branch length of each tree).

	Austronesian		Bantu		Indo-European		Pama-Nyungan		Uto-Aztecan	
	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI
ambi →matri	39.34	(25.00; 53.00)	–	–	–	–	–	–	4.83	(1.00; 8.00)
ambi →neo	29.10	(18.00; 40.00)	–	–	14.61	(7.00; 22.00)	–	–	1.27	(0.00; 3.00)
ambi →patri	28.28	(16.00; 38.00)	–	–	17.37	(9.00; 24.00)	–	–	2.86	(0.00; 6.00)
matri→ambi	62.98	(45.00; 80.00)	–	–	–	–	–	–	3.04	(0.00; 7.00)
matri→neo	10.96	(5.00; 17.00)	0.79	(0.00; 2.00)	–	–	–	–	1.65	(0.00; 4.00)
matri→patri	27.96	(17.00; 38.00)	8.30	(4.00; 12.00)	–	–	94.73	(76.00; 111.00)	1.88	(0.00; 5.00)
neo →ambi	15.02	(6.00; 25.00)	–	–	21.16	(11.00; 29.00)	–	–	1.61	(0.00; 4.00)
neo →matri	12.74	(4.00; 21.00)	1.03	(0.00; 3.00)	–	–	–	–	1.63	(0.00; 4.00)
neo →patri	13.91	(6.00; 23.00)	3.13	(0.00; 7.00)	20.95	(13.00; 28.00)	–	–	1.45	(0.00; 4.00)
patri →ambi	21.58	(12.00; 30.00)	–	–	8.57	(4.00; 14.00)	–	–	1.60	(0.00; 4.00)
patri →matri	38.97	(27.00; 52.00)	9.29	(6.00; 13.00)	–	–	92.84	(75.00; 107.00)	0.78	(0.00; 2.00)
patri →neo	1.28	(0.00; 3.00)	5.24	(3.00; 8.00)	24.92	(17.00; 32.00)	–	–	0.44	(0.00; 2.00)
total	302.11	(255.00; 351.00)	27.78	(20.00; 36.00)	107.58	(81.00; 130.00)	187.57	(153.00; 220.00)	23.04	(11.00; 33.00)
per substitution	156.53		4.71		47.39		260.51		9.40	
per branch	1.13		0.12		2.07		3.75		0.17	

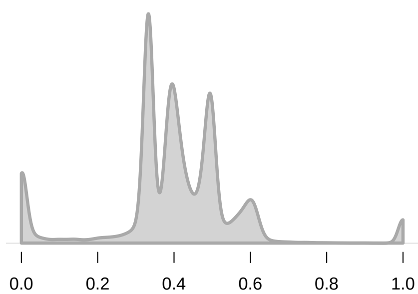
Supplementary Table 6: Rough estimates of time required for change of residence

	Years per transition per lineage	Age of tree analysed (years)	Reference
Austronesian	430	5500	Jordan et al. (2009)
Bantu	1280	~4000	Opie et al. (2014)
Indo-European	420	7000	Bouckaert et al. (2012)
Pama-Nyungan	80	6000	Bouckaert et al. (2018)
Uto-Aztecan	5530	5000	Brown (2010)

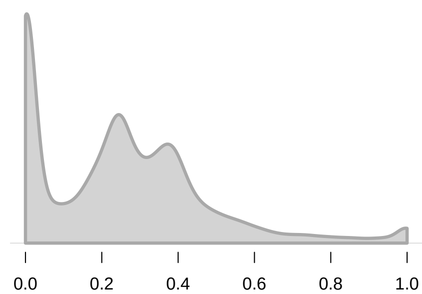
Note: Dates are rough estimates only. While values have some level of confidence for the most well-studied language families (Austronesian, Bantu and Indo-European), values have far less confidence for Pama-Nyungan and Uto-Aztecan.

Supplementary Table 7: The flow direction of rates. Ratio of rates that flow into and out of a given residence state. Values > 1 mean that transitions into a state occur more often than transitions from it, while values < 1 indicate the reverse.

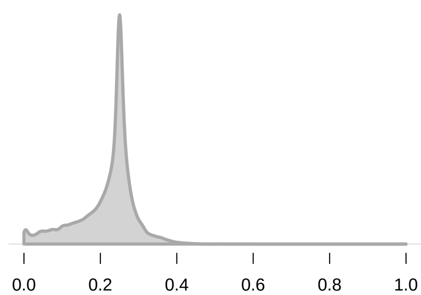
	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
ambilocality	0.82	–	0.55	–	0.88
matrilocality	1.25	1.42	–	0.16	0.87
neolocality	0.44	0.21	0.79	–	0.55
patrilocality	3.02	3.23	3.14	6.31	4.92



(a) Indo-European

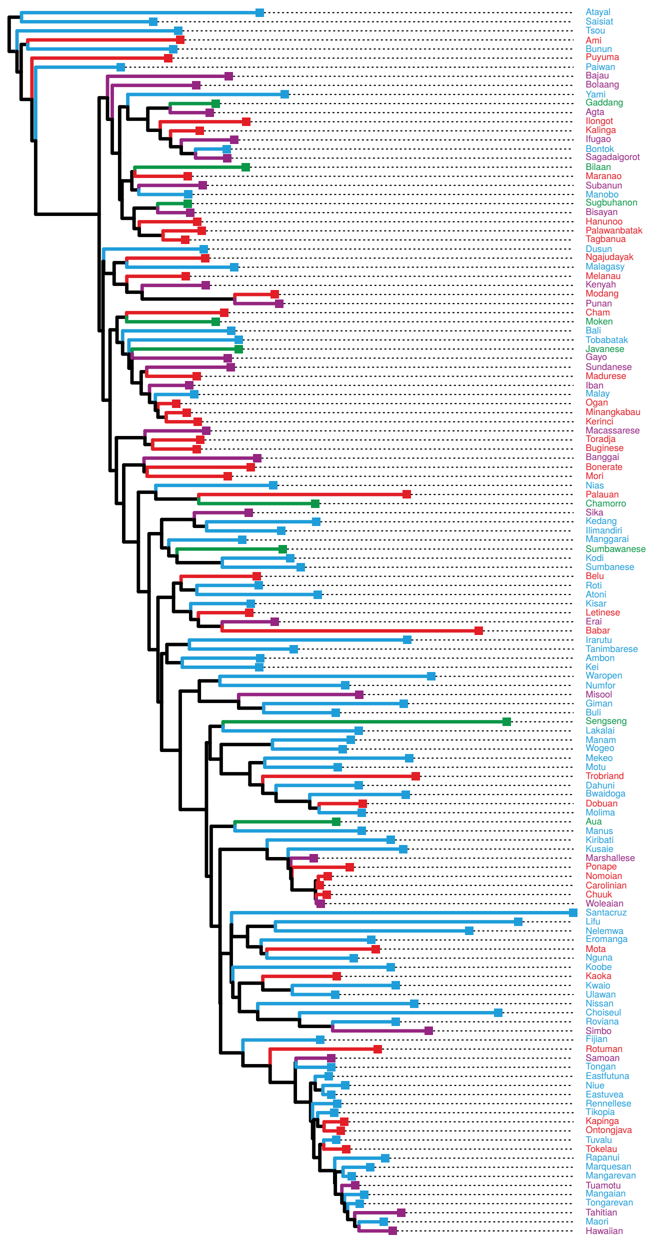


(b) Uto-Aztecan

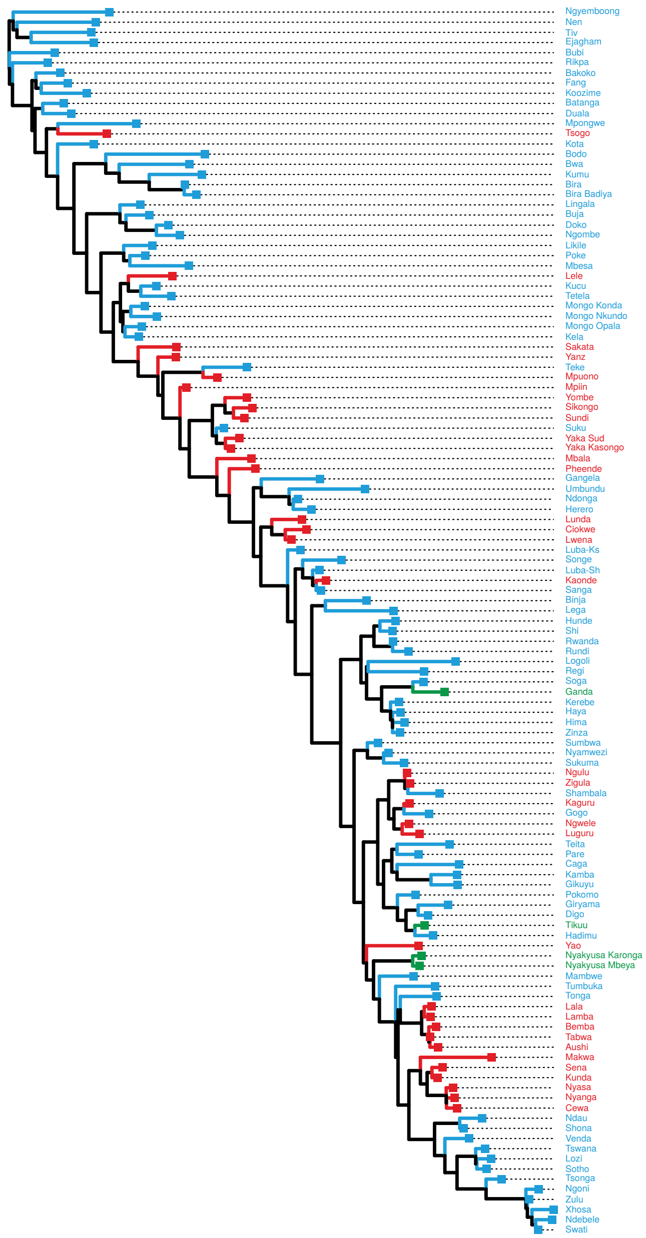


(c) Austronesian

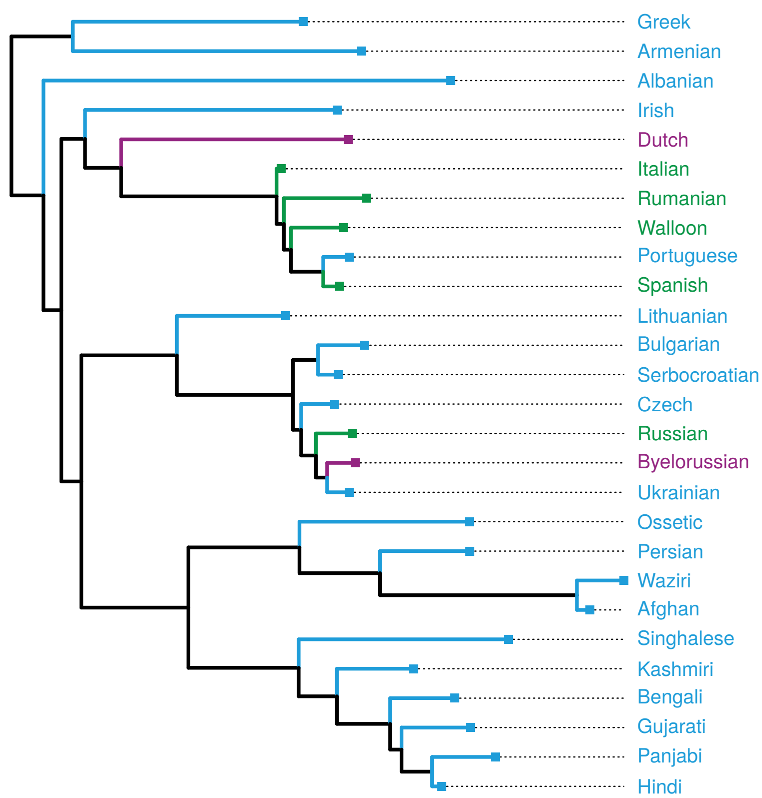
Supplementary Figure 2: Posterior distributions showing support for ancestral ambilocal residence. Note the multimodal nature of the Indo-European and Uto-Aztecan plots (upper). By way of comparison, the Austronesian distribution has a single peak (lower).



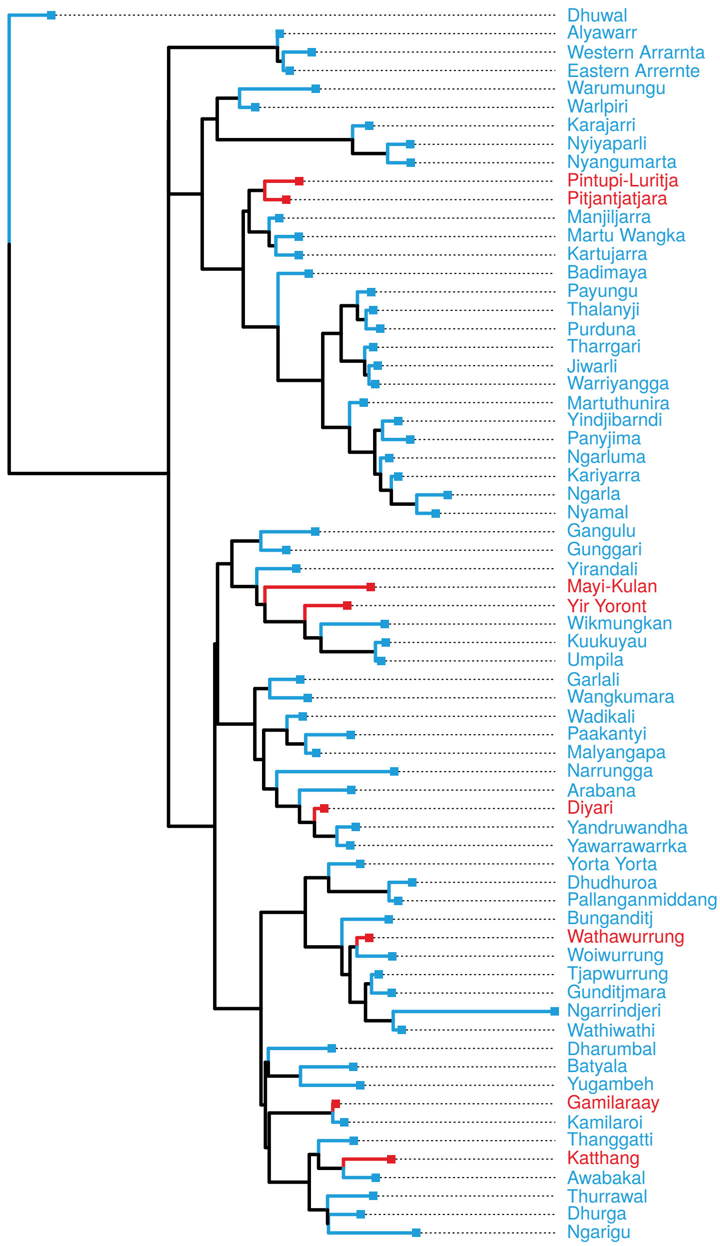
Supplementary Figure 3: Tree of Austronesian languages showing ethnographically-attested post-marital residence states. Patrilocal, blue; matrilocal, red; ambilocal, maroon; neolocal, green.



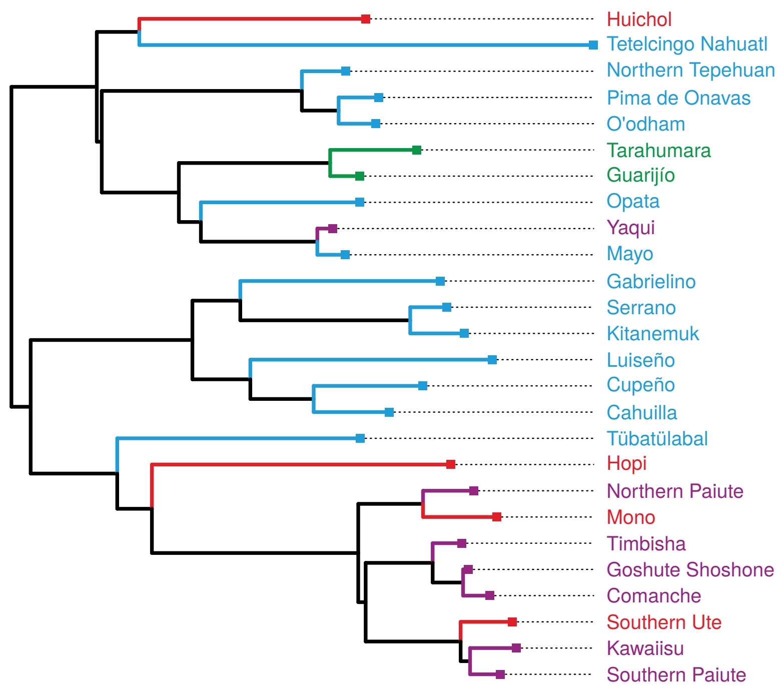
Supplementary Figure 4: Tree of Bantu languages showing ethnographically-attested post-marital residence states. Patrilocal, blue; matrilocal, red; ambilocal, maroon; neolocal, green.



Supplementary Figure 5: Tree of Indo-European languages showing ethnographically-attested post-marital residence states. Patrilocal, blue; matrilocal, red; ambilocal, maroon; neolocal, green.



Supplementary Figure 6: Tree of Pama-Nyungan languages showing ethnographically-attested post-marital residence states. Patrilocal, blue; matrilocal, red; ambilocal, maroon; neolocal, green.



Supplementary Figure 7: Tree of Uto-Aztecan languages showing ethnographically-attested post-marital residence states. Patrilocal, blue; matrilocal, red; ambilocal, maroon; neolocal, green.

Supplementary Table 8: Proportion of time spent in each post-marital residence state, calculated from SIMMAP simulations.

	Austronesian		Bantu		Indo-European		Pama-Nyungan		Uto-Aztecan	
	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI
ambi	0.17	(0.12; 0.22)	–	–	0.15	(0.08; 0.22)	–	–	0.23	(0.09; 0.40)
matri	0.27	(0.21; 0.35)	0.22	(0.18; 0.26)	–	–	0.14	(0.10; 0.17)	0.16	(0.03; 0.32)
neo	0.08	(0.04; 0.13)	0.03	(0.01; 0.05)	0.23	(0.15; 0.31)	–	–	0.12	(0.03; 0.27)
patri	0.47	(0.37; 0.57)	0.76	(0.71; 0.80)	0.62	(0.51; 0.73)	0.86	(0.83; 0.90)	0.49	(0.32; 0.75)

Supplementary Table 9: Estimated κ scaling values.

	Austronesian		Bantu		Indo-European		Pama-Nyungan		Uto-Aztecan	
	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI
Kappa	0.87	(0.23; 1.34)	1.24	(0.44; 2.01)	0.96	(0.06; 1.66)	0.86	(0.00; 1.61)	1.27	(0.60; 1.88)

Supplementary Table 10: Probability of the ancestral residence state for each language tree.

	Austronesian		Bantu		Indo-European		Pama-Nyungan		Uto-Aztecan	
	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI	mean	95% CI
ambi	0.22	(0.00; 0.31)	–	–	0.40	(0.00; 0.61)	–	–	0.25	(0.00; 0.68)
matri	0.26	(0.12; 0.42)	0.00	(0.00; 0.03)	–	–	0.40	(0.02; 0.50)	0.20	(0.00; 0.47)
neo	0.18	(0.00; 0.28)	0.03	(0.00; 0.36)	0.44	(0.00; 0.62)	–	–	0.30	(0.00; 1.00)
patri	0.34	(0.09; 0.68)	0.96	(0.63; 1.00)	0.16	(0.00; 0.96)	0.60	(0.50; 0.98)	0.25	(0.00; 0.99)

Supplementary Table 11: Comparison of models with and without the κ parameter. Likelihoods were estimated with the Harmonic Mean Estimator, and differences between the models with and without κ were then calculated using Bayes Factors. All values are presented as natural logarithms.

	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
without kappa	−161.64	−69.79	−22.42	−28.81	−27.85
with kappa	−161.49	−71.03	−22.88	−30.31	−28.06
Bayes Factor	0.15	−1.23	−0.46	−1.50	−0.21

Supplementary Table 12: Transformed rates of transitions between post-marital residence states and the overall rate μ.

	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
ambi →matri	0.75	–	–	–	1.00
ambi →neo	0.57	–	0.87	–	0.41
ambi →patri	0.53	–	0.95	–	0.66
matri→ambi	0.76	–	–	–	0.90
matri→neo	0.14	0.23	–	–	0.62
matri→patri	0.34	0.71	–	3.65	0.56
neo →ambi	0.60	–	0.86	–	0.71
neo →matri	0.50	0.91	–	–	0.72
neo →patri	0.53	1.71	0.76	–	0.57
patri →ambi	0.16	–	0.14	–	0.20
patri →matri	0.30	0.44	–	0.58	0.10
patri →neo	0.01	0.31	0.40	–	0.06
μ	157.78	5.92	48.40	76.98	27.30

Supplementary Table 13: Comparison of the fit of each transformed rate matrix to observed post-marital residence states and trees for the other language families using their estimated overall mutation rate. The transformed rate matrix estimated from one dataset was fitted to the overall mutation rate, tree and residence data for the other datasets to obtain a likelihood. All likelihoods are presented as natural logarithms.

	Rate matrix				
Dataset	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
Austronesian	-155	$-\infty$	$-\infty$	$-\infty$	-162
Bantu	-77	-65	$-\infty$	$-\infty$	-80
Indo-European	-29	$-\infty$	-21	$-\infty$	-25
Pama-Nyungan	-49	-42	$-\infty$	-25	-42
Uto-Aztecan	-25	$-\infty$	$-\infty$	$-\infty$	-25

Supplementary Table 14: Level of evidence for the transformed rate matrices compared to rate matrices estimated from different language families using the overall mutation rate from the original dataset.

	Rate matrix				
Dataset	Austronesian	Bantu	Indo-European	Pama-Nyungan	Uto-Aztecan
Austronesian	–	†††∞	†††∞	†††∞	†††13
Bantu	†††24	–	†††∞	†††∞	†††30
Indo-European	†††17	†††∞	–	†††∞	††7
Pama-Nyungan	†††49	†††35	†††∞	–	†††35
Uto-Aztecan	1	†††∞	†††∞	†††∞	–

† significant negative support

†† strong negative support

††† very strong negative support

∞ – the probability of obtaining the observed data under this rate matrix is zero

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3. Hierarchical Clustering of the Ethnographic Atlas

Societies are commonly divided along the main functional divisions that in one way or other defines their form. Most commonly, societies are divided according to the type of subsistence, such as hunter-gatherers, pastoralists or farmers, and this is assumed to be the most defining aspect (Pluciennik, 2001). This is because the type of subsistence puts a significant constraint on the possible styles of life. For example, hunter-gatherers are reliant on naturally-occurring sources of food, which constrain the maximal population density. On the other hand, farmers are tied to the land as they often need to invest substantial labour to produce food, but as the food produced scales with invested labour, they can reach much higher population densities then hunter-gatherers. However, while this division has strong explanatory power and the type of subsistence of societies can be easily studied even from extinct societies through their material culture, it might be misleading. While most environments do not permit a high population density for hunter-gatherers, if a particularly rich source of food is present, such as large herds of wild animals or rivers rich in fish, a hunter-gatherer society might reach much higher population density, and conversely develop a more complex social structure (Kelly, 1995). Thus a new division is required between simple and complex hunter-gatherers (Arnold, 1996). Similarly, a society reliant on farming might not possess an efficient farming technology or be forced into a marginal environment, such as mountains or rainforests, such that limits the agricultural gains. In such a case, the society might not be able to reach higher population densities and thus a higher complexity. Such societies are sometimes called simple horticulturalists, as opposed to societies with intensive agriculture. Horticulturalist societies do not even have to be sedentary and there are examples of migratory or semi-migratory agricultural societies (Kelly, 1992; Graham, 1993), while on the other hand, many hunter-gatherers and especially complex-hunter-gatherers can be sedentary. Given these properties, simple horticulturalists might have more in common with simple hunter-gatherers than intensive agriculturalists or complex-hunter gatherers (Zvelebil and Dolukhanov, 1991). This makes the commonly-used classification, which is then often used in correlation analyses, unsustainable.

In this work my aim is not to develop a new system of classification of societies, but to investigate how some form of classification might relate to post-marital residence as a particular post-marital residence was often prescribed to a particular society at one time, such as that horticulturalists societies tend to be matrilocal (Lancaster, 1976; Hart, 2001), hunter-gatherers tend to be either patrilocal (Kelly, 1995) or ambilocal (Kramer and Greaves, 2011) or pastoralist societies are patrilocal (Scelza, 2011). It is then no surprise when association studies fail to explain a clear relationship between particular variables and residence when analysing a particular class of societies if this class itself is highly variable. The main idea of this chapter is that societies can be divided into classes and these classes do in some way predict the post-marital residence. However, the division into classes is not a simple division into hunter-gatherers, pastoralists and farmers, but a more complex grouping based on a similarity between societies across a wide range of variables estimated directly from data. And consequently, a particular class is not supposed to completely determine residence, but a possible residence distribution. Still, I assume that some classes will be closely associated with a single type of residence. In other words, I assume that a post-marital residence is a functional response to a certain physical and social environment, but with a contextual significance. This means that grouping environments according to residence would inevitably group different societies with the same post-marital residence state in different clusters. However, by identifying groups of societies with a similar environment and residence distribution, the context in which the post-marital residence plays its functional role is preserved. This could lead to deepening our understanding of the functional role of post-marital residence in different societies.

The relationships between variables in anthropology were primarily studied by looking for linear, or at least monotone, relationships between two variables of interest, such as between post-marital residence and subsistence (Murdock, 1949). Even though strong correlation is often found, when tested for confounding relationships using a third variable, the correlations often disappear. Alternatively, the relationship can appear only when controlled for some other variable, the relationship between residence and subsistence is positive and strong only for North America (Ember, 2011). Also, significantly different results can be recovered when non-monotone relationships are considered. Korotayev (2001) found that if a female contribution to subsistence is either small or very large, society is patrilocal, which is caused by another confounding variable, non-sororal polygyny.

While these simple analyses have advantages, as they are often performed by anthropologists with intimate knowledge of societies and their functional relationship to their environment, so each tested relationship and variable is substantiated by experience. Human societies are complex and what is true in one area might not hold in another, such as if some trait is common in one area based on genealogical relationship rather than its function in a particular environment, the so-called Galton's problem (Naroll, 1961) (see Chapter 2).

In the past few decades, non-parametric methods have experienced a great surge of interest. This was mainly connected with the establishment of Machine Learning, which has a slightly different aim than standard statistics. Machine Learning is less concerned with obtaining knowledge about the relationship of underlying processes so that it could be understood, it is rather striving to complete a certain task, such as classification, as best as possible, by analysing and exploiting the structure of data, often without regard to some preconceived model. A typical example might be a spam filter, where classifying received mails as spam is more important than research into what spam is or what is its typical structure (see de Leeuw et al. (2016) for a discussion about the differences between statistics and data science).

However, non-parametric methods are highly useful outside of machine learning as well, such as during data exploration to discover and describe naturally occurring patterns in data. Often, both approaches can be combined, such as in DNA analysis, which was build by combining pattern discoveries, followed by testing hypotheses and building up explanation theories.

In this chapter, I will use such non-parametric methods to explore patterns in anthropological data. Using clustering methods, I will explore if societies contained in the Ethnographic Atlas (Murdock, 1967) can be divided into a small number of clusters with as low diversity of post-marital residence as possible. Existence of such clusters would mean that post-marital residence strongly influences properties of societies or that different types of post-marital residences occur under significantly different conditions. Another interesting condition would be a coexistence of mixed clusters and clusters with low variability of a particular residence, which would suggest that the residence can exist in two different contexts. This would mean that future tests of post-marital residence correlations could effectively treat them as separate cases.

Table 3.1: The 87 selected variables from the Ethnographic Atlas categorized into 14 classes.

Class	Variables
Age and occupational specialisation	11
Belief and religion	2
Class stratification and slavery	6
Descent	8
Games	1
Housing	10
Inheritance of property	4
Marriage	10
Political organisation	6
Settlement pattern and size	2
Sex differences	11
Sex related taboos and traditions	4
Societal rigidity	1
Subsistence	11

3.1 Materials and methods

3.1.1 Data

For the source of ethnographic data, I have used the most recent version of the Ethnographic Atlas (Murdock, 1967) available on D-place (Kirby et al., 2016)[1].

From the D-place version of the Ethnographic Atlas, 87 out of 94 variables were chosen for further processing. These can be further categorized into 14 classes (see Table 3.1. Not included were variables representing post-marital residence and population size, which was not present in the original version of the Ethnographic Atlas. The original version contained the total of 156 variables, however the majority of these variables are either identification of specific cultures and/or languages (such as iso639, the International Organization Standard for language identification) or geographical descriptors (such as continent, or longitude and latitude) which are not subjects of analysis. Variables related to the post-marital residence were omitted from the main dataset since they will be used to evaluate the results of the analysis. Variables related to post-marital residence were omitted from the main dataset since they will be used to evaluate the results of the analysis.

3.1.2 Multiple Correspondence Analysis

Many variables in the Ethnographic Atlas code similar information and thus the variables could be correlated. This is problematic, since if no weighting is applied, certain clusters might be disproportionately driven by the information coded in such variables. To solve this problem, I chose to use a Multiple Correspondence Analysis (MCA).

MCA serves a similar purpose for categorical data as PCA does for continuous data. It transforms the input variables into variables in a new orthogonal space. It performs this transformation by recoding each category in every categorical variable as a new dummy variable, with 1 signifying the presence of a certain category, while 0 is its absence. Since this process itself breaks relationships between categories of a particular variable, MCA corrects for this by holding information about this structure in a number of indicator matrices for each variable. Another difference from PCA is that, due to the large number

[1] `https://github.com/D-PLACE/dplace-data`

of dimensions created from dummy variables, the eigenvalues are generally smaller, as the amount of variance in the first few dimensions.

To perform MCA on data from the Ethnographic Atlas, I used the package `homals` (de Leeuw and Mair, 2009) which can process both categorical and ordinal data as well as deal with missing values. This enabled me to utilise all the available information coded in the Ethnographic Atlas, such as variables v1–v5, which code societal dependence on a particular type of subsistence, such as farming, fishing or hunting. The alternative package `FactoMineR` (Lê et al., 2008) is also investigated in the supplementary materials since it provides a number of additional tools coupled with overall better documentation (notably the `FactoInvestigate` package for automated analysis and interpretation of MCA results).

3.1.3 Hierarchical Clustering

(Agglomerative) hierarchical clustering is a clustering method that creates a hierarchy of clusters by merging the closest clusters, starting from individual objects, according to certain criteria until only a single cluster is left (divisive clustering, which starts from a single cluster and divides them, exists but is less common). Unlike other clustering methods, such as k-means, the number of clusters does not need to be set a priori and the resulting structure is tree-like. The clustering criterion specifies how the distance between clusters is computed. I have used 6 clustering criteria: single/minimal linkage, complete/maximal linkage, average linkage, median linkage and squared and non-squared Ward's methods. The single/minimal linkage takes the minimal distance that exists between all objects of two clusters. Similarly, the complete/maximal, average and median linkages take maximum, average and median respectively. Ward's method, sometimes also called Ward's criterion (Ward, 1963) minimises the total within-cluster variance. In R Ward's method is implemented using two algorithms: `Ward.D` and `Ward.D2`. The difference is that for `Ward.D` to correctly implement Ward's method, input data need to be squared distances, while `Ward.D2` algorithm square distances internally. While under normal circumstances one or the other algorithm would be used, Szekely and Rizzo (2005) suggest that the non-squared variation of Ward's method performs well and even outperform squared Ward in several cases, such as high dimensionality or when clusters have nearly equal means. Additionally, by exploring the implementation of Ward's method in scientific software, Murtagh and Legendre (2014) found that the `Ward.D` algorithms are often used without properly documenting the need to square distances beforehand, thus effectively utilising the distance suggested by Szekely and Rizzo (2005). For this reason, I am using both the non-squared Ward method implemented by `Ward.D` and squared Ward's method implemented by `Ward.D2`. For conciseness, I will refer to them as Ward and Ward^2 respectively.

The hierarchical clustering was carried out separately using both original and transformed variables from MCA. On transformed variables, simple Euclidean distance was used. However, for the original variables, a new distance needs to be defined.

Distance for categorical variables

For the original variables, the distance between two variables was defined as 0 for a match, 1 for no-match and NA (i.e., not available) when a missing value in one or both of the compared variables was present:

$$D(A_j, B_j) = \begin{cases} 0 & \text{when } A_j = B_j \neq \text{NA} \\ 1 & \text{when } A_j \neq B_j;\ A_j \neq NA \text{ and } B_j \neq \text{NA} \\ \text{NA} & \text{when } A_j = \text{NA and/or } B_j = \text{NA} \end{cases} \tag{3.1}$$

where $D(A_j, B_j)$ is the distance of variable j between societies A and B. The distance between the two societies is then a sum of distances over all its variables divided by the number of non-missing values. Let m_j indicate the presence or absence of a missing value in A_j and/or B_j. Then the distance between the two societies is:

$$D(A,B) = \frac{\sum_{j=1}^{n} D(A_j, B_j)}{n - \sum_{j=1}^{n} m_j} \tag{3.2}$$

with $\sum_{j=1}^{n} D(A_j, B_j)$ ignoring NA values. This means that the distance between the two societies is calculated only between variables that exist in both societies.

Clustering

Using these distances, a distance matrix was created and a standard hierarchical clustering algorithm was used. Hierarchical clustering offers a fast and convenient way to explore the structure of data. Unlike other clustering methods, the number of clusters does not have to be specified a priori and the hierarchical clustering explores the relationship between identified clusters.

To obtain an optimal number of clusters, the residence information of each society was extracted and the residence diversity of clusters was explored. The aim was to obtain clusters with small diversity, where a majority or even all of the societies will have one particular residence, I call this the "purity" of a cluster and chose to represent the purity of clusters with several methods: maximum relative frequency of the most common residence, threshold function, Gini-Simpson's diversity index and Shannon's entropy. Overall purity is then calculated as a weighted average of cluster purities so that the size of clusters is represented. Thus if the clustering method can divide societies into two clusters, one with purity 1 and size 100, another with purity 0 and size 10 (i.e., all the diversity is absorbed in this cluster), the overall purity will be: $P = \frac{1 \cdot 100 + 0 \cdot 10}{100+10} = \frac{10}{11}$. Let P_i be the purity of cluster $i, i = 1, \ldots, k$ and n_i the size of the cluster. Then the overall purity P is calculated as:

$$P = \frac{\sum_{i=1}^{k} n_i P_i}{\sum_{i=1}^{k} n_i} \tag{3.3}$$

where P_i is calculated according to one of the following methods:

Maximum

$$P_i = \max\{f_{i_1}, \ldots, f_{i_r}\} \tag{3.4}$$

where f_{i_j} is the relative frequency of the j-th residence state in the i-th cluster. In this analysis, I considered 4 residence states, so $r = 1, \ldots, 4$.

Threshold

$$P_i = \begin{cases} 1 & \text{when } \max\{f_{i_1}, \ldots, f_{i_r}\} > \tau \\ 0 & \text{otherwise} \end{cases} \tag{3.5}$$

where τ is some threshold. The threshold method is similar to the maximum method, but it more strongly emphasises clusters with purity above the threshold and de-emphasises clusters with purity below the threshold.

Normalised Gini-Simpson diversity

$$\mathrm{NGS} = \frac{1 - \sum_{j=1}^{r} f_{i_j}^2}{1 - \frac{1}{r}}$$
$$P_i = 1 - \mathrm{NGS} \tag{3.6}$$

Note that this slight modification means that the is the least diverse so that the values are in line with the other methods.

Normalised Shannon's entropy

$$\mathrm{NSE} = -\frac{\sum_{j=1}^{r} f_{i_j} \log_2 f_{i_j}}{\log_2 \frac{1}{r}}$$
$$P_i = 1 - \mathrm{NSE} \tag{3.7}$$

Similarly, this slight modification means that the maximum is the least diverse so that the values are in line with the other methods.

Since the overall purity will almost surely grow with an increasing number of clusters, it is penalised by $\alpha\frac{k}{n}$, where k is a number of clusters, n the total number of societies and α is some scaling factor. Since $k \in [1, n]$, $\frac{k}{n} \in [0, 1]$ and thus if $\alpha = 1$, both purity and penalisation are in the same range. The scaling parameter α can then be used to de-emphasise or emphasise the penalty for the number of clusters. The penalised overall purity P_P is then:

$$P_P = P - \alpha\frac{k}{n} \tag{3.8}$$

and an optimal number of clusters is found by maximising the penalised overall purity.

Comparison of clusters

Once an optimal number of clusters is found, we can compare the performance of clustering methods by comparing the distribution of societies across clusters. To simplify this process, I will ignore the underlying tree structure and compare only isolated clusters.

Let K and L be two clustering outcomes, with the number of clusters k and l. These clustering outcomes can be with the same clustering criterion, but a different number of optimal clusters and/or outcomes with different clustering criteria. Let the distance $D(K_i, L_j)$ between two clusters K_i from K and L_j from L be the percentage of shared societies or in other words, the percentage of societies of K_i in L_j. That is:

$$D(K_i, L_j) = \frac{K_i \cap L_j}{K_i}. \tag{3.9}$$

Since the set of societies is not changing, the distance of K_i to L, $D(K_i, L)$ is a vector of distances that sums to one. This vector also describes how the cluster K_i is distributed among clusters of the clustering outcome L. To quantify this, a diversity index is used. For convenience, we use the normalised Shannon's entropy defined in Equation (eq:entropy) and calculate the weighted average of individual cluster entropies according to number of societies they represent:

$$D(K, L) = \frac{1}{n}\sum_{i=1}^{k} n_i D(K_i, L). \tag{3.10}$$

Since $D(K, L)$ is non-symmetric ($D(K, L) \neq D(L, K)$), we simply average these two distances to get the final similarity:

$$S(K, L) = S(L, K) = \frac{1}{2}\left(D(K, L) + D(L, K)\right). \tag{3.11}$$

Identification of segregating variables

We identify the functional difference of clustered societies by comparing distributions of individual variables in obtained clusters. The original variables, instead of transformed variables from MCA, are used here for more straightforward interpretation. Two clusters differ in a particular variable if the frequencies of categories of this variable are significantly different. Let V and W be two random samples from a multinomial distribution with sizes v and w and frequencies v_i and w_i of variable i. I say that the samples V and W are different if the likelihood of them coming from a different distribution f_v and f_w respectively is significantly larger than the probability of them coming from the same distribution g:

$$\Pr(V|f_v)\Pr(W|f_w) > \Pr(V|g)\Pr(W|g). \tag{3.12}$$

I estimate the probabilities f_v, f_w and g using the Maximum Likelihood method:

$$f_{v_i} = \frac{v_i}{v} \qquad f_{w_i} = \frac{w_i}{w} \qquad g_i = \frac{v_i + w_i}{v + w} \tag{3.13}$$

and I use corrected Akaike information criterion (AICc) to penalize both hypotheses according to their number of parameters. While the χ^2 or Fisher's exact tests could be used instead, this explicit comparison gives a more accurate representation of relationships, especially for a small number of samples.

3.1.4 Supplementary materials

The source data, code and results of the analysis as well as additional details are available online on the author's github page: `https://github.com/J-Moravec/clustering_ethnographic_atlas`

3.2 Results

The chosen subset of the Ethnographic Atlas contains 1291 societies and 87 variables of interest with a total of 565 categories. About 27.28% of this subset of the Ethnographic Atlas is formed by unknown values. This highlights the importance of using methods that can handle unknown values as otherwise most of the variables would be removed. To see how categories are distributed across variables, I have used several methods. First, the normalised Gini-Simpson index measures the diversity of variables (Figure 3.1), with highly variable variables on the right side. A slightly different point of view is to explore variables according to their most-frequent value (Figure 3.2). This is the percentage of the total mass monopolized by the most common category. We can construct a similar graph for the least represented category in each variable (Figure 3.3) and for the percentage of unknown values per variable (Figure 3.4).

Thus, while most variables are relatively diverse, a number of variables are represented almost uniquely by a single category and others have only a few known values, making their benefit to the analysis questionable. This problem is more severe for MCA, given that each category will become a new transformed variable. Some authors (e.g., Husson et al., 2011) suggest that all scarcely represented categories should be reassigned, either by grouping with some other category or distributing the mass among all the other categories of a particular variable (so-called *ventilation*). In our case, this would mean that we would need to recode about 19% to 45% of all categories (for thresholds 1% or 5% of a variable mass, see Figure 3.5). I have decided against this as it could falsely introduce a lot of similarities between otherwise unrelated categories with low frequencies. Most values do not have low diversity index and relatively low relative frequency of categories is expected given that variables can have up to 10 categories. I will thus remove only the 5 worst-performing variables from Figure 3.1, Figure 3.2 and Figure 3.4, reducing the number of variables to 82 with a total of 549 categories and 26.72% of unknown values.

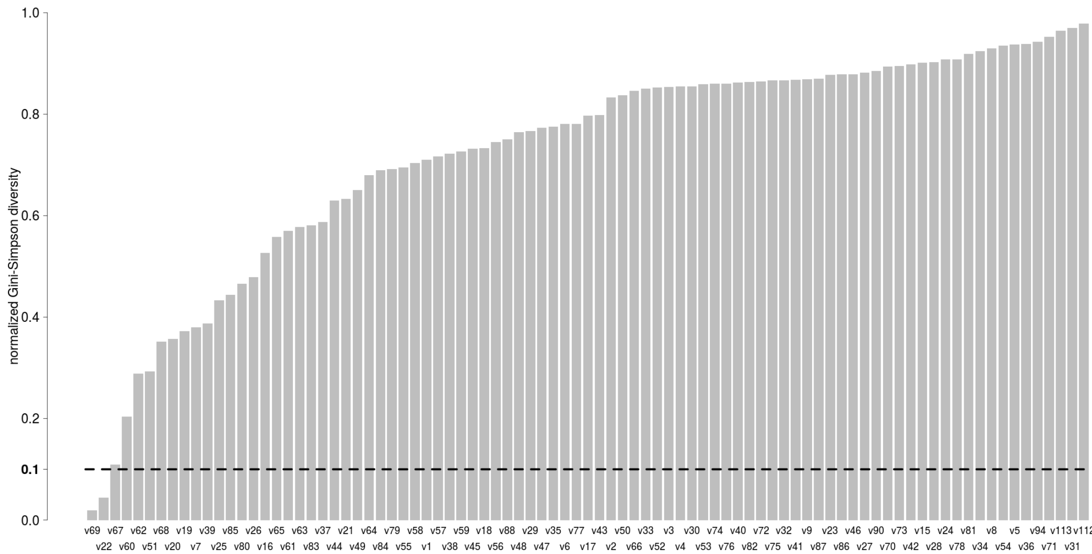


Figure 3.1: Normalised Gini-Simpson diversity of variables of interest with least diverse at 0 and most diverse at 1. While most variables have high diversity, about 9 variables (based on threshold 0.1) are not diverse enough to provide substantial information.

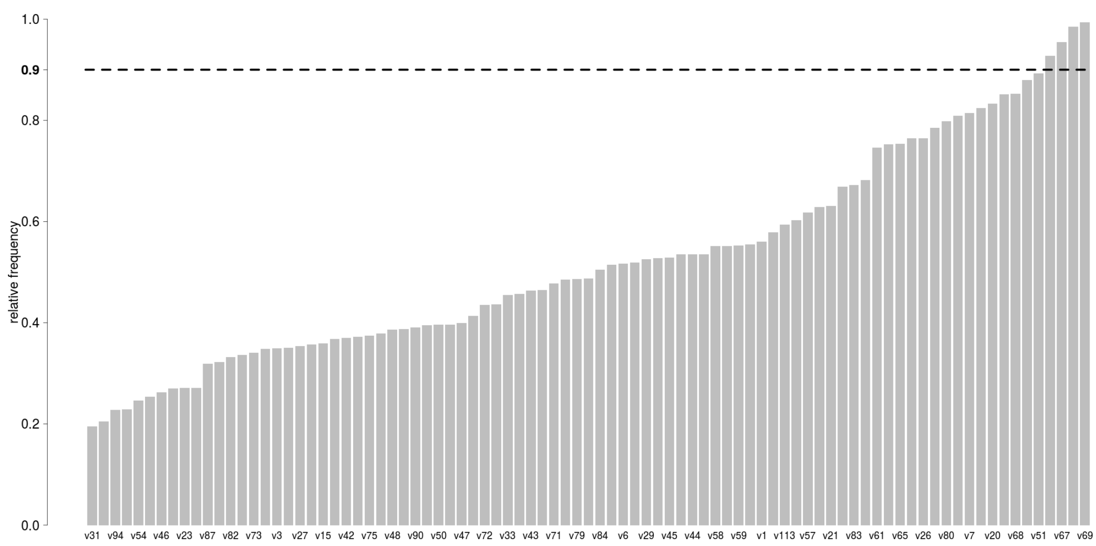


Figure 3.2: Variables of interest according to the mass in their biggest category. For several variables, a single category monopolizes the majority of the total mass (i.e., the relative frequency of all cases) and thus holds little value for analysis.

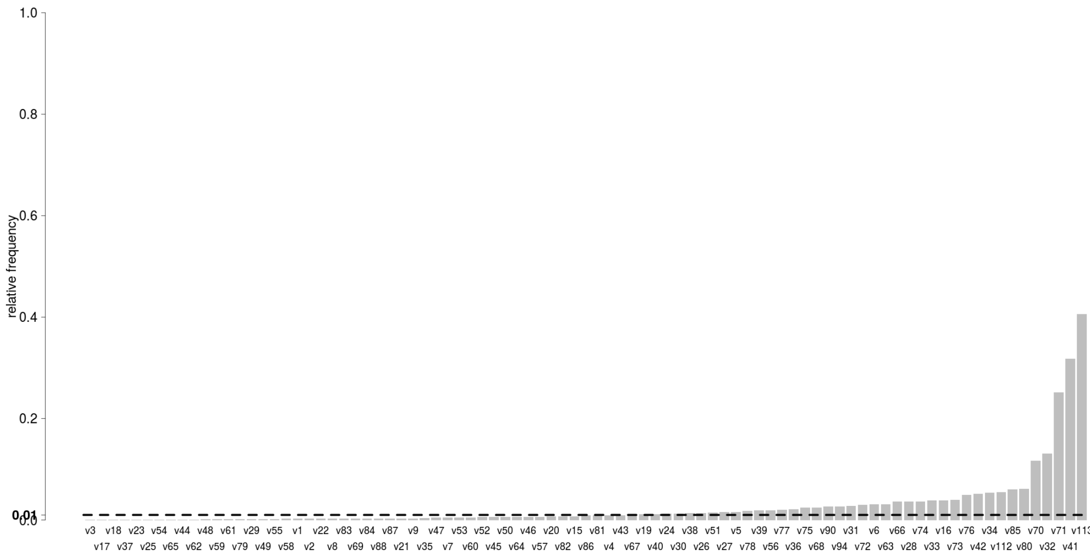


Figure 3.3: Variables of interest sorted according to the mass in their smallest category. In a number of variables, the smallest category has very low frequency. It might be a good idea to merge this category with the closest functional category when doing MCA, as suggested by Husson et al. (2011).

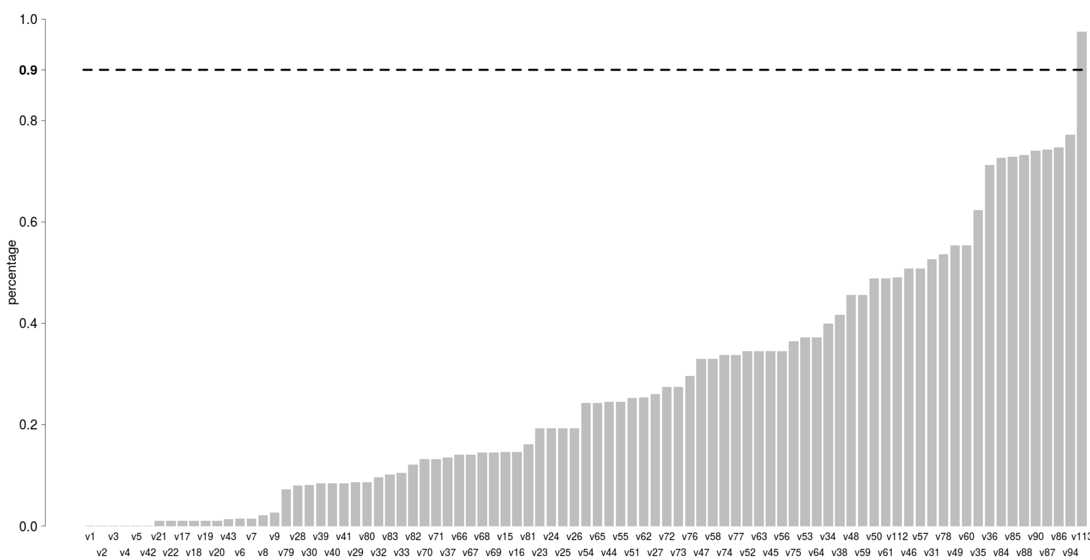


Figure 3.4: The percentage of unknown values (NA) in the variables of interest. Some variables are formed mostly by unknown values and thus they will most likely not bring any valuable information to the analysis.

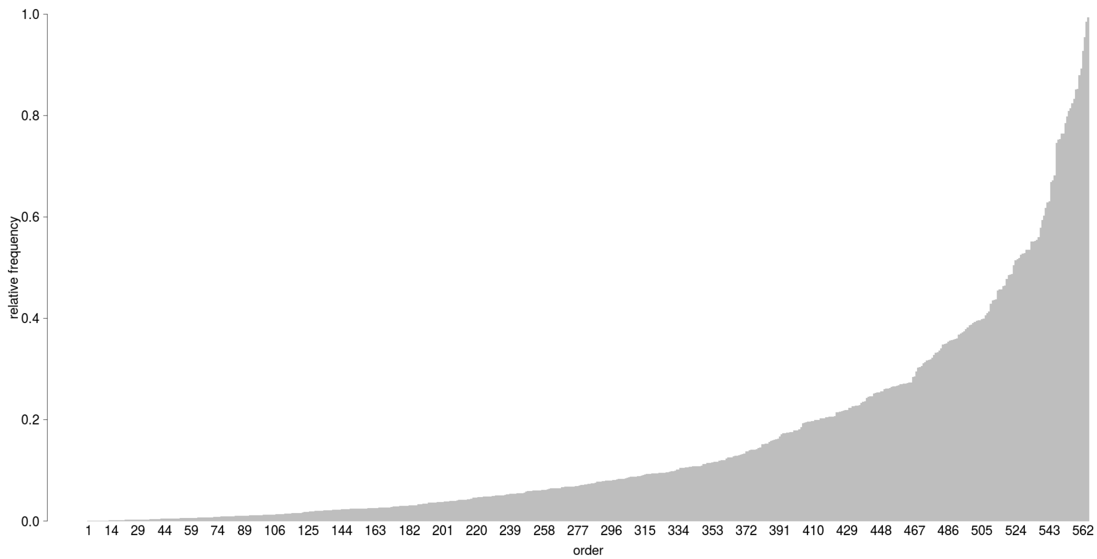


Figure 3.5: Relative frequency of all categories for all variables found in the Ethnographic Atlas. While a large number of categories have a very low relative frequency, this is to be partially expected given that variables can have up to 10 categories.

3.2.1 MCA

While the maximal number of dimensions (orthogonal base of transformed variables) was 549 (the total number of categories in all variables), the package `homals` was only able to extract the first (largest) 98 dimensions due to the level of accuracy of floating-point arithmetic. An attempt to extract more dimensions results in an error during the weighted Gram-Schmidt Orthonormalization. The proportion of the explained variability by each dimension was small, with the first 2 and first 5 dimensions explaining only 10% and 20% of total variability respectively (Figure 3.6).

Additionally, the percentage of the explained variability decreases very slowly, with each of the last 25 extracted dimensions holding between 0.5 to 0.6 percent of total variability and while under different occasions this could be considered minuscule, given the relatively small amount of explained variability by the largest dimensions and the slow decrease of variability of following dimensions, a substantial amount of variability could be hidden in these dimensions (about 24% if a constant decrease from the last 25 dimensions is assumed). This would further decrease the explained variability in the first dimensions. This lack of structure substantially decreases the benefit of analysing the first dimensions. The analysis of the first 5 dimensions explaining a total of 20% variability confirmed this, MCA was unable to discover a strong pattern in data and most variables and societies were not strongly associated with any dimension (Figure 3.7). See Appendix A for a more detailed exploration of MCA results.

3.2.2 Clustering

Non-MCA

Clustering using the original variables was able to discover a small number of optimal clusters. However, two criteria failed to find such patterns (Table 3.2). The optimal number of clusters selected by single/minimum linkage was 284, close to the explored maximum of the first 300 partitions. The situation with the median criterion was similar, except it also suggested a partitioning into two clusters.

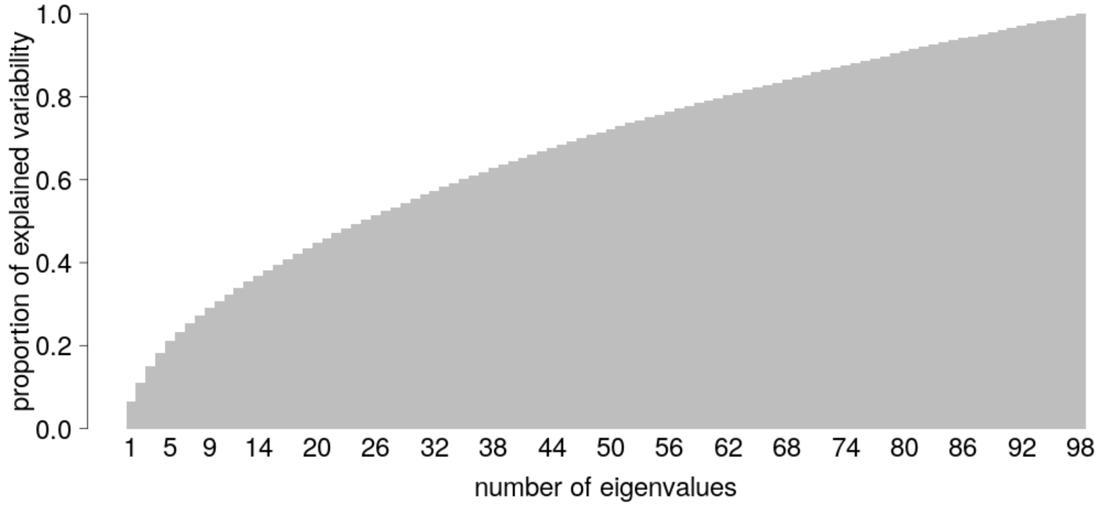


Figure 3.6: The cumulative percentage of explained variability in 98 extracted dimensions. Note that 1.0 is relative to the total variability in the first 98 dimensions and not to the total variability of the dataset.

A closer inspection reveals that this clustering is unsuitable, as it merely removes a single society from all others.

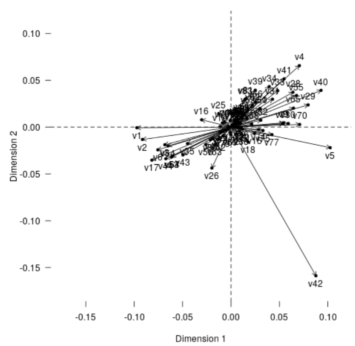
The inability of these two criteria to find a reasonable number of optimal clusters could be explained by their unique properties. The single/minimum linkage does not seem to produce a complex clustering structure, but each partition removes a single society from a large cluster. Conversely, the median criterion shows a sign of reversal behaviour (see Figure 3.8), a behaviour during which two merged clusters appear closer together than some two clusters merged previously, in the visualisation this appears as branches going back towards the root. Both clustering methods are thus unsuitable.

On the other hand, the complete/maximal linkage, average linkage and both Ward's methods (with non-squared and squared distances) seem to perform well, all of them, except the Ward^2, suggesting a number of optimal clusters between 5 to 13, with the number of clusters being stable over different purity methods and penalisations. Larger values of the number of optimal clusters were also found: 63 for complete/maximal linkage, 35 and 47 for the Average linkage, and 24 and 36 for the Ward^2 method. The double-digit cluster sizes generally outperform single-digit cluster sizes for low values of penalisation, however, the clusters found by squared and non-squared Ward's methods are stable even for high values of penalisation (Table 3.3).

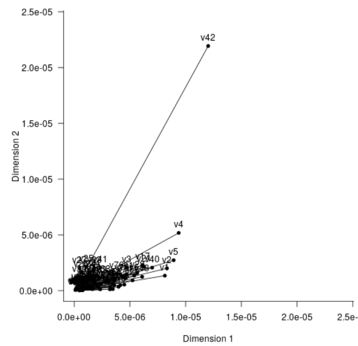
When the clustering outcomes are compared with each other, ignoring the underlying tree structure, the outcomes with a large number of clusters tend to be similar to each other and to other outcomes regardless of the size (Table 3.4). This is probably because the underlying division of societies into particular groups is done by each method, but they differ in the amount of partitioning required. The clustering outcomes with a smaller size then represent the divisions that are most important according to each method. When a small number of optimal clusters are compared across methods, the complete linkage criterion seems to produce a significantly different classification than the average linkage and Ward's method.

MCA variables

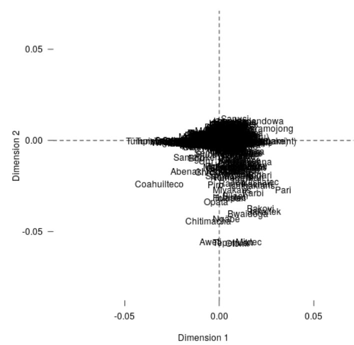
Unlike the clustering of non-transformed variables, the clustering of transformed variables from MCA failed to identify a small number of optimal clusters in any method (Table 3.5). Additionally, the same



(a) Relationship between variables and dimensions



(b) Correlation between variables and dimensions



(c) Association between societies and dimensions

Figure 3.7: An example of MCA output from the first two dimensions. Graphs show the association between variables and the first two dimensions (Figure 3.7a, correlation between variables and first two dimensions (Figure 3.7b) and association between societies and dimensions (Figure 3.7c). The prevalent type of subsistence economy (v42) is strongly associated with the second dimension. Some correlation can also be observed between other subsistence variables (v1–v5), but most variables or societies show no association. See Appendix A for a more detailed exploration of MCA results.

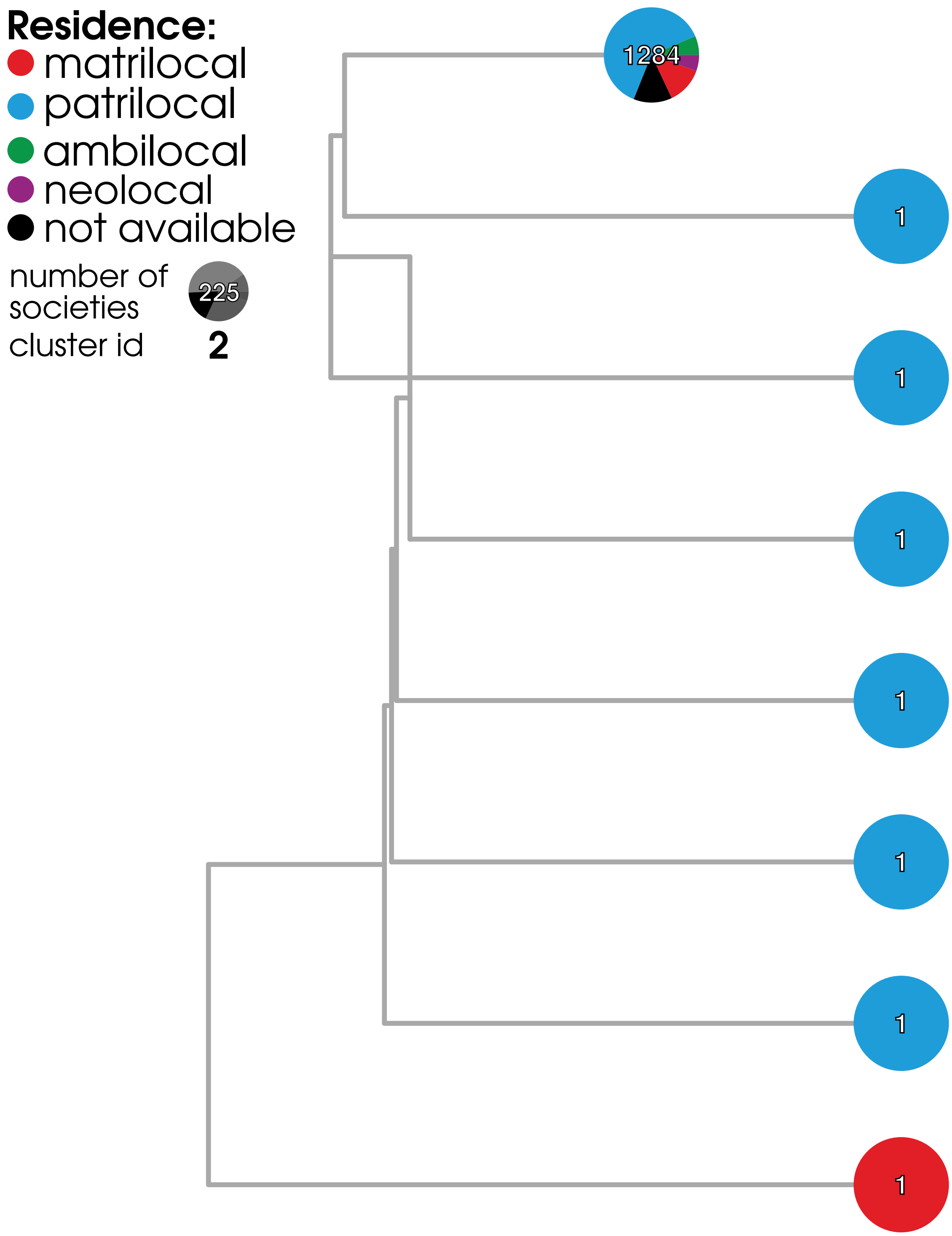


Figure 3.8: The peculiar shape created by branches of this tree is an example of the reversal behaviour. This is caused by two merged clusters appearing closer together than clusters that were merged in the previous step. This results in a negative branch lengths. This example shows the tree from the median clustering criterion with 8 clusters.

Table 3.2: Comparison of a number of optimal clusters found by 6 clustering criteria (single/minimal, complete/maximal, average and median linkage and two implementations of Ward's method) and 4 purity methods (maximum, threshold, entropy and Gini-Simpson index). The repeated optimal number of clusters for different penalisations of purity suggests that the purity surface is stable with a significant peak. The single/minimal linkage method seems to fail to find a reasonable number of clusters and while the median seems to extract three clusters, closer inspection of purity curves shows only a small peak and otherwise a similar monotone surface as the single linkage method.

Clustering criterion	Purity method	Penalisation				
		0	0.25	0.5	1	2
Single	Max	300	284	1	1	1
	Threshold	300	300	300	296	1
	Entropy	300	286	1	1	1
	Gini-Simpson	300	300	284	1	1
Complete	Max	291	230	38	5	5
	Threshold	297	287	114	114	8
	Entropy	299	230	64	63	7
	Gini-Simpson	299	291	230	63	7
Average	Max	295	245	47	35	5
	Threshold	300	300	13	13	5
	Entropy	300	238	81	35	7
	Gini-Simpson	300	295	238	47	35
Median	Max	281	281	2	1	1
	Threshold	293	293	293	114	1
	Entropy	293	278	2	1	1
	Gini-Simpson	293	293	281	2	1
Ward	Max	295	253	59	17	10
	Threshold	297	6	6	6	6
	Entropy	300	226	64	19	13
	Gini-Simpson	300	283	225	58	13
Ward^2	Max	292	259	63	29	12
	Threshold	297	24	24	24	24
	Entropy	297	259	78	36	17
	Gini-Simpson	297	283	106	64	36

Table 3.3: The optimal number of clusters and their purity values under the normalised entropy method for various utilised clustering criteria. The complete linkage criterion and both implementations of Ward's method seem to be the most successful in separating clusters according to their residences.

Clustering method	Optimal number of clusters	Penalisation				
		0	0.25	0.5	1	2
Complete	5	0.70	0.70	0.70	0.70	0.70
	7	0.72	0.71	0.71	0.71	0.70
	63	0.76	0.75	0.74	0.71	0.67
Average	5	0.71	0.71	0.71	0.71	0.70
	13	0.72	0.72	0.72	0.71	0.70
	35	0.75	0.74	0.73	0.72	0.69
	47	0.75	0.74	0.73	0.72	0.68
Ward	6	0.72	0.72	0.72	0.72	0.71
	13	0.74	0.74	0.73	0.73	0.72
Ward^2	24	0.75	0.74	0.74	0.73	0.71
	36	0.76	0.75	0.74	0.73	0.70

Table 3.4: The similarity between clustering outcomes from different clustering criteria and different sizes. Clustering outcomes with a higher number of clusters tend to be similar since they more likely represent all bipartitions found in a smaller number of clusters. The average linkage with 5 clusters and Ward's method with 6 clusters have very high similarity, which suggests that these methods agree on a division of societies into a small number of clusters.

Criterion	Clusters	Complete			Average				Ward		Ward^2	
		k5	k7	k63	k5	k13	k35	k47	k6	k13	k24	k36
Complete	k5	–	0.96	0.97	0.80	0.84	0.88	0.90	0.77	0.82	0.86	0.88
	k7	0.96	–	0.98	0.82	0.85	0.89	0.90	0.79	0.84	0.88	0.90
	k63	0.97	0.98	–	0.95	0.96	0.97	0.98	0.95	0.95	0.96	0.97
Average	k5	0.80	0.82	0.95	–	0.97	0.97	0.98	0.87	0.88	0.91	0.93
	k13	0.84	0.85	0.96	0.97	–	0.99	0.98	0.90	0.91	0.93	0.94
	k35	0.88	0.89	0.97	0.97	0.99	–	0.99	0.93	0.93	0.95	0.96
	k47	0.90	0.90	0.98	0.98	0.98	0.99	–	0.95	0.94	0.96	0.97
Ward	k6	0.77	0.79	0.95	0.87	0.90	0.93	0.95	–	0.95	0.93	0.94
	k13	0.82	0.84	0.95	0.88	0.91	0.93	0.94	0.95	–	0.94	0.95
Ward^2	k24	0.86	0.88	0.96	0.91	0.93	0.95	0.96	0.93	0.94	–	0.99
	k36	0.88	0.90	0.97	0.93	0.94	0.96	0.97	0.94	0.95	0.99	–

reversal behaviour of the median criterion as in non-transformed variables was observed. Typically the number of optimal clusters was highly unstable and if it was stable, it was closer to the explored maximum of 300 clusters. The few optimal clusters that were found were usually of large double-digit value with even non-penalised entropy values (Table 3.3) smaller then the clustering outcomes from non-transformed variables (see Table 3.3).

Identification of segregating variables

Since the MCA clustering failed to find a reasonably small number of clusters, I will investigate only the best performing clustering outcome with the original variables from the Ethnographic Atlas, the non-squared Ward's method with 6 clusters (see Figure 3.9). The figure shows that the clustering based on ethnographic variables managed to segregate societies based on their post-marital residence with relative success even with a low number of clusters. While the clusters are not completely pure, this is not to be expected given the complexity of human behaviour. Still, clusters 3 and 5 are formed almost uniquely from patrilocal societies with only a small degree of matrilocal and neolocal ones. Cluster 4, on the other hand, is to a large degree matrilocal, but patrilocal societies still form almost a quarter of its societies. Clusters 1, 2 and 6 are rather mixed with no prevailing residence pattern and all of them contain a large portion of societies with unknown residence state. However, the neolocal societies are heavily represented in cluster 6, forming about a quarter of the 160 societies represented by this cluster.

Traversing this tree (see Figure 3.9) and comparing the distribution of variables in individual bifurcations (divisions along the tree structure), I can identify which variables are important for particular clusters. To make comparison of 83 variables across multiple bifurcations less opaque, the delta AICc matrix was categorised into three states: a significant difference in both distribution, insignificant difference and a significant evidence for both clusters having the same distribution of tested variable, and these results were summed over all bifurcations (see Appendix A). To further compress this data I have summarised the 83 variables into 13 underlying variable classes (see Table 3.7).

Most variable classes were significantly different across all bifurcations (more than 60% of cases) with variables coding subsistence, marriage, the inheritance of property, class stratification and slavery and descent being the most different (more than 90% of cases). Even games, the worst-performing class, was different in 60% of cases. Interestingly, variables coding sex differences in occupations, such as hunting, weaving or boat building, scored relatively poorly (different in 76% cases), although some of them are supposed to play a major role in the adoption of residence. Likewise, variables for political organisation seems to not perform as well as perhaps expected, it seems that hunter-gatherers, pastoralists and farmers are more distinct in what kind of gods they believe rather than their political organisation. Table A.1 describes all the variables.

As previously mentioned, traditional societies are often categorized according to their primary type of subsistence. To find out how the 6 obtained clusters agreed with this traditional classification, I have investigated 4 different variables that are closely associated with these categories: Intensity of agriculture (v28), Settlement pattern and size (v30), Mean size of local communities (v31) and the Dominant mode of subsistence (v42). Using these categories, one can distinguish if the society cluster is primarily represented by hunters, pastoralists or farmers, their sedentism and their approximate population density. The full distribution of variables for each cluster can be seen in Figure 3.10. This was then summarized using the most common category for each variable and cluster in Table 3.8.

Looking at the distribution of selected variables, it seems that the clustering with non-squared Ward's method was able to divide societies into hunter-gatherers, several groups of simple farmers and two groups of complex farmers, one of them including pastoralists. Cluster 1 consist of gatherers, hunters and fishers with at least some degree of mobility and relatively low population density. Clusters 2, 3 and 4 are predominantly simple farmers, with cluster 2 having the simplest agriculture, including some migratory farmers and hunter-gatherers, while cluster 3 has more complex agriculture with some of its societies achieving high population densities. Clusters 5 and 6 contain societies with the most complex farming techniques. What is however surprising is that cluster 5 groups some of the most

Table 3.5: Comparison of the number of optimal clusters for MCA data found by 6 clustering criteria (single/minimal, complete/maximal, average and median linkage and two implementations of Ward's method) and 4 purity methods (maximum, threshold, entropy and Gini-Simpson index). Unlike with the non-transformed variables, there is an apparent lack of cluster stability, at least for a number of clusters in single and small double digits. Most of the stable number of optimal clusters (either discovered by more than one purity method or stable across different penalisations of a single criterion) are close to the tested maximum of 300 clusters and the only semi-successful criteria seems to be the complete linkage with 82 and 86 clusters, and the non-squared Ward's criterion with 42 and 77 clusters.

Clustering criterion	Purity method	Penalisation				
		0	0.25	0.5	1	2
Single	Max	300	92	1	1	1
	Threshold	300	300	300	1	1
	Entropy	300	181	1	1	1
	Gini-Simpson	300	300	92	1	1
Complete	Max	294	82	1	1	1
	Threshold	298	298	243	86	85
	Entropy	300	277	86	1	1
	Gini-Simpson	300	299	277	82	1
Average	Max	300	54	1	1	1
	Threshold	300	300	300	245	1
	Entropy	300	252	1	1	1
	Gini-Simpson	300	300	252	1	1
Median	Max	274	57	1	1	1
	Threshold	300	300	300	1	1
	Entropy	300	160	1	1	1
	Gini-Simpson	300	283	160	1	1
Ward	Max	294	294	1	1	1
	Threshold	285	285	285	77	77
	Entropy	300	291	113	42	4
	Gini-Simpson	300	296	291	78	42
Ward^2	Max	293	267	1	1	1
	Threshold	295	285	285	220	120
	Entropy	299	285	135	1	1
	Gini-Simpson	299	285	278	133	1

Table 3.6: The optimal number of clusters and their purity values under the normalised entropy method for various clustering criteria for MCA data. Even the best MCA clustering outcomes are outperformed by almost all outcomes found on non-transformed variables even for non-penalised entropy values (see Table 3.3).

Clustering criterion	Optimal number of clusters	Penalisation				
		0	0.25	0.5	1	2
Single	92	0.66	0.64	0.63	0.59	0.52
Complete	82	0.67	0.66	0.64	0.61	0.54
	86	0.67	0.66	0.64	0.61	0.54
Ward	42	0.69	0.68	0.68	0.66	0.63
	77	0.72	0.70	0.69	0.66	0.60

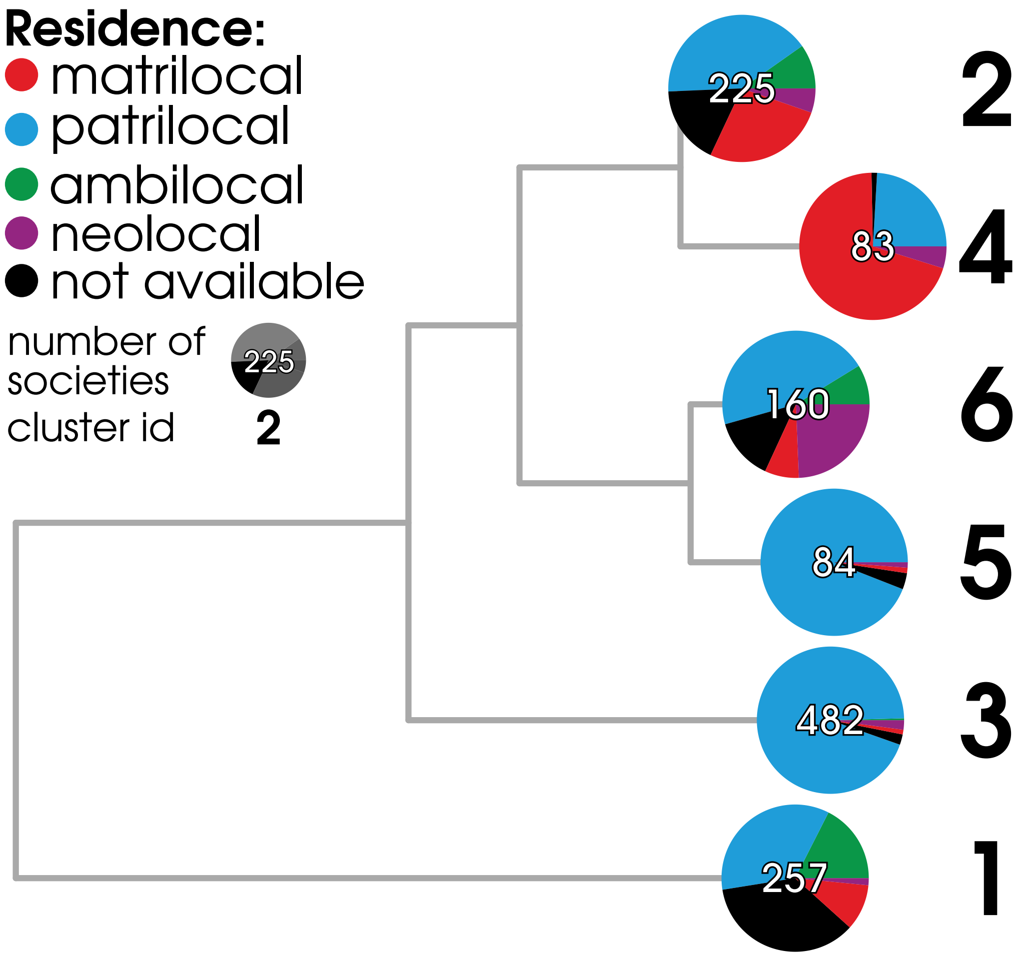


Figure 3.9: Tree constructed by clustering data from the Ethnographic Atlas using the non-squared Ward's method and extracting 6 clusters. The pie charts represent societies and a post-marital residence composition of each cluster, with red representing matrilocality, blue patrilocality, green ambilocality, purple neolocality and black standing for unknown data. The number inside each pie chart is the number of societies in each cluster and the number next to the pie-chart is the ID of the cluster.

Table 3.7: Comparison between distributions of variables across all bifurcations according to the non-squared Ward's method with 6 clusters. The 83 variables were categorized into 13 underlying classes. The columns show how many times the distribution of variables of a certain class was significantly different or the same based on AICc values of Bayesian multinomial test. Most variable classes were significantly different across all bifurcations, with variables coding subsistence, marriage, the inheritance of property, class stratification and slavery and descent being the most different (more than 90% of cases).

Class	Same	Not enough evidence	Different	Different (%)
Age and occupational specialisation	8	3	39	78
Belief and religion	1	0	9	90
Class stratification and slavery	1	0	19	95
Descent	2	0	33	94
Games	2	0	3	60
Housing	8	2	40	80
Inheritance of property	0	1	19	95
Marriage	0	2	48	96
Political organisation	5	0	25	83
Settlement pattern and size	2	0	8	80
Sex differences	9	4	42	76
Sex related taboos and traditions	5	0	15	75
Subsistence	2	0	53	96

Table 3.8: A typical value of chosen variables for each of the 6 final clusters. For each variable and each cluster, the most common value was taken after excluding unknown values and the percentage frequency of this value including unknown values is reported. For a full representation of variable distributions, see Figure 3.10.

Cluster	Intensity of agriculture (v28)	Settlement pattern and size (v30)	Mean size of local communities (v31)	Dominant mode of subsistence (v42)
1	absent (91%)	seminomadic (55%)	less than 50 (32%)	fishing (35%)
2	horticulture (42%)	compact and permanent (46%)	50 to 99 (13%)	extensive agriculture (56%)
3	extensive or shifting (57%)	compact and permanent (45%)	100 to 199 (7%)	extensive agriculture (52%)
4	extensive or shifting (84%)	compact and permanent (53%)	50 to 99 (11%)	extensive agriculture (80%)
5	intensive agriculture with irrigation (44%)	compact and permanent (30%)	cities with population over 50 000 (11%)	pastoralism (54%)
6	intensive agriculture (36%)	compact and permanent (64%)	cities with popopulation over 50 000 (31%)	intensive agriculture (64%)

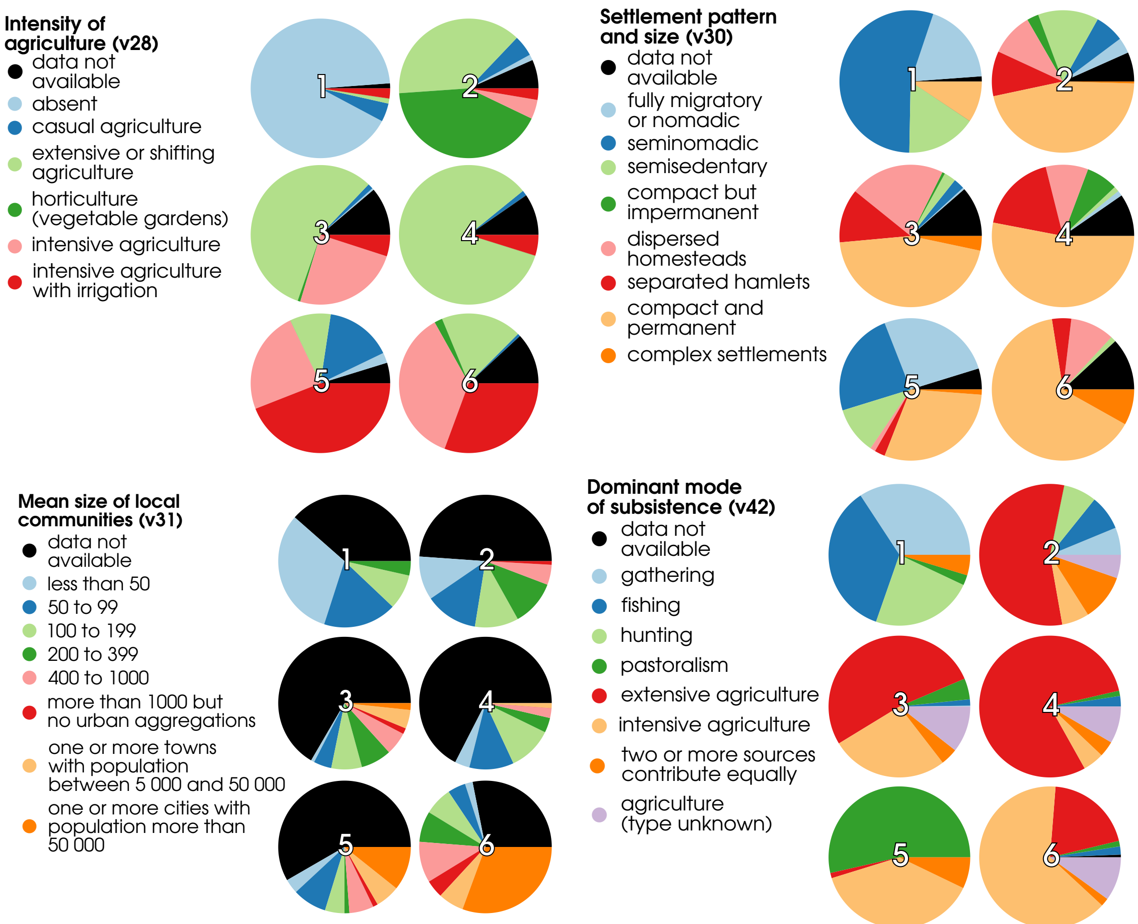


Figure 3.10: Distribution of values of four chosen variables for each final cluster from non-squared Ward's method. The four variables: Intensity of Agriculture (v28), Settlement pattern and size (v30), mean size of local communities (v31) and the Dominant mode of subsistence (v42) were chosen for their representation of the classical classification of societies into simple and complex hunter-gatherers, simple and complex farmers and pastoralists.

complex societies (which achieve high population densities using intensive agriculture with irrigation) together with mobile pastoralists. This shows that pastoralists and some complex farmers might be more similar to each other than to hunter-gatherers or even simple farmers. Finally, cluster 6, while having a slightly lower degree of irrigation agriculture, have much larger population densities. However, this might be caused by the large percentage of missing data in this variable.

Looking back at Figure 3.9, we can see that the hunter-gathering cluster 1 separates from all other clusters and the complex farmers (clusters 5 and 6) and two of the simple-farmers (clusters 2 and 4) form their own subgroups. It is interesting that cluster 4 groups with a semi-sedentary cluster 2 and not with cluster 3, which had relatively more advanced agricultural practices.

When these classifications are compared to the cluster residence states, there is no typical pattern. The previously mentioned trend from the literature, that horticulturalists tend to be matrilocal (Lancaster, 1976; Hart, 2001), is confirmed only to the degree that matrilocality seems to be rare among complex farmers and pastoralists. The simple farming clusters 2 and 4 attained the highest degree of matrilocality, at least compared to other clusters and some matrilocality seems to be replaced by ambilocality amongst the semi-sedentary societies in cluster 2. The simple-farmers from cluster 3 and complex farmers and pastoralists from cluster 5 are almost uniquely patrilocal. On the other hand, cluster 6 with the most advanced agriculture has a rather mixed residence with a high degree of neolocality and the hunter-gathering cluster 1 is also mixed (see Figure 3.11).

3.3 Discussion

In this chapter, I have analyzed the Ethnographic Atlas using six clustering criteria to get clusters with societies with a minimal diversity of post-marital residence. To do this, I performed a Multiple Correspondence Analysis to reduce cross-correlation between variables before clustering with both transformed variables from MCA and original unmodified variables in the Ethnographic Atlas. The optimal numbers of clusters for each clustering criterion were explored using four different purity methods to obtain clusters of societies with the least diversity in post-marital residence. The difference in variables between clusters was then explored on the best tree by comparing their distribution using AICc.

The MCA seems to have failed to discover a strong relationship between variables and dimensions. In fact, the package that implemented MCA failed to extract all the dimensions, which means that even the relatively low diversity found in the largest dimensions is overestimated. Otherwise, while a large number of variables seem to be correlated, these correlations are typically very small, with the strongest being typically among subsistence variables. This lack of apparent structure is a major concern. We would expect variables to be more determining and carry stronger information. However, it might just be that the structure in the Ethnographic Atlas is much more complex and nuanced and that presence of multiple variables, each of them in isolation not particularly informative, are required to significantly differentiate a society from other societies. However, except for few societies (e.g., Tepehuan, Mixtec, Otomi, Hadendowa, Karamojong and Uzbek), most societies seem to be not particularly associated with any dimension. This might be the reason why the clustering on the transformed variables from MCA failed to find a reasonably small number of clusters.

While it is quite disappointing that the clustering on MCA failed to extract a small number of clusters, the clustering on the non-transformed data seems to perform well. The best clustering outcomes on non-transformed data had better purity than the best clustering outcomes from MCA despite suggesting a significantly smaller number of clusters. Since MCA showed that the variables are not particularly correlated, I can only speculate why this happened. The low frequency of categories in some variables might be one of the reasons, especially since the MCA is particularly sensitive to this, as each category is transformed into a variable and a new dimension, while the distance defined for non-MCA data handles rare categories well. Alternatively, the lack of data structure uncovered by MCA and following clustering might be the correct representation of information from data while the non-MCA clustering

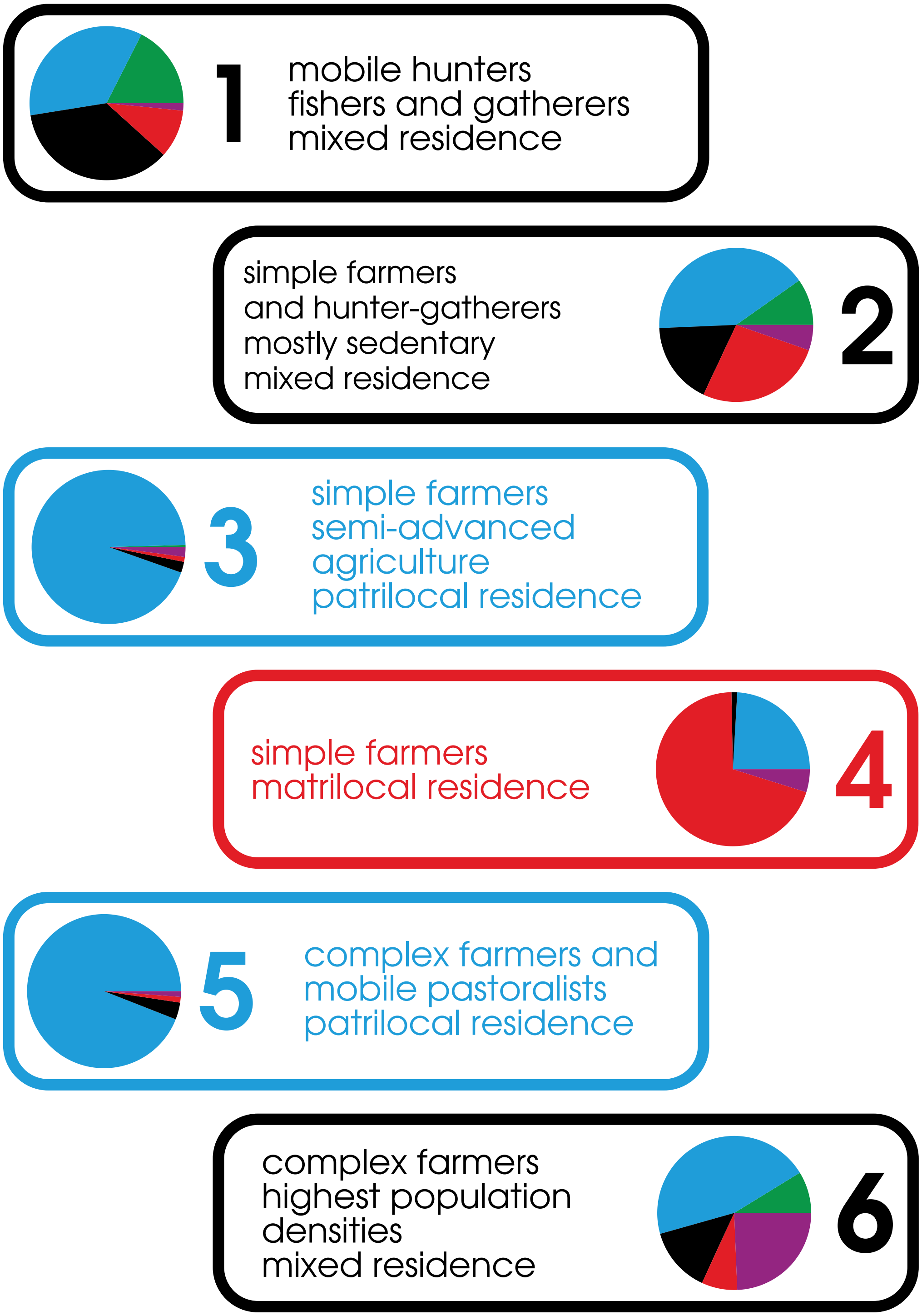


Figure 3.11: Visualization of identified clusters, their residence and categorisation into major societal classes. See Figure 3.9 for full description and colour coding of represented residences.

is an artefact from particular coding structure caught in the Ethnographic Atlas. This would however imply that the data bias in the Ethnographic Atlas is correlated with the post-marital residence state as the non-MCA clustering produced several clusters with a low diversity of residence types. And while this is certainly possible, it is also much less probable.

The extracted clusters had a significantly different distribution of their variables, with the variables related to subsistence, marriage, the inheritance of property, class stratification and slavery and descent being the most different. The least important seems to be variables associated with games.

When the clusters were classified according to the type of subsistence, settlement pattern, population density, the classification followed the standard classification into hunter-gatherers, pastoralists and farmers with several major exceptions. Simple farmers were represented by three different clusters each of the following completely different pattern of residence: patrilocal simple farmers, matrilocal simple-farmers and cluster of simple farmers with a mixed residence. Societies with complex farming techniques were contained in two clusters, one of them also included the majority of mobile pastoral societies and had patrilocal residence, while the other one had mixed residence, but with a large proportion of neolocal residence, which is relatively uncommon otherwise.

In this chapter, I have been able to successfully divide societies contained in the Ethnographic Atlas into a small number of clusters with significantly different patterns of post-marital residence. Closer inspection of their subsistence, settlement and agricultural variables showed a relatively clear-cut categorisation of found clusters into mobile hunter-gatherers, simple and complex farmers, each with its very specific pattern of post-marital residence. These results show that even though some societies might seem similar on the surface regarding their subsistence patterns, there is a much greater divide that once explored, could explain their differences in adopted post-marital residence. Further research should aim at a proper exploration of these differences and replicate this work on other databases, as Ethnographic Atlas lacks some types of variables, such as warfare, that are considered important regarding post-marital residence.

4. An Agent-Based Model of Warfare-Induced Post-Marital Residence Change

4.1 Introduction

As previously discussed (Chapter 1), factors influencing a change in post-marital residence are heavily intertwined and exhibit complex causative direction. Since association studies by definition cannot provide a resolution here since they examine only how closely two variables are associated with each other. In the past, this means that the explanation and causative direction suggested often stemmed from general knowledge and intuition of the researcher, but no actual test of these ideas was possible. And while there was an attempt to solve this problem by including time information (Divale, 1984), so that the causative direction could be resolved from time progression of residence changes, this proved to be difficult due to a very patchy interpretation-dependent dataset.

The modelling approach can help to solve this problem. Agent-based models are convenient in this situation as they can be constructed analogously to human societies with particular mechanisms or interactions in place. If the constructed model produces the desired behaviour, it is evidence that the particular mechanism can produce the desired behaviour, although not a direct evidence that such behaviour is produced by the mechanism in reality. Still, they provide a very convenient way to actually test particular ideas or causative direction.

In this chapter, I will introduce one such model to test if external warfare can induce residence change in societies. First, I will closely analyse the theories of warfare introduced in Chapter 1 to produce a theoretical base on which model can be built. Then I will describe an agent-based model of warfare-induced residence change. Finally, I will analyse and discuss the results of this model and implications for further research. A number of possible extensions of this model can be then seen in Chapter 5.

This chapter was published as *Warfare induces post-marital residence change* (Moravec et al., 2019)

4.2 Theories of residence change due to warfare

Warfare has been suspected of influencing post-marital residence due to being male dominated (Divale and Harris, 1976); fighting prowess increases the status of males (Murdock, 1949), who can often steal wives in warfare (Divale and Harris, 1976) further increasing their status or reproductive success. Several mechanisms by which warfare influences post-marital residence have been suggested: increase in the status of males compared to females (Murdock, 1949), internal warfare and division of labour (Ember and Ember, 1971), increased warfare mortality in border villages (Divale, 1984) and prolonged male absence from villages due to prolonged warfare (Korotayev, 2003). However, none were closely examined in a modelling framework that could explore causative mechanisms.

4.2.1 Warfare Theory of Matrilocality

As was discussed in Chapter 1, the first theory of residence change due to warfare, the *Warfare Theory of Matrilocality* (Ember and Ember, 1971), relates residence to a division of labour and warfare (see Figure 1.4). According to this theory, there are two sets of interactions that determine residence. The first is interaction with warfare: if a society fights in internal warfare (i.e., between culturally related villages or even inside a village, sometimes called feuding), families are forced to keep their sons close for protection. This pressure does not exist if warfare is purely external. The second interaction is between warfare and division of labour, where warfare can often disrupt a division of labour, such as when raiding is done at times when male labour would otherwise be required in the fields. In my interpretation, the two mechanisms playing a key role here are: centralization of the more economically productive sex (i.e., the division of labour) and maximizing the number of warriors, although, in the presence of internal warfare, warriors from other villages will not be particularly reliable for defence. The latter mechanism could lead to either patrilocality if internal warfare is present, or matrilocality if it is absent. However, while Ember and Ember (1971) explained factors influencing residence change, they did not explain conditions leading to these factors sufficiently; they commented on the presence or absence of internal warfare, but not how or why internal warfare could be absent. This was partially amended in Ember (1974), where presence or absence of internal warfare was dependent on the size of the community, where a familiar relationship (i.e., everyone knows each other) is often enough to prevent warfare. The diagram of the latter version of Ember's theory is shown at Figure 4.1.

4.2.2 Migration Theory of Matrilocality

The second theory, the *Migration Theory of Matrilocality* (Divale, 1974, 1984) describes a scenario of residence change explicitly. On top of residence, this theory describes a change in descent as well, since it incorporates the *Main Sequence Theory* (Murdock, 1949), according to which change in residence is followed by a change in descent. However, the descent is not the subject of study here, unless it may influence change in residence. And since most of the evidence suggests that residence influences descent instead (see *Main Sequence Theory* (Murdock, 1949) and Jordan and Mace (2007); Opie et al. (2014) for tests on language phylogenies), there is a little reason to pay attention to this side of the theory in this thesis. Divale proposes the following scenario which we can divide into two parts: external (migration) and internal (changes inside society) discussed in the following paragraph:

Suppose that a community (or at least, a significant subgroup of one) is forced to migrate to a new environment, which is already occupied. Such a situation could be caused by sudden environmental changes, such as a prolonged period of drought, societal collapse or when the community is pushed from its territory militarily. The sudden influx of people will put pressure on available resources, which will result in (external) warfare between natives and invaders. Due to this warfare, some villages will have greater mortality, typically those that are closer to a rival population. These villages would be pressured to replace their male population by persuading males from other villages not as affected by warfare to live there in exchange for wives, effectively adopting matrilocal residence. This is possible since males typically outnumber females due to female infanticide (Divale and Harris, 1976) and thus unmarried males are abundant in villages that practice warfare, but are not the target of raids. According to Divale, villages that adopt matrilocality will be more successful in waging warfare due to matrilocality preventing internal warfare. The other villages will recognize this peacefulness and adopt matrilocality as well, which will result in the adoption of matrilocality in the whole community. Divale's revised theory is shown at Figure 4.1.

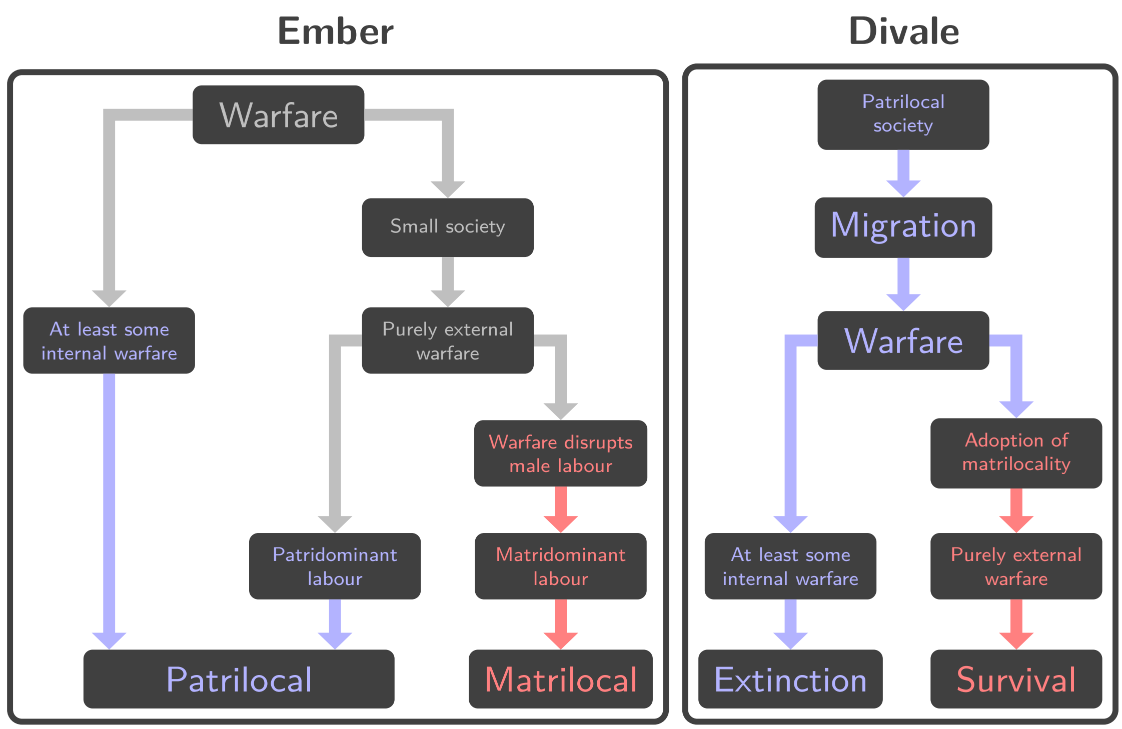


Figure 4.1: Comparison between Ember's and Divale's theories. Under Ember's theory, purely external warfare together with matridominant labour predict matrilocality, while any other conditions, such as some internal warfare or patridominant labour, produce patrilocality. Divale's theory on the other hands assume migration of patrilocal society into a new environment and if such society fails to adopt matrilocal residence, it faces extinction from internal warfare and lack of collaboration.

4.2.3 Comparison and synthesis

Both theories differ significantly not only in their content but also form. While Ember's theory describes conditions favouring one residence over other, Divale describes the development of residence with historical context. (Ember, 1974) stated that the main difference between those theories is in causal relationships of warfare and residence. In the *Warfare Theory of Matrilocality*, the type of warfare partially predicts residence, while in the *Migration Theory of Matrilocality*, the type of residence is partially responsible for the change in warfare pattern. This would however correctly describe only the internal warfare, as external warfare in Divale's theory is caused by resource competition between migrating and native population.

Regarding migration, Korotayev (2003) argues that the development of internal peace is a necessary precondition for a successful migration. And since the lack of internal warfare in medium-size stateless societies is connected with matrilocal residence, the proportion of matrilocal societies among migrating societies would be much higher since already matrilocal societies would be much more successfully in migration.

Note that if both Ember's lack of internal warfare in small society and Korotayev's abolishment of internal warfare as prerequisite to migration, are integrated into the Divale's theory, the difference of causal direction in both theories will disappear as this difference was in internal warfare which was removed from both theories through the effect of small society.

Under the assumption of small society without internal warfare, the modified Ember's theory (Ember, 1974) is as follows: Warfare, which is now only purely external, either disrupts patridominant labour, in which case the labour is matridominant and society is matrilocal or not, in which case the society will be patrilocal. Under the same assumptions, the modified internal part of Divale's theory (Divale, 1984) is following: After the migration, the purely external warfare cause increased the death rate of male warriors in the villages on the border of the society. If the village adopts matrilocal residence, it can replace its lost warriors by promising marriage to men from the core of the society which is not affected by warfare. However, if the village fails to adopt matrilocality, it cannot replace its warriors and goes extinct. Both modified theories are portrayed on Figure 4.2. This modified form makes both theories much more similar and much more comparable. Their main difference now lies in whether the adoption of a particular residence is influenced by warfare pressure or division of labour. In fact, with the additional modification described in the following paragraph, both (modified) theories can be conveniently merged.

In both versions of his theory (Divale, 1974, 1984), Divale suggested that the spread of matrilocality towards the core of society would be due to its recognized peacefulness by the members of core villages. These reasons were heavily criticized (Ember, 1974; Korotayev, 2003) and rightfully so. I don't think either that males would denounce their position of status and power just because neighbouring villages seem to be more peaceful. In fact, according to Divale the fraternal interest groups created by these males are the cause of the internal struggle. So either all villages must be close enough to the border to be affected by the pressure from warfare, but then there might not be enough males to replace, or some other social pressure must be in play, such as Ember's division of labour (Ember and Ember, 1971) or Korotayev's male absence (Korotayev, 2003). This modification of Divale's theory will essentially result in merging Ember's and Divale's theories into a single unified theory.

4.2.4 The Unified Theory of Matrilocality

The unified theory mentioned above is an amalgamation of Ember's and Divale's theories (see Figure 4.3. A small patrilocal society is engaged in warfare with another society. This might be due to migration as described by Divale (1974), but other cases might be possible. Since the society in question is small, warfare is purely external. In this situation, the patrilocal residence would be kept if the pressure from warfare was weak and/or with patridominant labour. On the other hand, the matrilocal residence would be adopted if pressure from warfare was sufficiently large, but without society going extinct, and if due

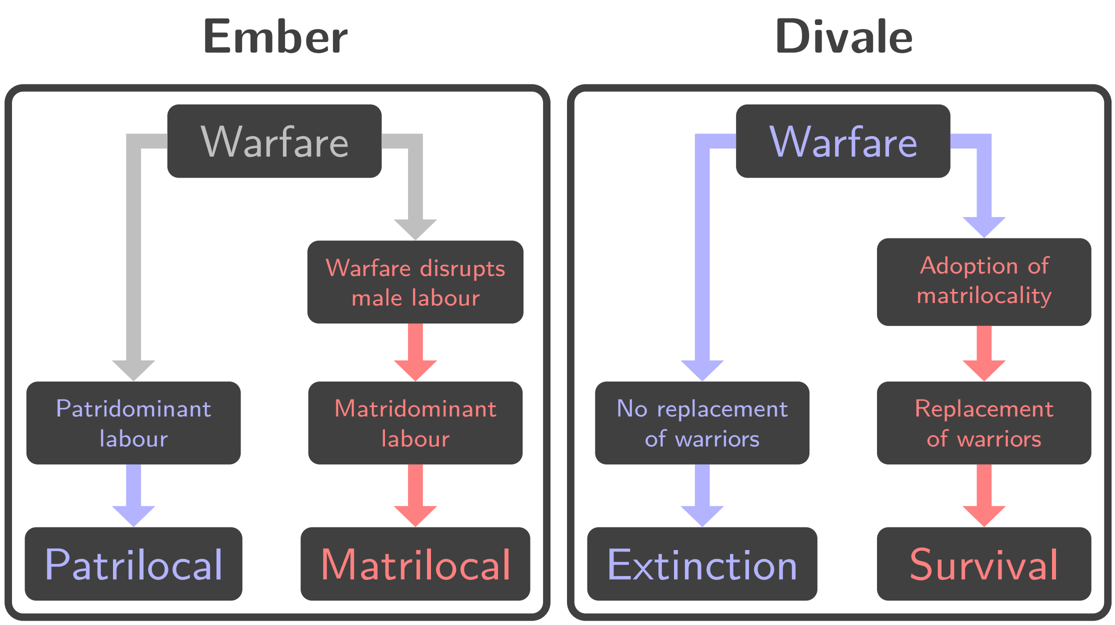


Figure 4.2: Modified Ember's and Divale's theories under the assumption of a small society. According to Ember, a small society is able to eliminate internal warfare due to the close relationship of most of its members. Applying this to Ember's and Divale's original theories (see Figure 4.1) significantly simplifies them and makes them more comparable. Under the assumption of small society and purely external warfare, the type of labour is purely responsible for the type of residence in Ember's theory, while in Divale's theory survival of society depends on whether it is able to adopt matrilocality as a response to the warfare pressure.

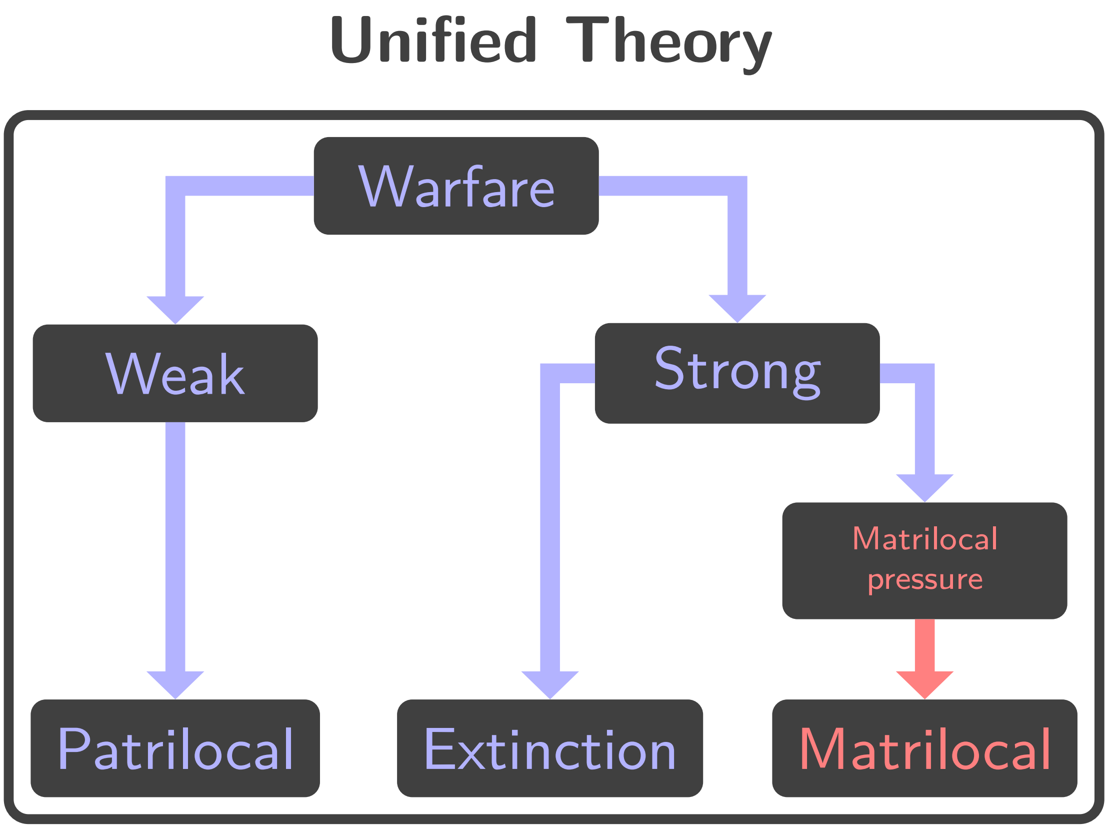


Figure 4.3: The Unified Theory of Matrilocality is an amalgamation of Ember's and Divale's theories. It connects the effect of the division of labour from Ember's theory, and warfare pressure and adaptive function of matrilocality from Divale's theory. This theory forms the base for the agent-based model described in this chapter.

to matridominant labour or some other societal pressure the matrilocal residence could propagate to the core of the society or majority of villages were under the warfare pressure without going extinct. This formulation of the unified theory of warfare is very convenient as a different aspect of this unified theory can be explored with an agent-based model.

4.3 Model of residence change

Following the discussion above, I have developed an agent-based model of warfare-induced residence change. The primary aim of the model is to simulate aspects of Ember's *Warfare Theory of Matrilocality* and Divale's *Migration Theory of Matrilocality*. Residence change is induced through three mechanisms: increased male mortality, the pressure to conform with residence norms of neighbouring villages and through a constant societal pressure towards the matrilocal residence.

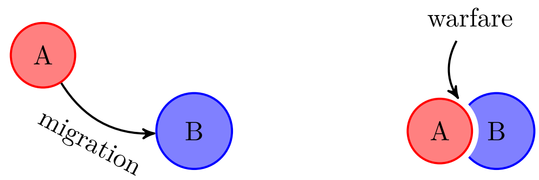


Figure 4.4: A simplified scheme of the *Migration Theory of Matrilocality*. Community A is forced to migrate to an environment already occupied by community B. Due to a lack of resources, this will result in external warfare between communities A and B.

4.3.1 Setting

The model simulates the Unified Theory of Matrilocality formed by restricting and merging Divale's and Ember's theories to small societies which prevent internal warfare. According to this unified theory, society is under warfare pressure from other society, perhaps because it migrated into the previously occupied environment (see Figure 4.4), which caused stress on some critically restricted resource as per Divale (1974). This external warfare will cause disproportional losses of males in villages near the border of the opposing community. Villages will adopt matrilocal residence to replace these loses by marrying males from the core of the society. Then, either through pressure to conform or through constant societal pressure towards the matrilocal residence, such as from division of labour, other villages will adopt matrilocal residence as well. In time, the whole society will become matrilocal.

4.3.2 Code availability

Source code for the model, implemented in Java using the Repast Simphony framework (North et al., 2013) is provided at `https://github.com/J-Moravec/abmwipmrc`. Analysis tools to process the model output, written in R, are available at `https://github.com/J-Moravec/abmwipmrc_data`.

4.3.3 Model structure

The model simulates the relationship between post-marital residence and external warfare for a set of interacting villages, the agent in our model, that together form a community. Villages are placed on grid 10 villages wide and 5 villages deep. One side of this grid borders another community, which is not closely simulated and which creates a constant warfare pressure and subsequent deaths of the male population in bordering villages. If all males die through this pressure, this cause village extinction and another village in the same row is subsequently attacked (see Figure 4.5).

Post-marital residence can change in three ways: through the warfare pressure mentioned above, marriage pressure, whereby villages are trying to change their residence to increase their access to the marriage market and through a constant social pressure for change towards matrilocality, which is added to the marriage pressure.

The villages interact with each other only through marriages between its members and subsequent population movement according to the post-marital residence of given marriage. Village population grows according to logistic growth.

Each simulation step represents five years, during which the demography of each village is simulated using a cohort model. During this time, marriage, population growth and warfare occur. In total, 1100 steps are simulated, with first 100 steps forming a warm-up phase without warfare to get remove the effect of starting conditions.

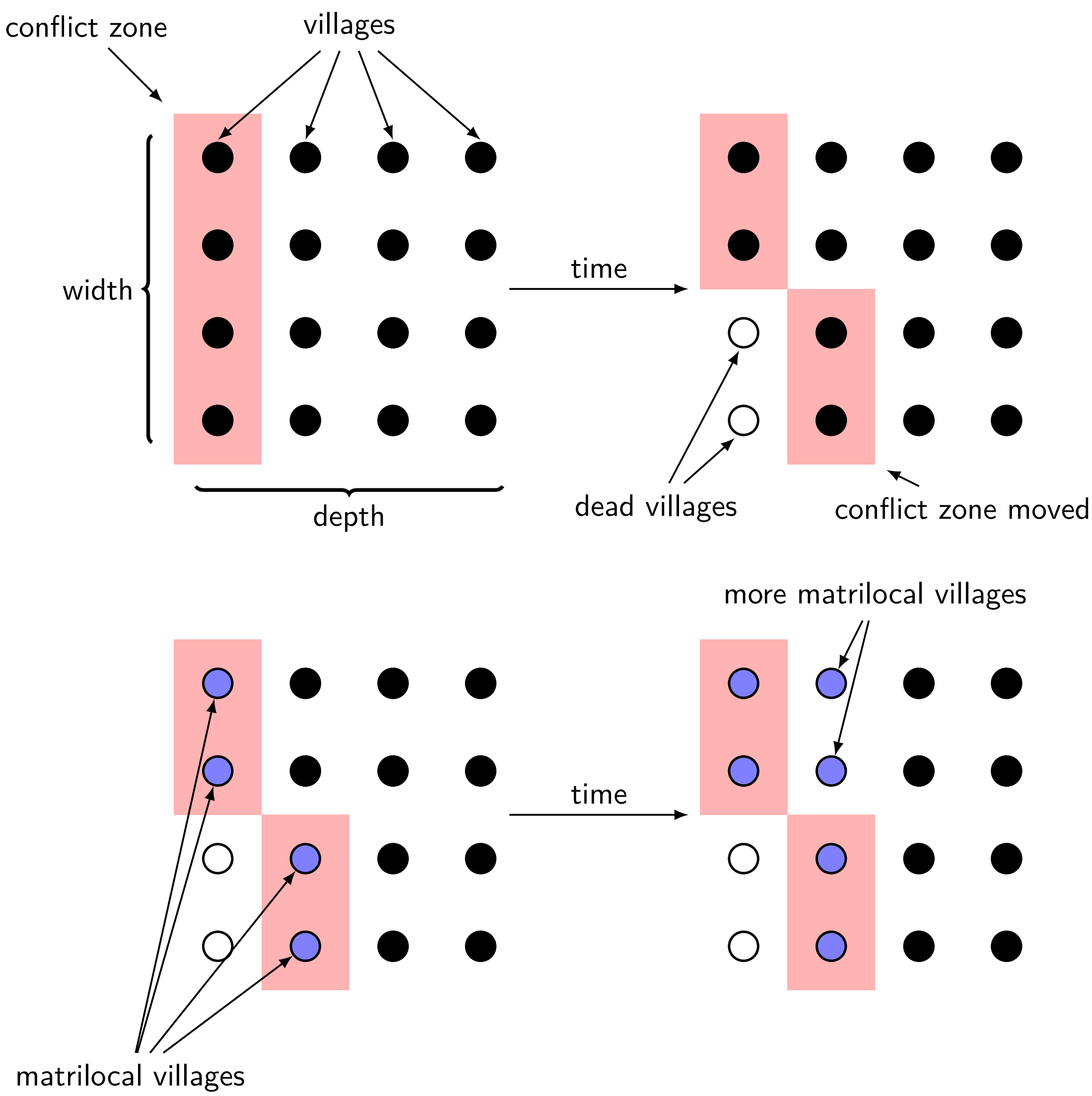


Figure 4.5: A graphical representation of modelled villages. Individual villages are positioned on a rectangular grid with all leftmost villages being under attack. When all the population in any leftmost village is killed, the next leftmost village in the same line will be attacked. At first, villages in the conflict zone change towards matrilocality due to significant male deaths from warfare. Later, due to marriage pressure from neighbouring villages, more villages can change to matrilocality, or revert back to patrilocality.

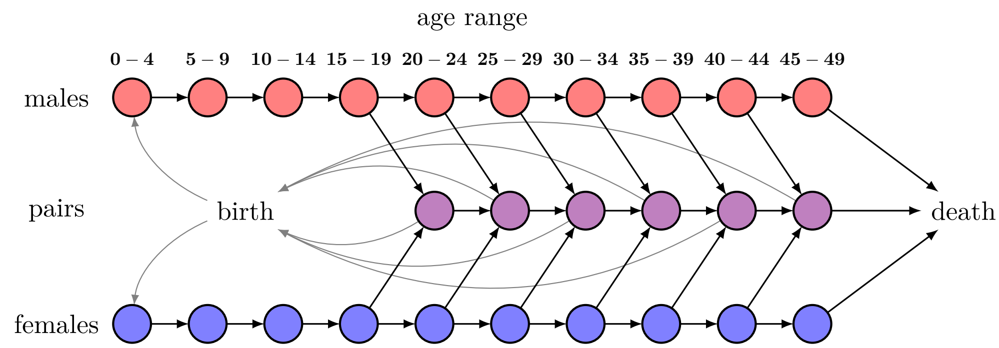


Figure 4.6: A graphical representation of cohorts and their dynamics. The population is tracked using cohorts for males, females and married pairs of various age. During each time-step, each cohort will age (represented by black arrows), until they die at age 50. During each time-step, unmarried males and females of eligible age can marry and form a pair, which produces children (represented by grey arrows). Not represented is warfare, where both unmarried and married males can die. If a married male dies, the pair is dissolved and the female becomes eligible to marry again.

4.3.4 Population structure

The population of villages was divided according to age, sex and marital status. People were grouped into age-groups (cohorts) spanning 5 years for a single simulation step, with the maximum age set to 50. After this age, death is assumed, although it could be interpreted as irrelevancy instead. In total, 10 age groups were created. The age of marriage was set to 20-25, which is also the year of first possible pregnancy. On the other hand, the first cohort capable of fighting was set to 15-20, since in many cultures, young males first need to show bravery in battle before they are allowed to marry. When two people get married, they are removed from their respective age-sex cohorts and put into a pair cohort; each pair thus represents two people. When one individual from a pair dies, i.e., due to warfare, the remaining individual is returned to its respective age-sex cohort (see Figure 4.6 for a visual representation).

The age of first marriage and birth significantly varies worldwide (Coale, 1992; Marlowe, 2005; Mensch et al., 2005), with men usually being a few years older then women. Given that marriage is allowed only between cohorts of the same age and the date of first birth follows usually a year or two after marriage (Meekers, 1992), I have opted for marriages and birth to be in age cohort 20-25, but age cohort 15-20 would be equally realistic.

4.3.5 Population growth

Population growth is assumed to be logistic. Only married pairs are eligible to have children and there is no difference in fertility between various age-groups. There is also no natural mortality except for the last age-cohort. The number of newborns is thus:

$$N_{newborns} = rN_{pairs}\left(1 - \frac{N_{total}}{K}\right) \tag{4.1}$$

where $N_{newborns}$ is the number of newborns, N_{pairs} is the number of pairs, N_{total} is the total population, r is growth rate and K is the capacity of the environment. The newborns are then distributed into respective sex cohorts according to a binomial distribution; this is to emphasize the importance of

Table 4.1: Mortality from primitive warfare across cultures.

Warfare mortality (population/year)	Reference	Note
$0.00069 - 0.00287$	Wrangham and Glowacki (2012)	69 to 287 dead chimpanzees per 10,000 individuals
0.00164	Wrangham and Glowacki (2012)	164 per 10,000 individuals
$0.00337 - 0.00404$	Chagnon (1988)	282 deaths from 1394 people over 50 to 60 years
0.000213	Mathew (1996)	8–25% of deaths from 400–500 warfare injuries for 375,000 people in Southern Highlands, New Guinea

marriage and to provide a slightly higher number of males. The ratio of males to females was set to: $\frac{116}{100}$, which means that the probability that newborn is male is $\Pr(\text{male}) = 0.537$.

4.3.6 Warfare

Only external warfare is implemented. This warfare is between simulated communities, only on the borders, and an abstracted enemy community, which influences the simulated community only through some warfare pressure. The warfare pressure W consists of two parameters: the number of soldiers P_e and the killing efficiency α.

The number of enemy soldiers P_e and the killing efficiency α are always used as part of the warfare pressure W, never alone. While this means that only a single parameter could be used instead, keeping them as separated parameters is more convenient as the P_e can be set to match population size of enemy village/society as approximately quarter of the population, while α can be estimated from literature (see Table 4.1).

4.3.7 Marriage

To simulate marriages, a randomly individual is selected to be married by first choosing a village, then cohort, then the sex of an individual. Then the type of marriage is selected, either corresponding to the village's residence (primary) or the opposite state (secondary). When an individual is selected, their partner can be determined by randomly choosing their partner from the same age-cohort, but opposite sex in the neighbourhood of the chosen individual. This process is repeated according to the following steps until no marriage is possible:

1. Choose a source village X from all villages with the probability proportional to the number of marriageable people.

2. For the source village X, choose a cohort c with the probability proportional to the number of marriageable people in it.

3. For the chosen cohort c and village X, choose a sex s with the probability proportional to the number of marriageable people of each sex in the specific cohort c.

4. Choose a type of marriage (primary or alternative) with predefined probability p.

5. Pick a target village Y from villages neighbouring X (including X) with the probability proportional to the number of marriageable partners of chosen cohort c and sex s marriage weights.

6. If no partner is possible, temporarily remove the person of the chosen sex and cohort from the source village. If this results in an empty village, remove it from a list of marriageable villages.
7. If a partner can be found, remove both people from their respective cohorts and create a pair in the village according to the chosen type of marriage (i.e., the pair moves to the husband's village if the marriage is patrilocal or to the wife's village if the marriage is matrilocal). If this results in empty villages, remove them from the list of marriageable villages.
8. Repeat until the list of marriageable villages is empty.

The probability that a village X will be chosen as a source village during the simulation step is:

$$\Pr(X\heartsuit) = \frac{\mathcal{M}_X}{\sum_{i \in \Omega \mathcal{M}_i}} \tag{4.2}$$

where $\mathcal{M}_X$ is the number of marriageable people in village X, i.e., all non-pair cohorts of both sex starting with the fifth age-cohort: $\mathcal{M}_X = \sum_{j=5}^{10} M_j + F_j$, where M_j are male and F_j female marriageable cohorts, and Ω stands for all villages in simulation (or all villages in list of marriageable villages). The probability of choosing a specific age-cohort index c is:

$$\Pr(c) = \frac{M_c + F_c}{\sum_{j=5}^{10} M_j + F_j} \tag{4.3}$$

The choice of sex s after the cohort was chosen is:

$$\Pr(s|c) = \frac{S_c}{S_c + \widehat{S_c}} \tag{4.4}$$

where S_c is the number of people of sex s in age category c and $\widehat{S_c}$ similarly for the opposite sex. The choice of marriage type depends only on the residence of village R_X. The probability of primary marriage (i.e., the same as village residence) is p and the probability of the alternative marriage is $1 - p$. This probability can range from 0.5 to 1, where 0.5 means no difference between marriage types and 1 means that no cross-marriage between marriage types is possible. This probability is also used as the marriage-weight later. The probability of choosing the target village Y is:

$$\Pr(X\heartsuit Y | X\heartsuit R, s, c) = \frac{w_Y \mathcal{M}_{scY}}{\sum_{i \in D_{I_X}} w_i \mathcal{M}_{sci}} \tag{4.5}$$

where $\mathcal{M}_{sci}$ is number of people in the specific unmarried age-sex cohort of village i and D_{I_X} are villages in interaction distance of X. The interaction distance was set to 1, so that only immediately neighbouring villages are considered. The marriage weight w_i is p if the type of marriage R is equal to the residence of i and $1 - p$ otherwise.

4.3.8 Residence change

Three mechanisms of residence change were implemented: change from warfare-induced loses, change to maximize marriages and a constant pressure towards matrilocality.

The probability that a village will switch from patrilocal to matrilocal residence from warfare-induced losses is:

$$\Pr(R_P \to R_M) = \frac{W}{P} = \frac{\alpha P_e}{P} \tag{4.6}$$

Table 4.2: Parameter sweeps used in the simulations.

Sweep	Extent	Set Size	Added Parameter	Values
1	Full	6,480		
2	Restricted	2,700	Depth	1, 2, 3
3	Restricted	4,500	Matrilocal pressure	0.1, 0.3, 0.5, 1, 2
4	Restricted	1,800	Matrilocality allowed	Yes, No

Where P is the military power of village, which is equal to the sum of all fighting cohorts, i.e.:

$$P = \sum_{i=4}^{10} M_i \tag{4.7}$$

where M_i are male cohorts and M_4 is the cohort with age-range 15-20.

The probability that a village will change residence due to marriage pressure is:

$$\Pr\left(R \to \widehat{R}\right) = \max\left\{0, 1 - \frac{\sum_c \left(F_{c_X} \frac{\mathcal{P}_{mcX}}{\widehat{\mathcal{P}_{mcX}}} + M_{cX} \frac{\mathcal{P}_{fcX}}{\widehat{\mathcal{P}_{fcX}}}\right)}{\sum_c \left(M_{cX} + F_{cX}\right)} + \gamma\right\} \tag{4.8}$$

where R is current village residence, $\widehat{R}$ is alternative residence, F_{c_X} and M_{c_X} are specific marriageable female and male age cohorts of X, γ is matrilocal pressure (negative, if village is matrilocal, positive if patrilocal), and $\mathcal{P}_{mcX}$ and $\mathcal{P}_{fcX}$ are potential partners for a specific male or female age cohort:

$$\mathcal{P}_{scX} = \sum_{i \in D_{I_X}} w_i \mathcal{M}_{sci} \tag{4.9}$$

This means that village will change its residence if it expands its access to the marriage market, the number of potential partners, or if the loss of marriage access is compensated by the social pressure towards matrilocal residence.

4.3.9 Order of evaluation

Each 5-year time-step in our model includes marriage, growth and warfare and. residence change, evaluated in this order. Each step, except marriage, is computed for all villages before the following step begins. Marriages are evaluated for all villages at once according to the marriage model described above.

4.3.10 Experimental design

The behaviour of the model was explored using four parameter sweeps. The first parameter sweep used a broad parameter grid (full parameter set) to explore the effect of warfare under a broad range of parameter values. This was restricted for other three parameters sweeps (restricted parameter set) to reduce the computational intensity as additional parameters ere added: the depth of the village grid, matrilocal pressure, and the ability to prevent transitions to matrilocality altogether. For an overview, see Table 4.2 for parameter sweeps, Table 4.3 for variables in parameter sets, and Table 4.4 for other fixed parameters used in simulation.

The model was run 50 times for each parameter combination to obtain a reliable sample of model stochasticity. Each run was simulated over 1100 time steps with the first 100 steps being a burn-in

Table 4.3: Parameter values in the full and restricted parameter sets.

Parameter	Name	Set	Values	No. Parameter Values
r	Growth rate	Full	0.4 – 0.8; increment 0.05	9
		Restricted	0.4 – 0.8; increment 0.1	5
P_e	Enemy soldiers	Full	0, 100, 200, 300	4
		Restricted	100, 200, 300	3
K	Carrying capacity	Full	100, 500, 1000	3
		Restricted	500, 1000	2
α_y	Yearly warfare mortality	Full	0.005 – 0.06; increment 0.005	12
		Restricted	0.005 – 0.055; increment 0.01	6
p	Preferred marriage weight	Full	0.5 – 0.9; increment 0.1	5
		Restricted	0.5 – 0.9; increment 0.1	5

Table 4.4: Fixed model parameters.

Parameter	Value
Number of cohorts	10
Starting Population of each cohort	10
Male cohorts that participate in warfare	3 to 10
Male and female marriageable cohorts	4 to 10
Male to female birth ratio	116:100
Total number of steps	1100
Length of the warming phase (no warfare)	100

phase without warfare to remove the effect of starting conditions. This burn-in phase was excluded from subsequent analyses.

Parameter values

An extensive literature search was performed to assure that the model is run under realistic parameter conditions.

In the model, the growth rate is perceived as an average number of children that survive to maturity born to a single female during a time-step. This number thus includes not only fertility, birth spacing, but also survival rate. The interbirth interval is about 4 years for hunter-gatherers (Konner and Worthman, 1980), conveniently close to the model time-step of 5 years, and is further reduced in sedentary societies (Armelagos et al., 1991). Natural fertility, the total number of children per female, is on average 5.5 for hunter-gatherers and horticulturalists and 6.6 for agricultural societies (Bentley et al., 1993), in the model where pairs can produce children during 6 time-steps, the growth rate without survival would be between 0.91 and 1.1. However, 30% to 40% of children would not survive until adulthood (Michael and Hillard, 2007), this would produce a growth rate 0.54 to 0.77. I chose the values of growth rate 0.4 to 0.8, given that 0.4 is a value close to replacement value given death at age 50. These final values would produce 2.4–4.8 children per female that survived to adulthood. These numbers are very close to 2.85–3.4 values estimated by Hassan and Sengel (1973).

For the capacity of an environment, I have chosen values: 100, 500 and 1000. These values cover the most probable village sizes. And while larger agricultural population are possible (see e.g., Kuijt, 2000), the village sizes for most societies in the ethnographic atlas are under 1000 and it is doubtful that a larger group would migrate and settle during the assumed scenario. Related to the capacity of an environment is the warfare pressure, i.e., a number of enemy warriors of non-simulated enemy villages. Chosen values were 100, 200 and 300, which represent 10%, 20% and 30% of the largest allowed population.

Killing efficiency α was set to value range between 0.005 and 0.06 and while these may be higher than the historical values in Table 4.1, the chosen values represent mortality during an intensive warfare period and only individuals engaged in warfare. Yearly values of warfare mortality are then recalculated into the time-step period as they would be applied every year.

Finally, for the preferred marriage weight, the full range between no preference (0.5) and almost exclusive preference (0.9) for the primary marriage was explored.

4.4 Results

A significant warfare pressure was consistently able to cause the transition towards matrilocality in villages neighbouring the enemy population for a wide range of parameters. While this is a good indicator that a correct part of parameter space is being explored, it is not entirely unexpected. Given that the change of residence due to warfare is coded into the model, we would expect villages under significant warfare pressure to transition towards matrilocality. Similarly, the high values of matrilocality with runs surpassing 80% (Figure 4.7) or even 90% outside of time-points of interest (Figure 4.8) are not surprising, since due to village extinction, a large portion of villages are under warfare pressure and thus higher values of matrilocality are to be expected as well.

To solve this problem, I therefore define the Expected Matrilocality (EM) as the highest value of matrilocality that would be expected for a particular number of villages: $\min\left\{1, \frac{10}{\text{villages}}\right\}$. Note that EM is reached only for parameter combinations with a significant warfare pressure since without it even villages neighbouring the enemy population might not be forced to turn towards matrilocality and thus runs with matrilocality lower than EM are readily observed. By comparing EM with the average reached matrilocality of all villages, we can identify runs where, through marriage pressure, matrilocality was able to spread beyond the area under the warfare pressure (i.e., the first line of villages). I call this Surpassed Expected Matrilocality (SEM) and it will come in two forms, first the number of runs (and/or time-points of interests) with matrilocality greater than EM (nSEM) and their average value of SEM (vSEM). Using these two statistics, we can easily summarize a large number of runs of interest, either whole parameter sweep, performance at the time-points of interest or effects of specific parameters. Furthermore, we can state that these statistics would be sufficient, at least regarding matrilocality, given that the model runs can be divided into a relatively limited number of classes (see Figure 4.8).

4.4.1 Switch to matrilocality

While a significant warfare pressure was able to consistently cause transition towards matrilocality in parameter seep 1, this however did not significantly transition into the spread of matrilocality beyond the villages under the warfare pressure and across time points. If the expected matrilocality was surpassed, then only barely (nSEM(%) = 0.0362, vSEM= 0.0009, see Table 4.5). This is concerning as this parameter sweep was designed to cover a wide range and combination of parameters, such as strong warfare pressure and weak growth rate or weak warfare pressure and strong growth rate, and their effects were identified and observed in the shape and behaviour of time series (Figure 4.8), but did not have a significant effect on the spread of matrilocality past the area under warfare pressure. Even the maximal value of vSEM (0.0362) in parameter sweep 1, which was observed at the end of the simulation at time 1000 and is much higher than any other observed value, is still very far away from the maximal possible value for the given number of villages (0.3342) and the maximal value for the whole dataset (0.8) (see Figure 4.7). While I cannot completely rule out that there is a parameter combination that can produce a significant value of vSEM, this is strong evidence that the adoption of matrilocality due to warfare is by itself insufficient for a spread of matrilocality through the community and its fixation in this model.

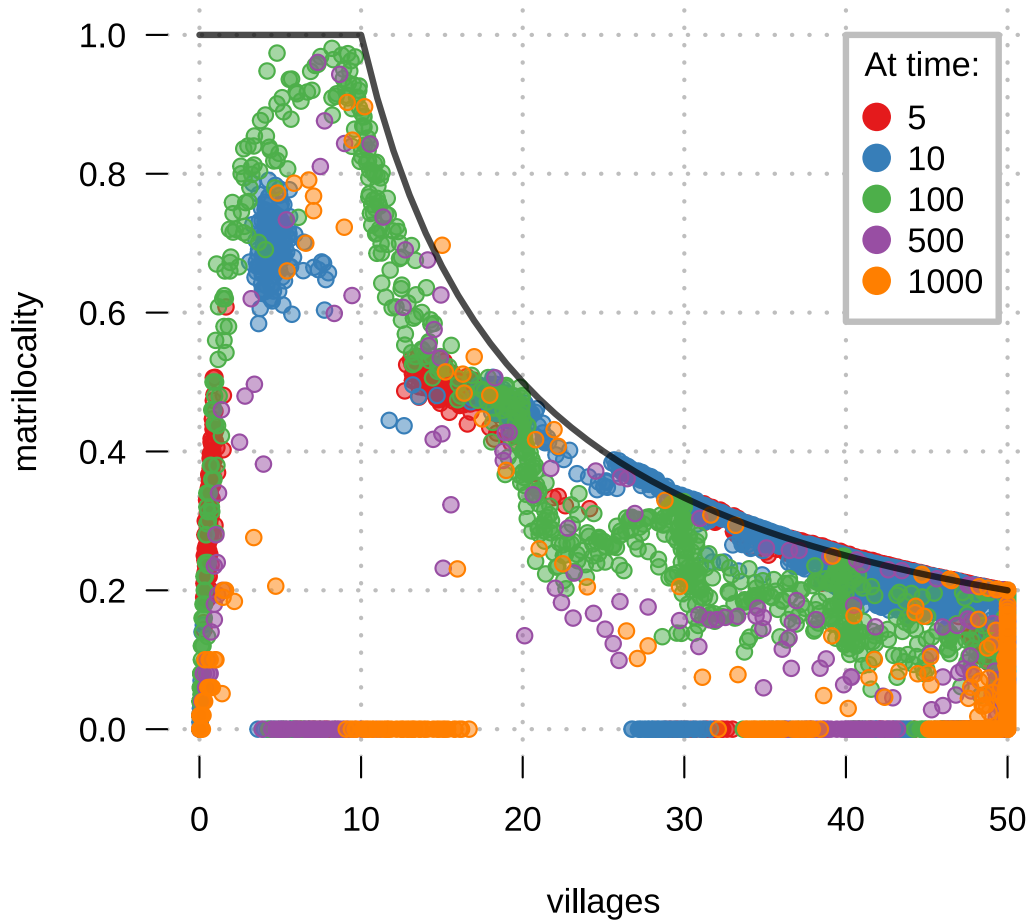
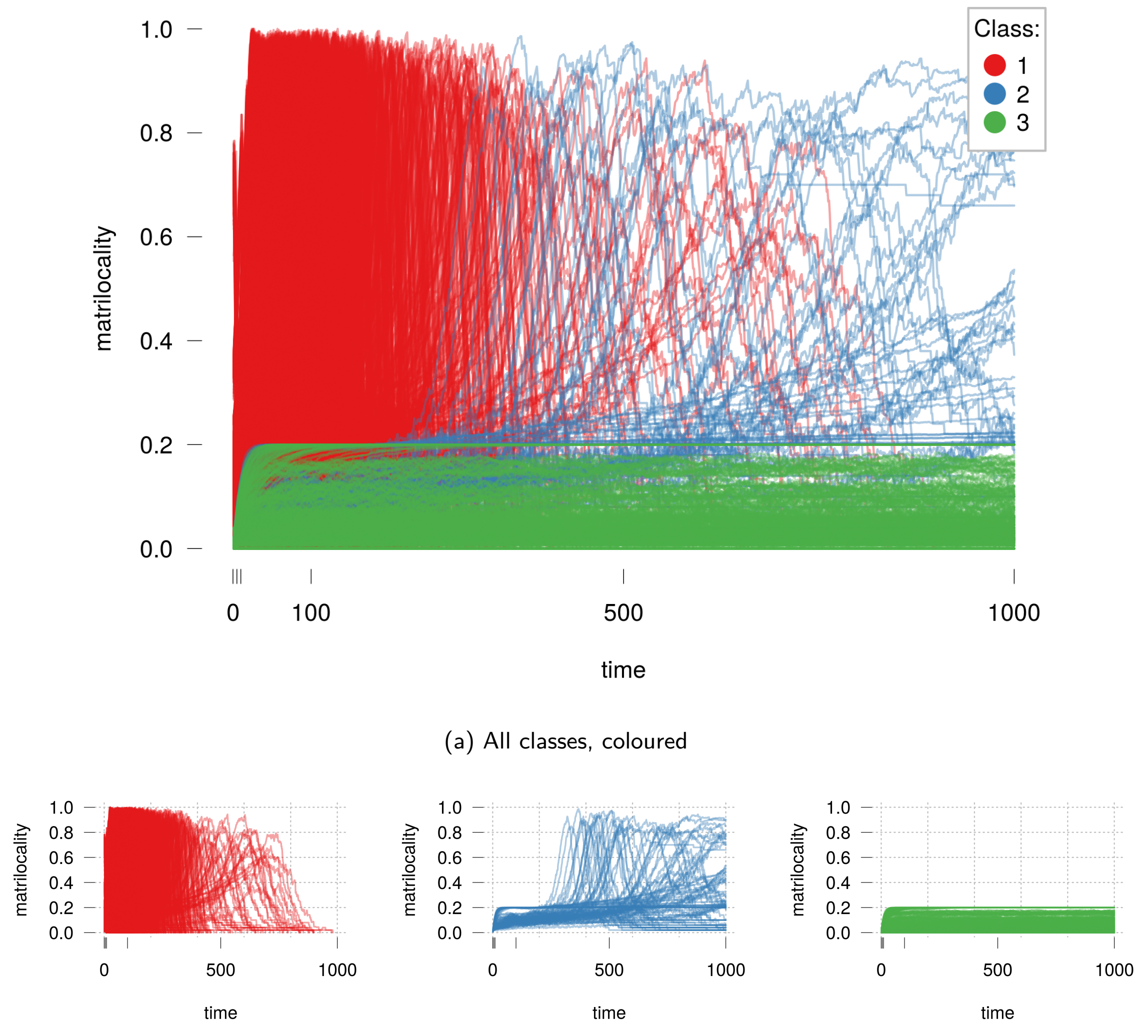


Figure 4.7: Percentage of matrilocality and number of villages in studied time-points. Each point represents a simulation with different parameter combination with the black line representing the expected matrilocality for the current number of villages. A higher percentage of matrilocal villages is reached only when a significant portion of villages was already destroyed by warfare and thus a large percentage of villages is affected by warfare pressure.



(a) All classes, coloured

(b) Class 1

(c) Class 2

(d) Class 3

Figure 4.8: Time-series of matrilocality for all runs from parameter sweep 1 divided into 3 classes major classes according to their characteristic shape and behaviour. Runs from Class 1 (4.8b) are characterized by rapid growth, peaking close to 100% matrilocality and then followed by a drop to zero, these represent cases where the whole population went extinct due to a combination of strong warfare pressure and small growth rate. Runs from Class 2 (4.8c) can have similar progress, but either grow much more slowly or later and do not drop to zero in the observed time-frame. These represent cases with both significant warfare pressure and growth rate so that the extinction of all villages do not occur or is at least significantly delayed. Finally, runs from Class 3 (4.8d) never reach values higher than 20% of matrilocality and represent runs where a significant growth rate prevents the extinction of any villages and cases where the warfare pressure might not be significant enough to cause the change of residence. Note that Class 2 is relatively variable and could be subsequently divided into a more detailed classification.

Table 4.5: Summary of runs from the parameter sweep 1.

Time	Runs						vSEM	
	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
5	6,480	6,269	96.74	654	0.10	10.43	0.0009	0.0052
10	6,480	6,143	94.80	517	0.08	8.42	0.0009	0.0055
100	6,480	2,664	41.11	0	0	0	0	0
500	6,480	1,804	27.84	0	0	0	0	0
1000	6,480	1,713	26.44	2	0	0.12	0.0159	0.0312
all	32,400	18,593	57.39	1,173	0.04	6.31	0.0009	0.0312

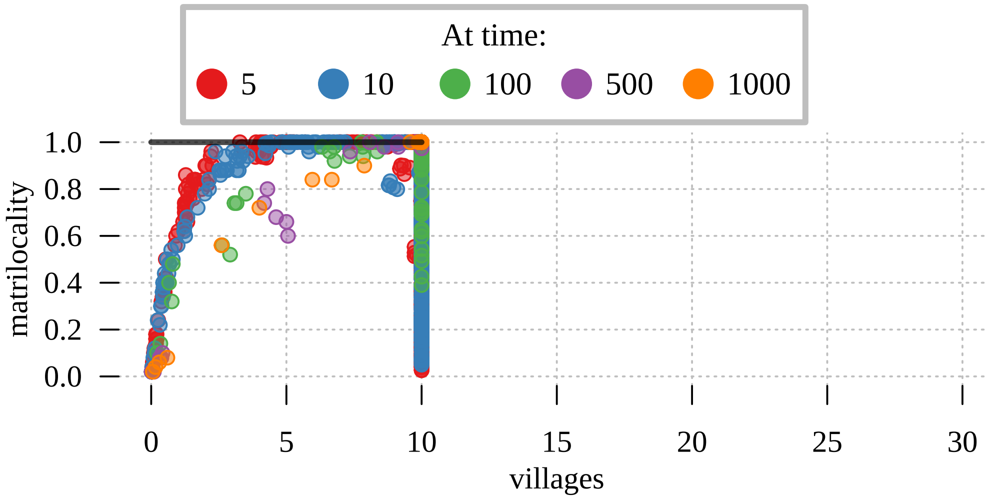
Table 4.6: Summary of runs from parameter sweep 2.

Time	Runs						vSEM	
	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
5	2,700	2,624	97.19	214	7.93 8.16	0.0037	0.0174	
10	2,700	2,266	83.93	151	5.59	66.66	0.0041	0.0142
100	2,700	527	19.52	20	0.74	38.00	0.1269	0.3560
500	2,700	358	13.26	64	2.37	17.88	0.3421	0.500
1000	2,700	340	12.59	81	3.00	23.82	0.3883	0.500
all	13,500	6,115	45.30	530	3.93	8.67	0.1081	0.500

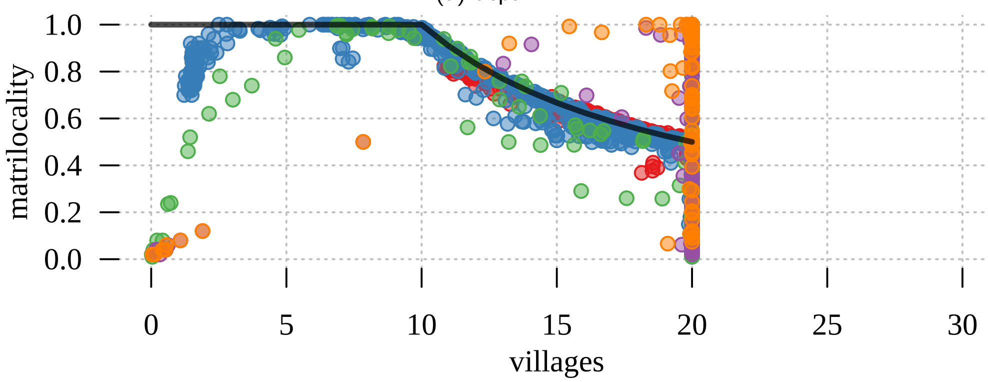
Size of community

The parameter sweep 1 explored behaviour of the model on a fixed grid to ascertain if the warfare-induced matrilocality can spread through the community and concluded that the marriage pressure from patrilocal communities behind the area under warfare pressure forms a significant barrier against the spread of matrilocality. To test if a smaller depth of community (i.e., a higher portion of villages engaged in warfare) can decrease the marriage pressure and allow the spread of matrilocality, I have simulated the model with parameter sweep 2 which allowed the depth to take values between 3 to 1. With width remaining constant, the total amount of villages decreased to 30, 20 and 10 for depth 3, 2 and 1 respectively. In these cases, the reached proportion of matrilocal villages is much higher, readily reaching 100% (Figure 4.9), but that is not as surprising, since the EM= 1 for depth 1 and while the total percentage of nSEM is not different from parameter sweep 1 (sweep 1 nSEM(%) = 0.362, sweep 2 nSEM(%) = 0.393), the values are significantly higher (sweep 1 vSEM= 0.0009, sweep 2 vSEM= 0.1081) (Table 4.6). A closer look reveals that the most successful configuration in reaching high values of vSEM is the depth 2, which consists of two layers of villages with one engaged in warfare (see Table 4.7) and the maximal values for depth 2 are reached at least in the second half of the simulations from time 500 onwards. Not only that the high percentage of matrilocality could be reached without loss of a single village, but the percentage of matrilocality was higher than in other simulations with a higher starting number of villages (i.e., parameter sweep 1).

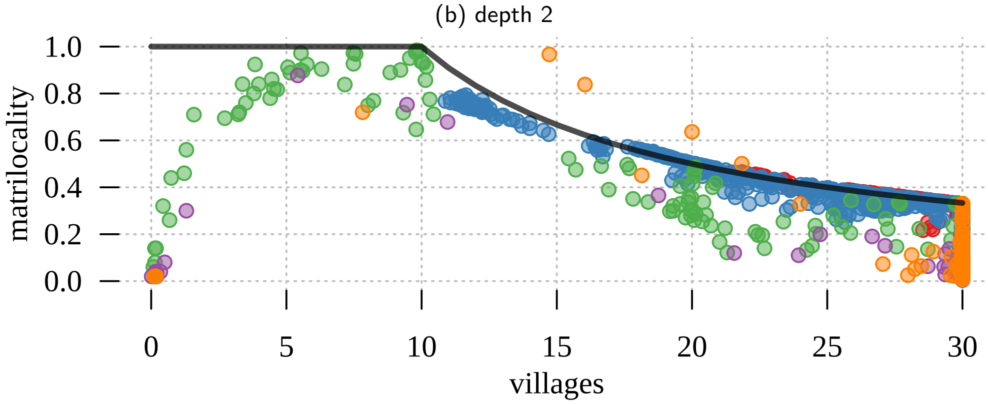
While in hindsight these results are not surprising since the change of residence due to warfare is encoded into the model and by increasing the percentage of population under the warfare pressure, we are also increasing the role of this predetermined behaviour, i.e., in the extreme case of depth 1, EM= 1 and thus by definition nSEM= 0. This however means that certain types of networks, other than simple grids, could promote residence changes and this network effect (especially for more complex structures) was ignored by both Ember and Divale apart from a realization that smaller societies tend to be more matrilocal than larger societies. And while I would not go so far as to suggest that during world wars, a



(a) depth 1



(b) depth 2



(c) depth 3

Figure 4.9: The proportion of matrilocality and number of villages for varying depth of community in studied time-points. Each point represents a simulation with different parameter combination and the black line represents the expected percentage of matrilocality for the current number of villages. Figure 4.9a represents a situation with all villages under warfare pressure and thus a high percentage of matrilocality is expected. In Figure 4.9b, there are two layers of villages with one layer under warfare pressure. In this situation, a high percentage of matrilocality is reached even without any extinction event. Finally, Figure 4.9c is similar to Figure 4.7, the two layers of villages not under warfare are sufficient to stop the spread of matrilocality.

Table 4.7: Summary of runs of parameter sweep 2 for different values of depth.

Depth	Runs						vSEM	
	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
1	4,500	1,594	35.42	0	0	0	0	0
2	4,500	2,236	49.69	406	0.09	18.16	0.1384	0.5000
3	4,500	2,285	50.78	124	0.03	5.43	0.0089	0.2873

Table 4.8: Summary of runs of parameter sweep 3 for different values of matrilocal pressure.

Matrilocal	Runs						vSEM	
Pressure	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
0.1	4,500	2,444	54.31	742	0.16	30.36	0.5626	0.8000
0.3	4,500	2,475	55.00	1,446	0.32	58.42	0.5737	0.8000
0.5	4,500	2,487	55.27	1,795	0.40	72.18	0.5794	0.8000
1	4,500	2,494	55.42	2,262	0.50	90.70	0.6438	0.8000
2	4,500	2,498	55.51	2,439	0.54	97.64	0.7767	0.8000

large portion of the population was under warfare pressure and thus according to my model a society should turn to matrilocality, the way a pre-state societies wages warfare should be considered in this regard. For example, if a number of villages band together to create an organized response against an enemy, this (at least partially) negates the need to replace soldiers in villages near the enemy, as a local defender is no different from an allied one, and this prevents the need to change towards matrilocality.

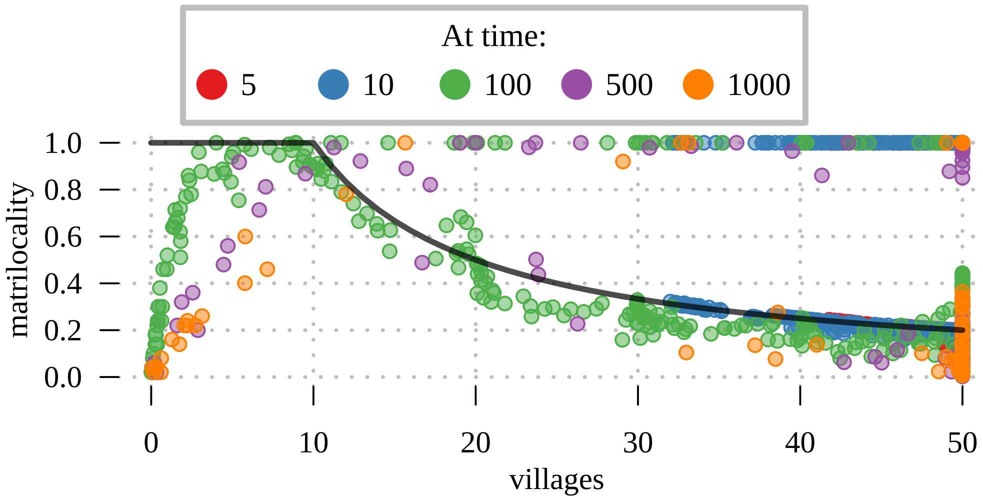
Matrilocal pressure

By including a small matrilocal pressure as a value that is added or subtracted to marriage pressure in favour of matrilocality we can simulate the effect of the matridominant division of labour and subsequently test its effect on adoption of matrilocal residence (parameter sweep 3). Surprisingly, even a small matrilocal pressure (Figure 4.10) was able to increase an adoption of matrilocality (vSEM= 0.5626 for matrilocal pressure 0.1, see Table 4.8) and in numerous cases even lead to its fixation. A more detailed exploration of data shows that the adoption of matrilocality comes relatively

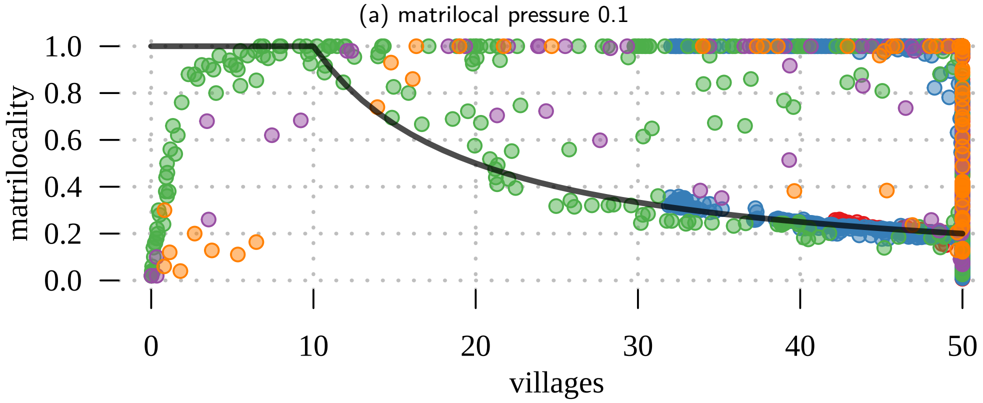
To further isolate the effect of matrilocal pressure from warfare, an additional simulation with matrilocal pressure, but without warfare, was performed. In this simulation, matrilocal pressure alone was able to induce residence change towards matrilocality (Table 4.9). However, large population and marriage weights could effectively block transitions towards matrilocality. This is not s problem when matrilocal pressure is combined with even small amount of warfare. This suggests that pressures other than warfare are sufficient for adopting post-marital residence, but the transitions are more likely in a wider range of conditions when combined with warfare.

4.4.2 Adaptive effect of matrilocality

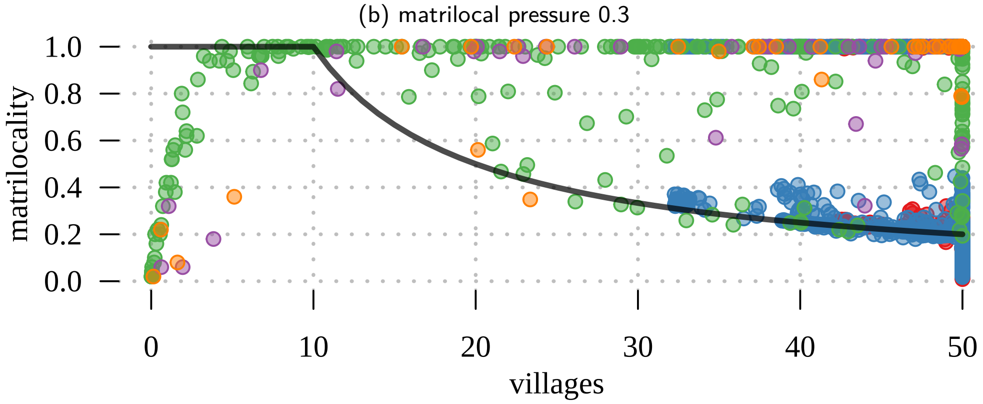
The adoption of matrilocal residence while under strong warfare pressure is intended to reflect adaptive qualities of matrilocality. However, adopting a different residence state can cut a village from the rest of the population due to cultural barriers decreasing the probability of marriage. It is thus not completely clear if matrilocality does provide an adaptive advantage. This was tested by modifying the model and disabling the switch to matrilocality altogether (i.e., during the model run, no residence change happens



(a) matrilocal pressure 0.1



(b) matrilocal pressure 0.3



(c) matrilocal pressure 0.5

Figure 4.10: The proportion of matrilocality and the number of villages for various sizes of matrilocal pressure at studied time-points. Each point represents a simulation with a different parameter combination and the black line represents an expected percentage of matrilocality for a current number of villages. Figures 4.10a, 4.10b and 4.10c show runs with values 0.1, 0.3 and 0.5 of matrilocal pressure. Even small values of matrilocal pressure lead to an increase of matrilocality and its fixation in the population.

Table 4.9: Comparison between matrilocal pressure with and without warfare.

Warfare	Runs						vSEM	
Pressure	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
0.0	1,250	1,200	96.00	643	51.44	53.58	0.7752	0.8000
0.5	1,250	1,118	89.44	792	63.36	70.84	0.7514	0.8000

Table 4.10: Summary of runs for parameter sweep 4. This sweep tests if adoption of matrilocal residence provides an adaptive function.

Matrilocality Allowed	Runs						vSEM	
	Total	Survived	Survived (%)	nSEM	nSEM (%)	nSEM (% surv.)	Mean	Max
Yes	4,500	2,429	53.98	91	0.02	3.75	0.0006	0.0027
No	4,500	2,369	52.64	0	0	0	0	0

and all villages stay patrilocal) against a normal run (parameter sweep 4).

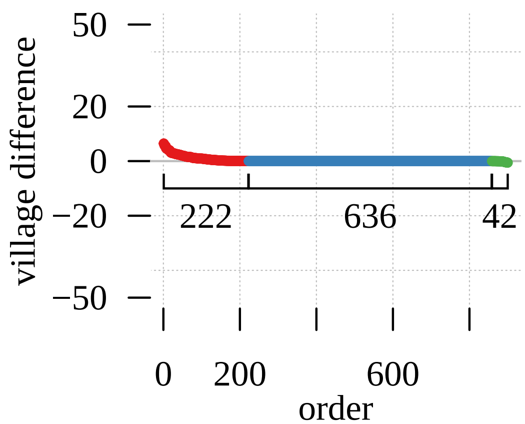
While the values summarized across all time-points Table 4.10 show small, but probably not a significant difference in survival (52.5% compared to 54% when the transition to matrilocality is permitted), by comparing directly the difference in the number of villages between these two runs for all parameter combinations, we can get a much more detailed and accurate answer. Figure 4.11 shows that matrilocality provides a significant adaptive advantage, while the small distance from zero can be explained by the stochastic nature of the model, the big distance from zero means that there is a significant difference in behaviour between matrilocal and non-matrilocal runs. Since the red part is always more dominant, this means that there is a significant benefit for the population from the ability to switch to matrilocality that increases in time. If the green part was dominant, this would mean that the ability to switch to matrilocality is actively harming the society. In rare cases, the switch to matrilocality can prevent the extinction of the entire population (Figure 4.11e). This explains the small difference in survival rates summarized overall time-points since while the difference between matrilocal and non-matrilocal runs is clearly visible, in most cases switch to matrilocality does not completely prevent an extinction and when it does, the effect is significant only at the end of the simulation, while points from the start of the simulation are over-represented.

4.5 Effect of individual parameters

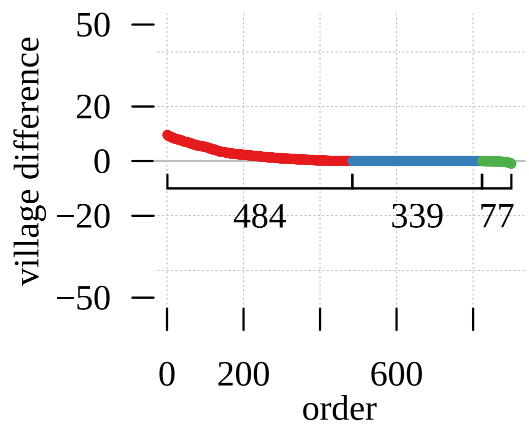
The parameters used in this model can be divided into two groups, demographic parameters, which could be further divided into growth-related (growth rate and carrying capacity) and warfare related (warfare pressure and yearly warfare mortality), and the marriage parameters, which are represented only by the preferred marriage weight, which represents a marriage preference for a person with the same residence state.

Most of the demographic parameters across parameter sets had relatively monotone behaviour, with the most common pattern being a decreasing nSEM and increasing vSEM with an increasing value of the parameter for warfare related parameters and increasing nSEM and decreasing vSEM for growth-related parameters. In a few cases, the pattern disappears when the nSEM is corrected for a survival rate since the population in a run (in a particular time-point) must be alive in the first place to be counted into nSEM and thus parameters that decrease survival rate will decrease a possible pool of SEM runs.

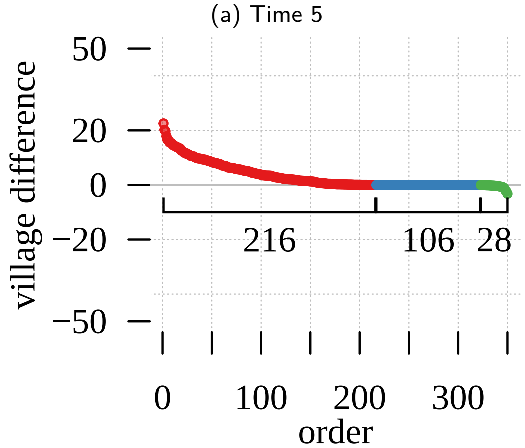
The only consistently non-monotonic behaviour of demographic parameters was found in the growth rate. There the smallest value of parameter attained the highest values of nSEM, followed by a drop



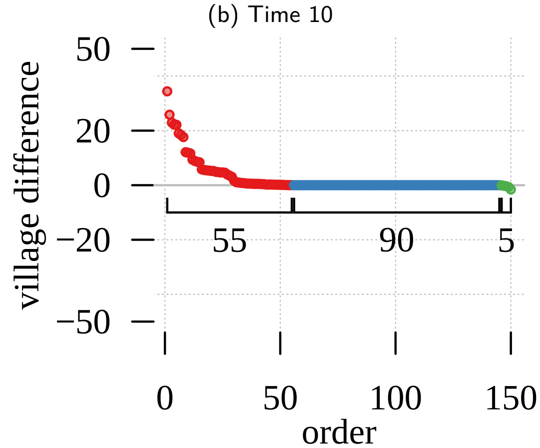
(a) Time 5



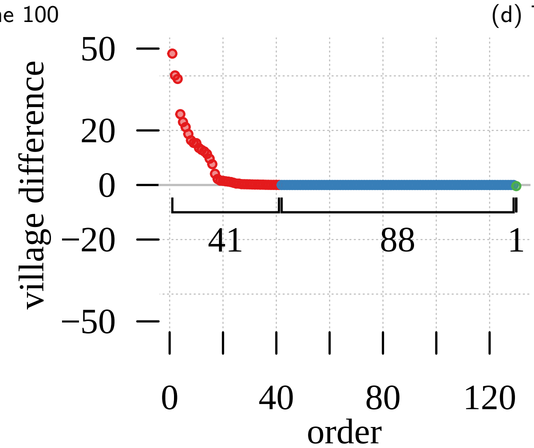
(b) Time 10



(c) Time 100



(d) Time 500



(e) Time 1000

Figure 4.11: Effect of matrilocality on survival. Graphs show the difference in the average number of villages between matrilocal (i.e., where a switch to matrilocality is allowed) and non-matrilocal (where a switch to matrilocality is not allowed) runs. Each point represents a particular combination of parameters and is coloured according to the difference between matrilocal and non-matrilocal runs, red when matrilocal runs have a higher number of villages, blue when they are equal and green when matrilocal runs have a smaller number of villages. Combination of parameters where both matrilocal and non-matrilocal runs had 0 villages are not shown.

and slow rebound, but to a considerably smaller value. While this may indicate a possible point of interest in this area of parameter space, this is unlikely since the vSEM values were maximized on the opposite side of parameter space.

The effect of preferred marriage weight differed between parameter sets. In parameter set 1, the behaviour was monotonic with greatest nSEM and vSEM for the maximal value of the weight which might suggest that the existence of the barrier is important for maintaining matrilocality, however since no run in set 1 significantly surpassed EM, this probably holds little value. In parameter set 2, the smallest value of marriage weight (0.5, indicating no preference between residences) had the smallest nSEM and vSEM, for the other values of marriage weight, the nSEM was relatively constant, but the vSEM reached a maximum at the second smallest value and then slowly decreased. Finally, for the parameter set 3, the nSEM and vSEM are both monotonous with a maximum at the smallest value. This behaviour shows a complex relationship between a cultural tradition and its convenience in a particular situation.

4.6 Discussion

In the past, post-marital residence was studied only through association tests (e.g. Driver, 1956; Brown, 1970; Ember and Ember, 1971; Divale, 1974). While these were able to discover associations between residence and factors such as warfare, division of labour by sex or size of community (Ember and Ember, 1971; Ember, 1974; Divale, 1984), due to tight relationships between each of these factors, they could not be used as substantial evidence of a direction of causal relationships or even an existence of certain relationships in general. Simulation-based approaches solve these issues by explicitly simulating given relationships and while not without their weak points, the ability to successfully simulate particular relationships provide strong evidence of its existence and information on its magnitude. The work described here forms an important milestone in a transition from association to simulation methods for the study of post-marital residence.

In this chapter, I have used an agent-based model of warfare-induced residence change to simulate the effect of warfare on the adoption of matrilocality. In total, four different experiments were run to examine the ability of warfare to cause a residence transition in the community of villages under various conditions.

The results of the model provided several significant discoveries regarding the effects of warfare on post-marital residence change and the conditions required for a spread and full adoption of matrilocality in the community of several villages, notably the requirement of either the majority of villages being under the warfare pressure or some additional internal pressure for change towards matrilocal residence, such as division of labour. An important discovery is also confirmation that matrilocality has an adaptive function and helps in survival. This confirms that some of the assumptions I made regarding a change towards matrilocality due to warfare pressure are justified.

An interesting synergic effect was also discovered between warfare pressure and matrilocal pressure. If only warfare pressure is applied, villages on the border of the society, directly under warfare pressure, will adopt matrilocal residence, but this does not spread towards the core of the society. On the other hand, when matrilocal pressure is applied without warfare, villages will readily switch towards matrilocal residence regardless of their position, but only if their population is small or there are no significant social norms in place against cross-marriage. In the case of a large population or significant social norms, both warfare and matrilocal residence are required to successfully induce and spread matrilocal residence through society.

While the results do not directly refute Divale's theory (Divale, 1974, 1984), it shows that the transition to matrilocality due to warfare pressure occurs only for a very limited set of conditions, when most of the community is under attack. This causes the adoption of matrilocal residence in the part of the community engaged in warfare and since this part forms a majority of the society, matrilocality can then spread further through matrilocal pressure alone. However, in the tested scenario, the marriage opportunities of villages not affected by warfare were significantly limited, it is thus possible that it is not the percentage of society under the warfare pressure, but the structure of the marriage network that plays a role here.

Instead, the result provides support for Ember's idea of the importance of the division of labour in this scenario (Ember and Ember, 1971). Matrilocality as a cultural practice is unable to spread through the area unaffected by warfare, due to a strong conservative bias towards keeping a current state, without some additional pressure that would compensate for the natural conservatism. This can be the division of labour, male absence or other factors which might be insufficient to cause a residence transition by themselves, but can efficiently spread matrilocality once it is introduced through warfare.

While the model analysed here was designed around Ember's *Warfare Theory of Matrilocality* (Ember and Ember, 1971) and Divale's *Migration Theory of Matrilocality* (Divale, 1974) (see Chapter 1), it should not be however taken as a perfect representation of those theories. To be able to model the change of residence, multiple processes described in those theories had to be significantly simplified either due to lack of mechanistic understanding, sheer complexity or a lack of knowledge about particular parameters. Still, the model was able to show many different behaviours and properties specific to both Warfare theories. In the following chapter, I will try to show possible future venues for expansion of the model, notably I will discuss ways to include internal warfare, expand upon marriage network and ways to simulate migration.

5. Extensions of the Agent-Based Model of Warfare-Induced Post-Marital Residence Change

5.1 Introduction

In the previous chapter, I designed an agent-based model of warfare-induced post-marital residence change. This model was designed to simulate the Unified Theory of Matrilocality, which was created by combining Ember's *Warfare Theory of Matrilocality* (Ember and Ember, 1971) and Divale's *Migration Theory of Matrilocality*. While the model was relatively simple, it was able to model behaviours predicted by both Ember's and Divale's theories, explore particular conditions required for adoption of matrilocality and investigate the relationship between residence, warfare and division of labour.

However, while the simplified nature of the model made the scenario significantly more computationally feasible, it made it also highly unrealistic. This simplification could have inadvertently removed an important interaction between marriages, warfare and residence and thus reducing the model's relevance.

In this chapter, I will explore possible extensions of the model. First, I will discuss large conceptual changes that would significantly influence the structure and behaviour of the model, such as an individual-based approach or modelling the relationship between villages. Then I will expand each interlocking part of the current model: population and its structure, warfare and the model for marriages. Finally, I will comment on the purpose of this chapter in relationship to Chapter 4 and future research in this area.

5.2 Individual-based approach

Ember's and Divale's theories work on three scales: society, village and individual (see Figure 5.1). External warfare exists on the society or community scale as it is an interaction between two (culturally) different communities. On the other hand, internal warfare works on a village scale since it is defined as infighting between intermarrying villages. Finally, the last scale describes marriage interactions between individuals.

In the model, I decided that simulation on the village scale is sufficient as there was no immediate need to track the history of every individual. Villages became agents in the model and individuals were abstracted as an internal state of villages. This meant that I could use well-known deterministic population models to simulate demography of villages, such as logistic growth or the Leslie matrix and also provided a significant improvement in model performance: instead of having to model hundreds or even thousands of agents for every village, the population was efficiently modelled with just three small arrays. At the same time, the cohort model also limited possible behaviours.

For example, in the current system, marriages between men and women of different age or even

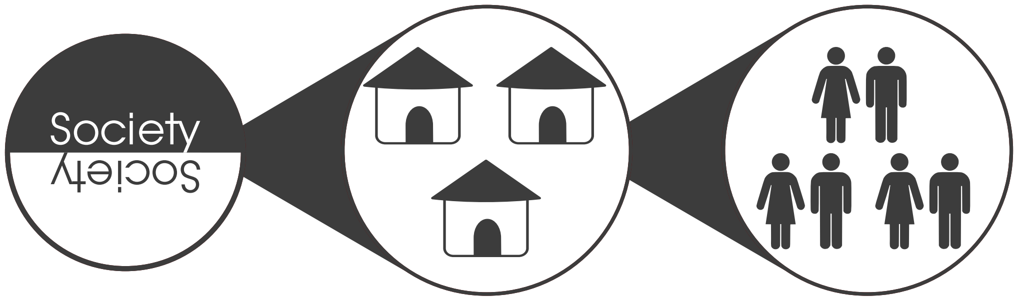


Figure 5.1: Three scales of interactions: society, village and individual. Each of these levels must be simulated in some form to represent Ember's and Divale's theories of matrilocality.

polygamous relationships are essentially impossible to implement, while relative easy in an individual-based approach. Additionally, the relationship between family members or family traditions would be possible.

5.2.1 Example

Let individuals be the agents in this example. Individuals are represented by their age, sex, marital status and the village in which they live. These agents will grow, marry unrelated partners of the opposite sex and optionally move to a different village according to the post-marital residence of the marriage.

This model would not be substantially different from what was implemented. However, it could be significantly extended by including more complex interactions.

Households

Households could be defined as groups of related individuals. Using households, extended families, family relationships, and post-marital residence could be directly simulated. However, mechanisms to establish new households would need to be included as households could still die, either through warfare or by not producing enough offspring, but strict patrilocal or matrilocal residence does not produce new ones.

Using households, matrilocal alliance system (Ember and Ember, 1971; Divale, 1974) could be implemented. Under this system, matrilocal residences can utilize both husbands and brothers for warfare. This gives matrilocal societies significant warfare advantage that was not captured in the original model (see Chapter 4).

Detailed marriage simulation

Instead of simply redistributing people, a more complex model based on an individual decision can be implemented, such as the Wedding Ring (Billari et al., 2007) or Wedding Donut (Silverman et al., 2013) models. In these models, each individual has a social network that might include potential partners and social pressure to marry. Increase in this social pressure leads to widening of a social network and a higher chance of finding a partner. In our model, an increase in the social pressure could be additionally caused by the warfare pressure and could also lead to younger brides, although matrilocal societies tend to have a higher age of first marriage (Meekers, 1992).

5.2.2 Disadvantages

While the individual-based approach provides many advantages, there are a few drawbacks. First of all, there is not enough detailed information to implement such systems. For example, the age difference between wife and husband varies greatly worldwide. While some societies favour small age difference in others young men have to prove themselves before marriage, either in warfare or by amassing enough property (White and Burton, 1988; Meekers, 1992; Glowacki and Wrangham, 2015), which leads to an increased age difference. This is further exacerbated if polygyny was to be implemented. Secondly, utilizing the individual-based approach would greatly increase model complexity. This would not only affect the size of parameter space that needs to be explored thus increasing the required computation resources, but each new extension is essentially a new model of human behaviour. Finally, the individual-based approach would greatly reduce model performance. The implemented model could run 1100 steps, including the Java Virtual Machine notoriously long start time, in less than a minute and this enabled a more thorough exploration of parameter space (see Chapter 4). Employing the individual-based approach would lead to a reduction of time-steps and parameter space, which would lead to a worse understanding of model behaviour.

5.2.3 Conclusion

The individual-based approach models interactions between individual people instead of larger structures. This enables a greater complexity and extendability where detailed knowledge and data on the behaviour of simulated subsystems are available. If however the detailed knowledge and data are missing, the individual-based approach would not provide greater insight into the behaviour of the model, while still greatly increasing required computational resources. For these reasons, the cohort model was implemented instead, favouring "simple and nice" (Sun et al., 2016) modelling decision, while investing the computational resources to make a detailed exploration of model behaviour.

5.3 Modelling relationships between villages

Another conceptual change that would significantly change how the model works is to model a relationship between villages. By modelling the relationship between villages, internal warfare can be modelled, which would enable a proper simulation of both unrestricted models of warfare without having to limit them to a small community. This was further motivated by the similarity between Ember's description of warfare and the demographic model of internal warfare described by Turchin and Korotayev (2006), in which population growth leads to internal warfare, which leads to revenge (see Section 5.6 for a detailed description).

5.3.1 Example

Relationship between villages would affect marriages, warfare and residence change. Individuals likely marry other individuals with whom they, or their families, have a good relationship. Likewise, individuals who like each other would not fight each other or support their villages in doing so. Finally, individuals would respect and adapt to the traditions of other individuals they like instead of ones they dislike. In this way, a tightly-knitted society might be able to resist (in warfare or through cultural pressure) a more loosely aligned one, something we observe in historical data (Murphy, 1956).

The relationship between villages, or *bond*, represents a memory of previous interactions. A lot of positive interactions might lead to further collaboration, while negative interactions to warfare. This is realistic, as revenge is often considered a primary reason, if not for the start of warfare, then for its continuation (Chagnon, 1988; Christensen, 2004; Wrangham and Glowacki, 2012), although numerous examples of peacemaking mechanisms exist as well (Ferguson, 2008). However, if warfare in the past would increase the likelihood of warfare in the future, and analogously, past marriage interactions would increase the likelihood of future marriages between two villages, this would create two positive feedback. A possible way to escape this might be to make both marriages and warfare between villages a density-dependent effect. This was already suggested for warfare in model with density-dependent warfare with additional revenge effect (Turchin and Korotayev, 2006) and a density-dependent increase in endogamy as village population grows is equally realistic.

Definition

Denote by B_{XY_T} a relationship or a *bond* between villages X and Y at time T. The change in the bond is driven by three primary sources: a positive change from every marriage between individuals of the two villages B_M, a negative change for every causality of warfare B_W, and a rate of forgetting those two events f. The change of bonds between two villages is thus:

$$B_{XY_{T+1}} = B_M + B_W + fB_{XY_T} \tag{5.1}$$

The form of B_M and B_W depends on whether the bond is shared between both villages, i.e., $B_{XY} = B_{YX}$ – a two-way or bidirectional bond, or a unidirectional bond, i.e., $B_{XY} \neq B_{YX}$. In the former case, the effect of marriages and warfare would influence both villages equally, even if one village would benefit more strongly from marriages or accrued higher losses from warfare. In the latter case, however, both villages form their own opinion. This reflects a situation where one village could be disproportionally more affected by shared interactions, such as due to a smaller population and thus small populations would be able to change their relationship much quicker.

The effect of marriage

In traditional societies, marriage is a common and effective peacemaking practice (Ginty, 2008). Marriage between representatives of two communities symbolizes their shared future. In medieval Europe, marriages among noble families became a strategic tool to form alliances, end feuds or obtain title claims (Rawcliffe, 1988) for similar reasons. Here I assume that every marriage between two communities increases the relationship between them equally. In reality, marriage between powerful noble families would cement the fate of two nations, while the marriage between two serfs would hardly matter at all, but we assume that every member is indistinguishable and thus equal.

Let M_{XY} be the number of marriages between village X and Y. Then the change of relationship from marriages, in the case of a unidirectional bond, would the number of marriages M_{XY} scaled by the total population N_X and scaled by some constant g:

$$B_{M_{XY}} = g\frac{M_{XY}}{N_X} \tag{5.2}$$

or perhaps scaled by the total number of marriages of X (M_X) instead. Additionally, if density-dependent endogamy is implemented, then as a population increases, the number of endogamous marriages M_{XX} increase as well, which will in weaken the relationship between villages by lowering the number of marriages that can be redistributed among them. In time, this might lead to warfare and depopulation.

Note that the value of the positive effect of the bond depends on the number of neighbours that a village can interact. A village has only a fixed number of possible marriages it can distribute among its neighbours. So the larger is the pool of neighbours, the smaller on average would be the bonds between villages. This can be prevented if g is a function of the number of neighbours. It is, however, reasonable to expect that a village has to pick and choose its friends, as resources are limited. The effect of both options remains to be explored in the future.

The effect of warfare

Warfare can change a relationship in three ways: First, the act of fighting itself can create a hostile relationship, but without significant suffering, it will probably not be particularly long-lasting and can be absorbed into the random change ϵ (see below). Secondly, by stealing resources, especially if said resources were in critical need, it might create a stronger animosity. Finally, the strongest influence on relationships will probably be caused by the death of a friend or kin. Let P_Y be the power of village Y and α the efficiency of killing. Then the change of bonds due to warfare after X gets attacked by Y is:

$$B_{W_X Y} = \alpha f(B_{YX}) P_Y \tag{5.3}$$

where $\alpha f(B_{YX}) P_Y$ represents the warfare mortality of village X. Here, village Y does not use its full military power, but only part of it according to the animosity between villages. As population density increases, warfare mortality will increase as well and the relationship between villages will decrease. This will cause depopulation and drop in warfare intensity. Eventually, $B_{W_{XY}}$ is surpassed by fB_{XY} and the conflict is forgotten.

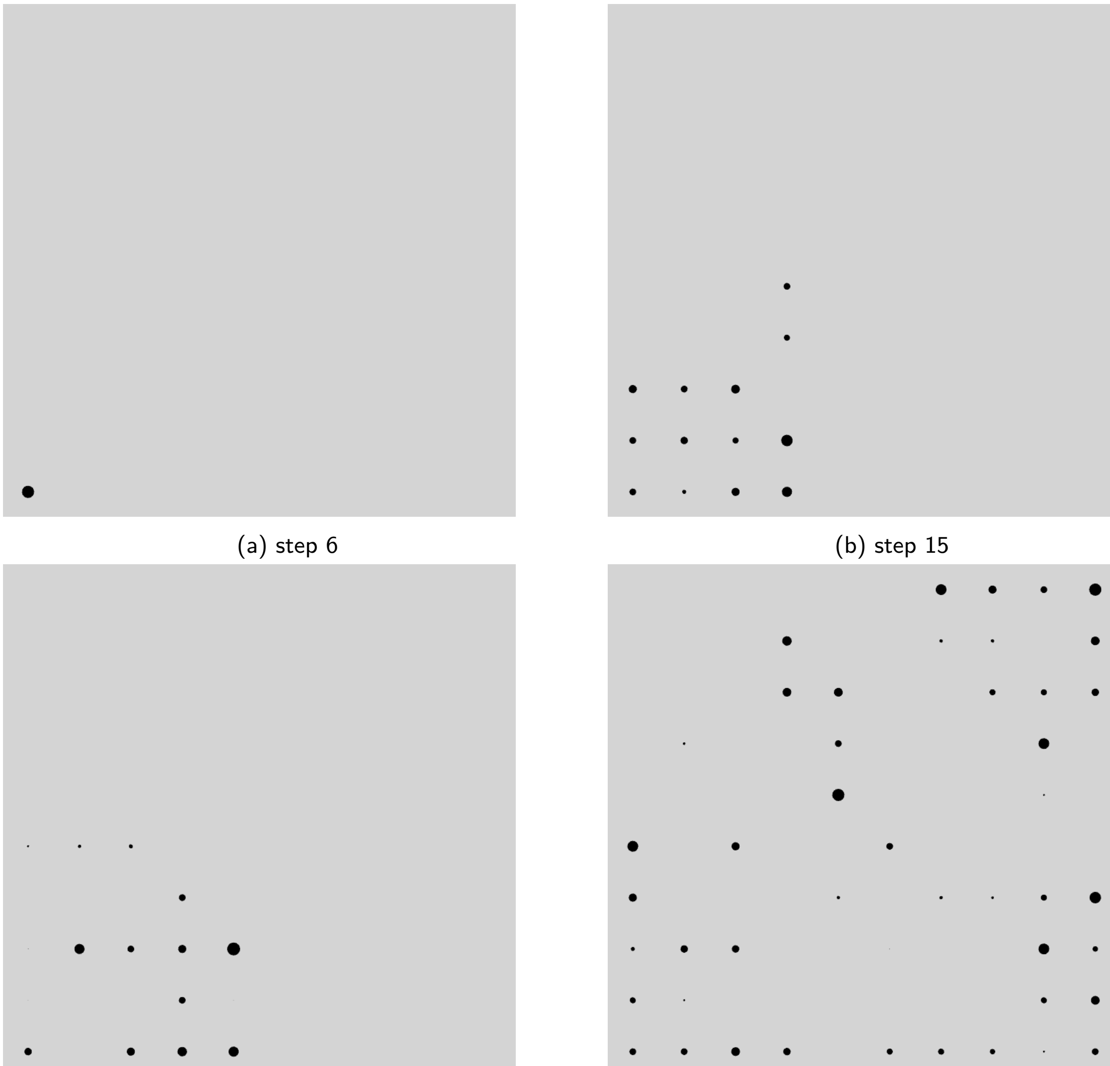
An early version of the model was able to, through the implementation of the relationships between villages, produce an interesting pattern of development (see Figure 5.2). In this version of the model, basic demography, marriages, (internal) warfare, but not residence dynamics, were implemented. Additionally, unlike in the final version of the model, villages could colonize new spots on a grid. The simulation starts with a single village in one corner of the grid. This village proceeds to colonize neighbouring spots. At the start, villages share a good relationship with their colonies, but they deteriorate in time and this ultimately leads to infighting followed by depopulation, but not before previously developed colonies are able to colonize neighbouring regions themselves. A distinct cyclic pattern of a core to periphery development is observed, which resembles the one predicted by World-systems theory (see Chirot and Hall, 1982).

5.3.2 Conclusion

Modelling the relationship between villages seemed to be necessary for the implementation of Ember's and Divale's theories of matrilocality and significant work was invested to attempt to model it, but with only partial success. This is because marriage networks, internal warfare and their interactions are complex problems on their own and to include them into the model of residence change, they would need to be solved first. Instead, the original problem definition was reworked to remove the effect of internal warfare and thus the need to model the relationships between villages.

5.4 Spatial structure of communities

The model presented in Chapter 4 implemented a fixed grid of villages. This significantly restricts possible village dynamics and while this might be acceptable for a short time-span, assuming that a large population movement is a rare event and the simulations start with one, it is not an ideal solution, as simulation took place over 5000 simulated years. Thus either the simulation time needs to be significantly reduced so that the no population movement assumption is valid or a more dynamic model needs to be produced. The total time over which simulation takes place could be reduced, but not significantly, as Divale (1984) suggested that the changes from patrilocal to matrilocal residence take place over relatively long time-scale, on average 1000 years (see Figure 1.5). On this time-scale, many demographic changes are possible. For example, there are several famous examples of warlike matrilocal ethnic groups, such as the Ibans of Borneo (Vayda, 1961) or the Mundurucu of Amazonia (Jones, 2011), expanding into areas depopulated by their aggressive raids. Similarly, an (peaceful or aggressive) expansion played a major role in the language and post-marital residence composition of North America (see Figure 5.3), especially the Southwest USA, where migration and contact might



(a) step 6

(b) step 15

(c) step 30

(d) step 110

Figure 5.2: Sample run from an older version of the model that simulated bonds, colonization, warfare, marriages, but not residence. Black circles represent villages, their population size is represented with the size of circle. The model starts with a single village (Figure 5.2a), which colonizes neighbouring regions (Figure 5.2b). In time, relationships worsen and a pattern of warfare emerges in the core of a society, while on the outskirts, expansion continues (Figure 5.2c). Similar patterns of growth, colonization, warfare and depopulations emerge all across the simulated landscape (Figure 5.2d).

Table 5.1: Range of travel distances for various societies. Table shows maximal repeated travel distance. Typical travel distance is highly variable and depends heavily on environment, but also material support.

Travel distance	Tribe, Nation or Ethnic group	Reference
80 km	Australian Aborigines	Scelza (2011)
40-60 km (1 day)	Himba	Scelza (2011)
50 km	Basotho, Lesotho	Marks et al. (2012)
150 km	modern Spain	Marks et al. (2012)
192 km	Jívaro, long distance raiding	Blick (1988)

have caused numerous transitions towards matrilocal residence, or during the Austronesian expansion from Taiwan into South-East Asia and Oceania (Lansing et al., 2011). Since population expansion is implicated in theories of residence change (Divale, 1974, 1984; Ember and Ember, 1971; Pasternak et al., 1997; Ember, 2009), a more dynamic model that can simulate large scale demographic changes is required.

Here I present two possible solutions for this problem: a flexible grid, that grid does not represent villages, but empty village spots that can be dynamically occupied, and a grid-free solution with continuous space.

5.4.1 Flexible grid

Similarly to the fixed grid, the flexible grid assumes that resources are distributed uniformly and that the villages are regularly spaced. Both assumptions are fairly realistic (Vayda, 1961; Otterbein, 1979; Kelly, 1995; Maier, 1999) except for extreme environments, such as desert, or abundant sources of food, usually in the form of big animal herds or rich fishing sites. Unlike in the fixed grid, the flexible grid model does not represent villages, but village spots, that can be dynamically occupied by villages. Actual travelling distance between villages can be abstracted and only the maximal interaction distance D_I, defined in the units of village spacing, needs to be specified. In this model, a village can interact with other villages (or village spots) only if they are within its interaction distance (Figure 5.4). With small D_I, only a few connections are produced (Figure 5.5) and it can be assumed that the village interacts with all neighbouring villages uniformly. However, if D_I is large, this would include too many connections and some additional filtration would be required. This could produce a secondary network structure.

An example of a flexible grid model, where villages can colonize nearby spots, together with internal warfare, marriages, but not residence change, is shown in the Figure 5.2.

5.4.2 Continuous space

An alternative option is to abandon the fixed grid altogether. While more realistic, this would, however, introduce several complications. By using a grid approach, environment and movement distance are discretised and abstracted out. With continuous space, a travelling distance would depend heavily on the type of environment. For instance, travelling through the rainforest is much more difficult than across plains (see Kelly, 1995) and the travel distance of individuals between villages is also varied (see Table 5.1). Another problem might stem from resource distribution. With a grid, resources are assumed to be distributed uniformly but are situated on a regular grid. This abstracts out competition over resources, which might otherwise arise when a simulation would be performed on continuous space. One way to solve this would be to randomly generate village/resource spots. This is effectively a grid approach, but instead of a regular grid, a more irregular pattern is chosen.

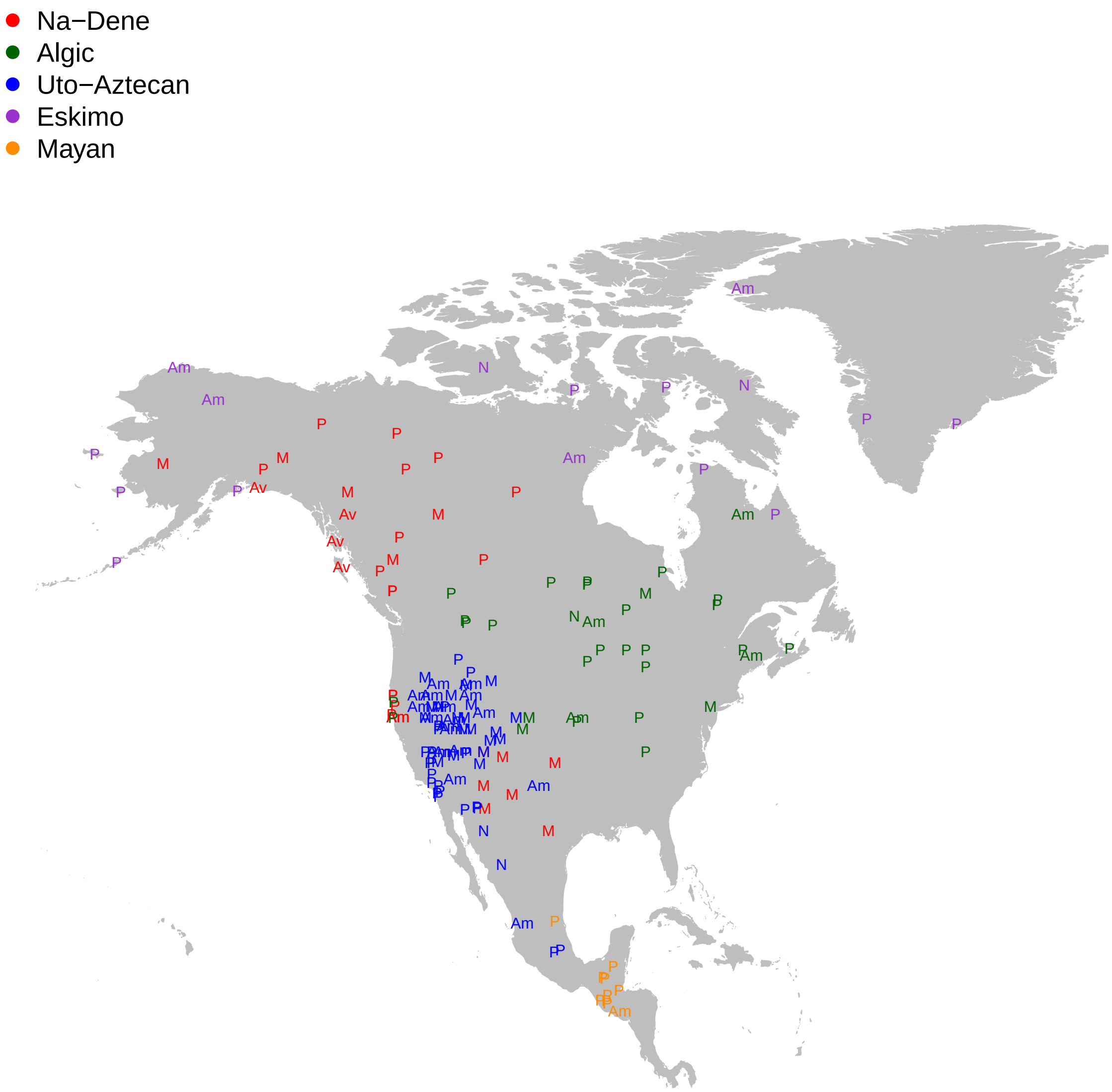


Figure 5.3: Map of post-marital residence for major North American language families (colours in legend) obtained from the corrected Ethnographic Atlas (Gray, 1999). Letters show post-marital residence states: Matrilocal (M), Patrilocal(P), Ambilocal (Am), Avunculocal (Av) and Neolocal (N). Note the Southwest USA, where three language families came into close contact and matrilocal residence was adopted.

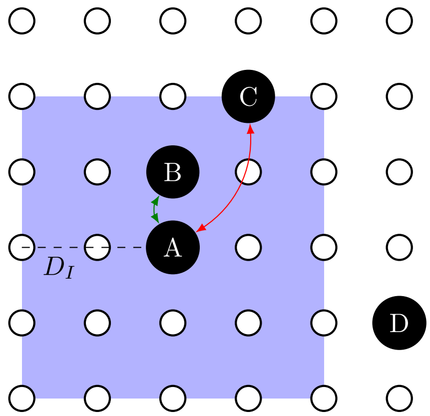
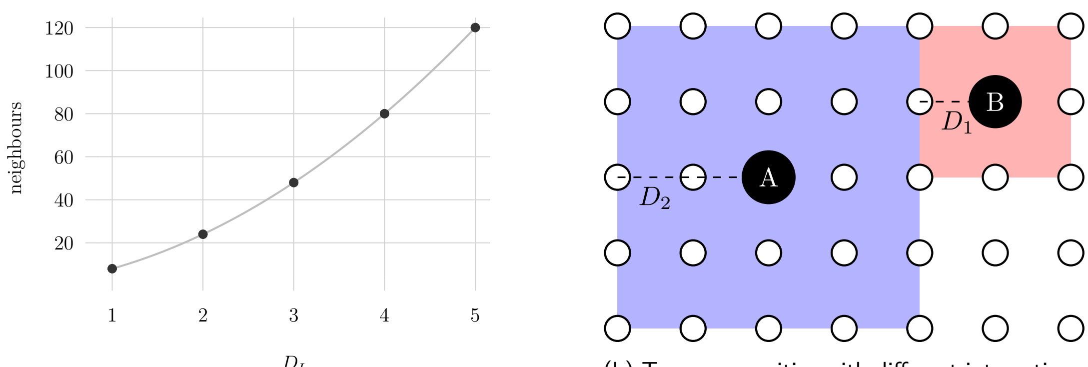


Figure 5.4: Example of a model lattice with community A and its interaction with communities B,C and D. A shares positive interactions with B (green arrow), negative mutual interaction with C (red arrow) and no interaction with D, as it is outside A's interaction distance D_I.



(a) Number of potential neighbours based on the size of the interaction distance D_I

(b) Two communities with different interaction distances. While community A with distance $D_2 = 2$ has 24 potential neighbours, community B with distance $D_1 = 1$ has only 8.

Figure 5.5: Effect of interaction distance D_I on the number of neighbours. Figure 5.5a shows their functional relationship and Figure 5.5b shows a visualization of this relationship on a lattice.

This approach was tested using a simple migration model. Villages were assigned to a random position on a continuous space with migration defined according to the gravitational model (see e.g. Poot et al., 2016). While the model was misspecified, which caused centrally-located villages to in time absorb all the population, this at the same time showed an important factor of spatial position. For instance, if this network effect was implemented, centrally located villages would have an important effect on adoption of residence, either stopping the spread of matrilocality or enhancing it.

5.5 Expansion of population simulation

The population in the model was divided into age, sex and marital status cohorts with growth according to the logistic growth model. This implementation was inspired by the Leslie matrix, a popular and well-studied model of population growth:

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{10} \end{pmatrix}_{T+1} = \begin{pmatrix} r_1 & r_2 & \cdots & r_9 & r_{10} \\ s_1 & 0 & \cdots & 0 & 0 \\ 0 & s_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & s_9 & 0 \end{pmatrix} \cdot \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ \vdots \\ n_{10} \end{pmatrix}_{T} \tag{5.4}$$

The Leslie matrix describes a population, usually only of females, divided into different age cohorts or stages of development. The age-specific growth rates r_i and survival rates s_i can be further used to distinguish cohorts with age-dependent effects. However, the Leslie matrix cannot fully represent a population at the detail required for marriage simulation and thus age, sex and marriage cohorts were established.

5.5.1 Age-specific effect

As currently implemented, the model allows the specification of several age-specific effects, such as female fertility or male age-specific contribution to warfare (Figure 5.6). With slight modification, age at which a cohort can marry could be transformed into age-specific marriage probability as well (although there might be different ways to represent the age-marriage curve, see Section 5.7.1). They were not utilized during simulations as they would require further literature research and given the highly simplified structure of the population, I am not sure if there would be a direct benefit, unless the model moves towards microsimulation, i.e., to simulate residence change in a specific society.

5.5.2 Semi-individual approach

One of the disadvantages of the age-cohort model is that marriage is possible only between the same age-cohorts of the opposite sex, or at least between only two different cohorts, i.e., either male cohorts 20-25 could marry female cohorts 20-25 or male cohorts 20-25 could marry female cohorts 15-20, but not both, since the outcome will always be the same pair cohorts. This also makes polygamy essentially impossible. This problem would be solved by individual-based approach, i.e., if individuals are agents. Alternatively, a semi-individual-based approach could be implemented, since the only information that needs to be tracked about individuals is their marital status. By keeping track of marriage status, but still representing cohorts as simple arrays, the implemented model would probably still be faster than a fully individual-based model. However, the implementation structure would become less straightforward and the full individual-based approach is much more extensible, so the later would be probably preferred.

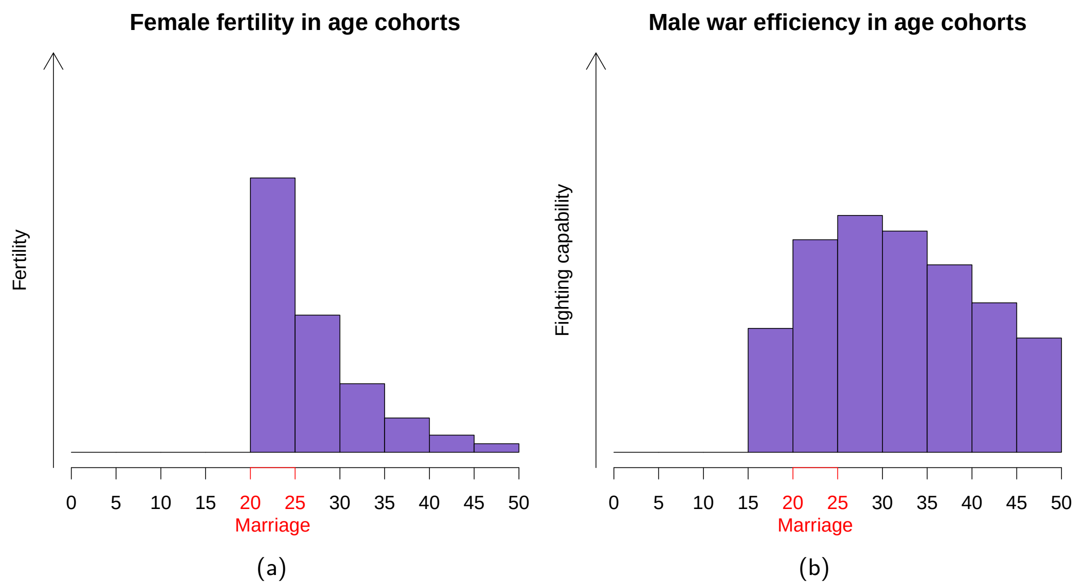


Figure 5.6: Example of two age-dependent effects, (5.6a) is female age-dependent fertility rates and (5.6b) is male fighting capability or their contribution to village military power. Values are only illustratory.

5.6 Expansion of warfare simulation

Ember's *Warfare Theory of Matrilocaliy* and Divale's *Migration Theory of Matrilocality* distinguish between the effect of internal warfare, infighting between intermarrying communities, and external warfare. Due to numerous problems, the model described in Chapter 4 implemented only external warfare in the form of constant warfare pressure that affects villages on one side of a simulated society. The relationship between population and warfare losses was described using Lanchester's laws (Lanchester, 1916).

Lanchester's laws, originally developed for the study of aerial combat between biplanes, model the relationship between losses of two opposing sides using two different sets of differential equations depending on the type of combat. *Lanchester's linear law* models one-on-one "ancient" combat or unaimed fire and is similar to a *Lotka-Voltera* predator-prey equation, where the change is density dependent both on the population of predator and the population of prey:

$$\frac{dN_X}{dt} = -\alpha_Y N_Y N_X \qquad \frac{dN_Y}{dt} = -\alpha_X N_X N_Y \tag{5.5}$$

The second set of equations, *Lanchester's square law*, simulates direct/aimed fire:

$$\frac{dN_X}{dt} = -\alpha_Y N_Y \qquad \frac{dN_Y}{dt} = -\alpha_X N_X \tag{5.6}$$

where N_X and N_Y are the population sizes of soldiers of X and Y respectively and α_X and α_Y are military prowess, training or how effective they are at killing.

While the *linear law* might be more suited for a primitive, often heavily ritualized warfare (Mathew, 1996; Gat, 1999; Christensen, 2004), I can hardly imagine the situation where military losses of X would grow if the population of X grew, while Y remained constant. Since primitive warfare tends to consist predominantly of raiding (Gat, 1999; Wrangham and Glowacki, 2012; Christensen, 2004), where small bands of men went near an enemy village to kill or maim an isolated target (Chagnon, 1988), losses would almost exclusively depend on the ability of the enemy village to send raiding parties, rather than on the density of the target population, since the position of the village would usually be known. For these reasons, I chose *Lanchester's square law* to represent the relationship between (military) population and losses. This, together with the constant population of warriors of the abstracted enemy society, led to a very simple representation of warfare pressure W and warfare losses δN:

$$\delta N = W = \alpha P_e. \tag{5.7}$$

Since the enemy military power P_e is constant, this makes the effect of warfare predictable and the village can either replenish its losses or it goes extinct. Additionally, only two parameters are introduced, the killing efficiency α, which can be estimated from the literature (Table 4.1), and the size of the enemy population P_e, which can be scaled according to the capacity of the environment.

5.6.1 Simulating both societies

One obvious way to expand the model is to simulate both societies that wage external warfare. In this setting, the warfare pressure would not be constant, but equal to the military power of the village (or possibly the whole row of villages) of the other society in the same row. This means that under most scenarios, the military losses on both sides would decrease in time until the population stabilises and extinction would be less common. Using Lanchester's linear law instead of the square law could provide an additional stabilizing effect.

5.6.2 Military alliances

In the context of expanded external warfare and especially if the model is expanded with internal warfare, military alliances between villages, i.e., sharing a portion of military power according to the size of relationship, could be implemented. This might be especially important for correct representation of military advantages of matrilocal residence, as both non-localized brothers and localized husbands are expected to defend the community against an external enemy.

In the case of external warfare, the total military power T of village X would be a simple sum of all military powers P of neighbouring villages multiplied by the relationship between village X and neighbouring village i:

$$T_X = P_X + \sum_{\substack{i \in D_{I_X} \\ B_{iX} > 0}} B_{iX} P_i \tag{5.8}$$

where D_{I_X} is the interaction distance of X and B_{iX} is the relationship (or bond) between village i and village X. In the case of internal warfare, allies of X would help only if they liked X more then the target village Y:

$$P_{XY} = P_X + \sum_{\substack{i \in D_{I_X} \\ B_{iX} > 0 \\ B_{iX} > B_{iY}}} B_{iX} P_i \tag{5.9}$$

This way mortality from the warfare pressure W would be spread to a larger area, which could help facilitate the spread of matrilocality through warfare alone even to villages not under direct warfare pressure.

5.6.3 Density-dependent internal warfare

A possible approach to extend the model with internal warfare would be to assume that warfare is a density-dependent effect of population size. As the population grows, this creates resource stress, which results in internal warfare. By adding revenge as another reason for pursuing warfare (Chagnon, 1988; Christensen, 2004; Wrangham and Glowacki, 2012), we get cyclic behaviour in which the population grows towards the capacity of the environment, which causes warfare and so a drop in population, but due to desire for revenge, warfare continues. After some time, the population density and warfare losses are too small to sustain warfare, peace emerges and the cycle continues. This model was described by Turchin and Korotayev (2006) and is composed of two differential equations, a logistic growth equation:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - WN \tag{5.10}$$

and warfare intensity equation:

$$\frac{dW}{d} = aWN - bW \tag{5.11}$$

where N is population, r growth rate, K capacity of environment, W is warfare intensity, a proportionality constant and b rate of forgiveness for past actions.

However, this model works on the societal scale and adaptation to the village scale would be required. One way would be to model warfare intensity through the relationship between villages (as per Section 5.3). An alternative is to model the resources stress explicitly.

5.6.4 Raiding for resources

In situations when local resources are failing or local environments cannot support growing populations, the amount of conflict is increased (Kelly, 1995). For example, it was very laborious to cut down rainforest to create fields; many Māori thus preferred to conquer enemy tribes instead (Vayda, 1961). Here I will try to model this behaviour explicitly rather than as a simple density-dependent effect of warfare.

Let the probability of warfare W_{XY} between X and Y be a function of gain (G_{XY}), bond (B_{XY}) and aggressiveness or belligerence of X (A_X):

$$W_{XY} = f(G_{XY}, A_X, B_{XY}). \tag{5.12}$$

I would like the following behaviours from this function:

- $\uparrow G_{XY} \Rightarrow \uparrow W_{XY}$ – the greater the (estimated) gain, the greater the probability of attack
- $\uparrow A_X \Rightarrow \uparrow W_{XY}$ – the greater the belligerence, the greater the probability of attack
- $\uparrow B_{XY} \Rightarrow \downarrow W_{XY}$ – with increased bond, the probability of warfare decreases

I will investigate all components of W_{XY}, starting with gain.

Gain is some assumed benefit of warfare, the amount of stolen resources. Gain (naturally) depends on the military power of both villages and also the available resources (derived from the capacity of environment K):

$$G_{XY} = g(P_X, P_Y, K) \tag{5.13}$$

Additionally, instead of the whole capacity of the environment, maybe raiding is done only for the untapped resources, i.e., $K - N_Y$. This would make small villages a primary target, they will be destroyed and then colonized, which would effectively reduce the stress factor.

We can also treat gain similarly to losses as per *Lanchester's Square Law.* However, we might make some modification. First, instead of gain being equal to just village military power $G_{XY} = P_X(K - N_Y)$, we might assume that the village will try to defend itself and thus the target's military power will play a role, for example, every soldier could stop one enemy soldier, i.e.,:

$$G_{XY} = \max\{0, \beta(P_X - P_Y)(K - N_Y)\} \tag{5.14}$$

Alternatively, we might also consider that even if a village has superior forces, some portion of its resources might be stolen:

$$G_{XY} = \beta \frac{P_X}{P_Y}(K - N_Y) \tag{5.15}$$

The β here is some resource-stealing parameter. The untapped resources could also serve as a limit instead, i.e., $\min\{G_{XY}, K - N_Y\}$, which fits equation (5.14) better, but I also like the idea that if the military power is overwhelming, some resources required for subsistence can be stolen as provided by equation (5.15).

The relationship described above prioritizes raiding for unused resources. This would mean that an attacker can gain a huge amount of resource by raiding villages occupied by a single person, which is a very unlikely behaviour. This would also imply that the capacity of the environment is some freely available resource that can be easily captured without serious work. This might be somewhat likely for big game; the raid would essentially represent conflict over hunting grounds and a war party could hunt on territory that belongs to the defender (although these hunters would then effectively hunt in their territory and territory of the defender, which would have to be addressed). However, for gatherers, fishing or horticulturist types of subsistence, this is highly unlikely. Resources need to be first obtained from the environment and stored. While we could try to model stored resources explicitly, we could use total population instead and assume that raids were in the step between production and consumption (i.e., resources were produced, but not yet consumed). Using the total population N_Y instead of $K - N_Y$, both of our gain functions will make more sense:

$$G_{XY} = \min\{\max\{0, \beta(P_X - P_Y)\}, N_Y\} \tag{5.16}$$

$$G_{XY} = \beta \frac{P_X}{P_Y} N_Y. \tag{5.17}$$

This means that the estimated gain is a trade-off between the strength of the military force and a village's total population.

The second mentioned parameter of the probability of warfare is aggressiveness A_X. Including this, we can modify the behaviour of villages, essentially decreasing or increasing the probability of warfare for the same population pressure. If W^*_{XY} is the probability of warfare without A_X, then:

$$W_{XY} = (W^*_{XY})^{\frac{1}{A_X}}. \tag{5.18}$$

The value of A_X influences the point from which a village would decide to raid for resources. Values $A_X < 1$ delay the decision to raid until a significant portion of resources are depleted (see Figure 5.7).

Now that we have gain G_{XY} and aggressiveness A_X, and we know how they behave, we can consider the form of the probability of warfare again. There is no point in raiding an empty village, thus the gain from warfare must substantially increase the current capacity of environment K_X, e.g.:

$$W^*_{XY} = \frac{G_{XY}}{K_X + G_{XY}} \tag{5.19}$$

Since K_X is fixed as N_X grows, this does not increase the probability of warfare with depletion of K_X. Thus we might use $(K_X - N_X)$ instead:

$$W^*_{XY} = \frac{G_{XY}}{K_X - N_X + G_{XY}} \tag{5.20}$$

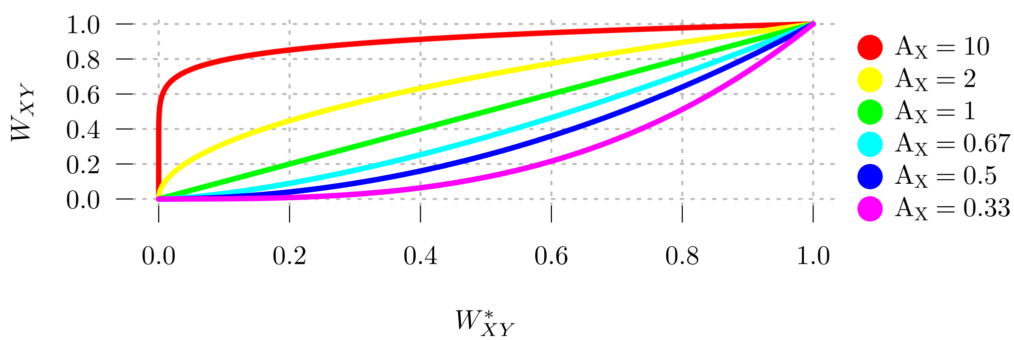


Figure 5.7: Probability of warfare for various values of aggressiveness.

Now if we transform bond B_{XY} from range $(-1, 1)$ into $(0, 1)$, where 1 is hatred:

$$B^*_{XY} = \frac{1 - B_{XY}}{2} \tag{5.21}$$

we can put this modified bond into Equation (5.20) together with aggressiveness:

$$W_{XY} = \left(B^*_{XY} \frac{G_{XY}}{K_X - N_X + G_{XY}} \right)^{\frac{1}{A_X}}. \tag{5.22}$$

Additionally, we might add the previously mentioned revenge as a function of the bond:

$$W_{XY} = \underbrace{a \left(B^*_{XY} \frac{G_{XY}}{K_X - N_X + G_{XY}} \right)^{\frac{1}{A_X}}}_{\text{warfare from resource pressure}} + \underbrace{b \left(B^*_{XY} \right)^{\frac{1}{A_X}}}_{\text{warfare from revenge}}. \tag{5.23}$$

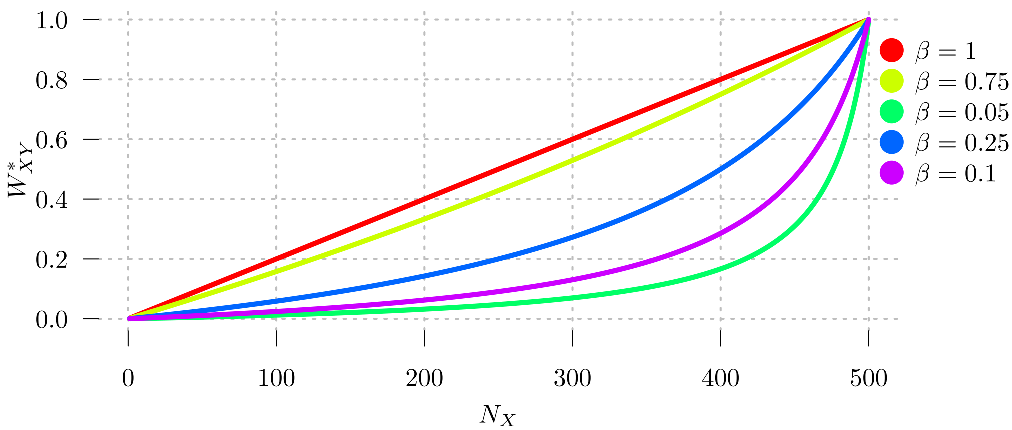
To see how this formula performs, we first assume that power is some fixed ratio of population $P = pN$ and that both populations are of the same size: $N_X = N_Y$. This will simplify gain into $G_{XY} = \beta N_X$. If we further assume that $K_X = oN_X$, $o \geq 1$, we can simplify the probability of warfare into:

$$W_{XY} = a \left(B^*_{XY} \frac{\beta}{o - 1 + \beta} \right)^{\frac{1}{A_X}} + b \left(B^*_{XY} \right)^{\frac{1}{A_X}} \tag{5.24}$$

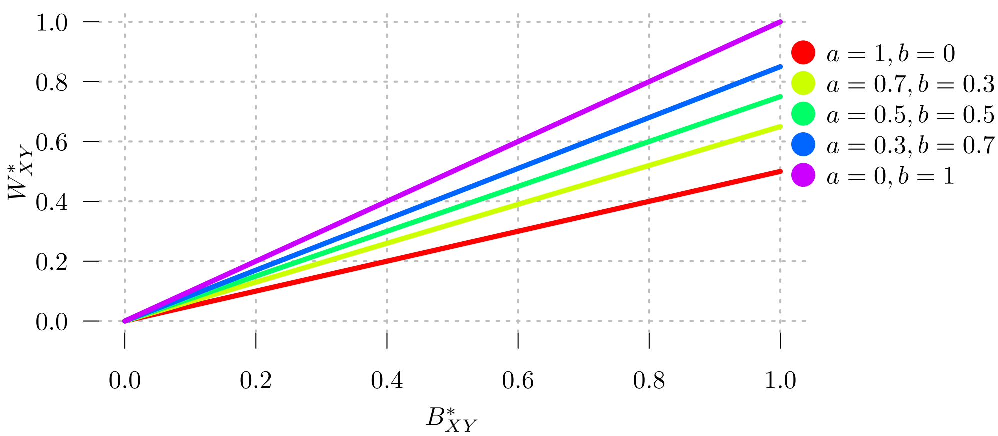
This relationship is visually explored in Figure 5.8.

5.7 Expansion of marriage simulation

A central part of the simulation of post-marital residence dynamics is the proper simulation of marriage preferences. The basic function of marriage is procreation, but while doing so, they have multiple additional functions, such as redistribution of individuals, preservation of cultural traditions, or establishing or preserving relationships between communities. In time, these practices develop into marriage rules and traditions, such as post-marital residence, which is being studied here.



(a) Relationship the between resource-pressure (here as W^*_{XY}) and β parameters.



(b) Relationship between probability of warfare and modified bond value for various combinations of warfare from resource pressure and revenge.

Figure 5.8: Visualization of relationship between the probability of warfare and its various variables under certain assumptions. Both visualizations assume that $P = pN$, $N_X = N_Y$ and $K_X = oN_X$. Figure 5.8b also assumes that $o = 2$ and $\beta = 1$.

Marriage rules are however not absolute, while not conforming to them might decrease the social standing of one or both partners (Verdu et al., 2013), and thus willingness of individuals to undertake such marriages, economic needs and conditions might force them to do so (Zhang, 2008). Such conditions are often connected with a need for land or property management (Kuchiba and Tsubouchi, 1968). This means that even within a single community, some marriages will conform to an alternative type of residence state. Marriage rules should thus be understood as idealized forms of marriage, rather than a common practice.

The implementation of marriages in the model is relatively simple, yet marriage simulation still forms the most complex part. First, a random unmarried individual of the right age is chosen to be married. Then, the residence type of marriage is chosen according to the residence type of individual's village. Finally, target village is chosen from villages neighbouring the village of the chosen individual (with the source village included) according to the number of marriageable people of the same age and opposite-sex multiplied by the marriage weight.

Through marriage weight and marriage type (see Chapter 4 for more description), four types of marriages can be simulated with just a single parameter, such as marriage of two individuals with the same primary residence, with the same secondary residence and finally two different types of cross-marriage.

This model of marriage could be expanded in multiple ways, such as introducing specific weight for marriage between two patrilocal societies, matrilocal societies or between different types of cross-marriages. More extensive changes would require a change in the modelling paradigm, such as an individual-based approach to implement the Wedding Ring (Billari et al., 2007) or similar type of marriage model. However, given that the model allows re-marriage between older individuals, there is an immediate improvement that could be implemented, a probability of no marriage.

5.7.1 Must all people get married?

Historically, some people did not find their partner immediately; in some rare cases, some people never get married (or have a partner and family). Let $\mathcal{N}$ be a special case when the randomly chosen person from X will not find a partner and ν be the marriage weight of no marriage. Let $\Pr(X \heartsuit Y | X, R, s, c)$ be the probability that X marries Y in a single step of marriage simulation (after the source village X, residence type R, sex s and age cohort c were already chosen):

$$\Pr(X \heartsuit Y)|X, R, s, c) = \frac{w_{XY} \mathcal{M}_{Ysc}}{\sum_{i \in D_{I_X}} w_{Xi} \mathcal{M}_{Ysc}} \tag{5.25}$$

where w_{XY} is a marriage weight for marriage between villages X and Y, and $\mathcal{M}_{Ysc}$ are marriageable people of sex s and cohort c. By modifying this equation with $\mathcal{N}$ instead of Y, we will get the probability that X will not marry:

$$\Pr(X \heartsuit \mathcal{N} | X, R, s, c) = \frac{\nu}{\nu + \sum\limits_{i \in D_{I_X}} w_i \mathcal{M}_{s_i}} \tag{5.26}$$

To visualize the effect of ν, I have performed a small simulation for a single community of 200 marriageable people divided equally into males and females. Under this simulation, people are being married and the number of no-marriage events $\mathcal{N}$ is counted. This simulation is repeated 1000 times for each ν value (see Figure 5.9).

5.8 Conclusion

In their review of agent-based models, Sun et al. (2016) divided models according to their complexity, with a simple "toy" models on one extreme and complex data-driven "photograph" models on the other.

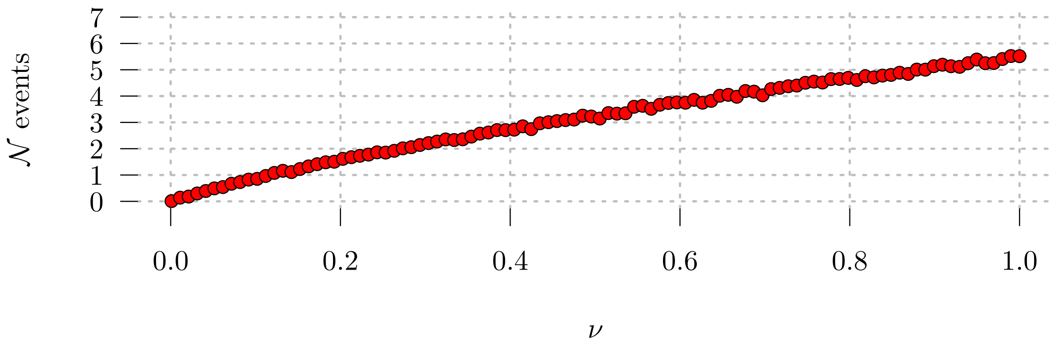


Figure 5.9: Effect of ν on the number of no-marriage events $\mathcal{N}$ in a single village. 100 males and 100 females from a single population are set to be married and the number of no-marriage events are counted. The figure shows the mean value of no-marriage events for 1000 simulations for different values of ν.

However, despite the current trend in growing complexity, Sun et al. (2016) suggest that simple models are preferable for theory-building due to their transparency and as a prevention of overfitting. The model described in Chapter 4 follows this idea with a clear preference for simple transparent solutions. This favoured an exploration of post-marital residence problem, rather than finding the best representation of warfare, marriage or the effect of population structure.

In this chapter, I have presented possible extensions for the model introduced in Chapter 4, with many of them explored during the development of the original model. Implementing any of the extension would significantly increase the complexity of the model, often requiring detailed knowledge about a particular parameter or further increasing the computational cost required for a detailed parameter exploration, which is one of the reasons why none of these extensions was included in Chapter 4.

The purpose of this chapter was to explore if the model has sufficient complexity to simulate the interactions between post-marital residence change and warfare and to further communicate the reason behind some design decision in Chapter 4 by extending each submodel with a more detailed simulation and comparing required information with increased complexity and benefits. Finally, by extending the model further while obtaining more detailed information, data-driven simulations could be performed that could test if the residence-warfare interaction tested in this model is sufficient to explain residence change in particular historical situations. From this point of view, this chapter is just the beginning of a new journey.

6. Conclusion

The post-marital residence is the residence that a pair takes after marriage. It is both an individual decision by the pair and a cultural practice. Previously, post-marital residence was studied by association methods, methods that measure an association or correlation between post-marital residence and variables of interests. Rather than direct hypotheses testing, these results were used as a guide during a qualitative evaluation (e.g., see Lippert and Murdock, 1931; Murdock, 1949; Driver, 1956; Ember and Ember, 1971)

This thesis was conceived as an exploration of post-marital residence using computational methods, utilizing modelling and data-mining techniques to give quantitative rather than qualitative answers. An advantage of this more formal approach is that all assumptions are explicitly mentioned, which helps to frame the debate, since both the weaknesses and strengths of the techniques are often more apparent. The use of computational methods for the study of post-marital residence is not new; it was previously used by e.g., Greene (1978) and Anderson (2006) for the study of parental investment, Jordan et al. (2009) and Opie et al. (2014) with the language-tree based approach, Ji et al. (2016) for sex dispersals and many others. Thus, this work follows an already-established trend.

6.1 Summary of results

In this thesis, post-marital residence was explored from three different angles: a model-fitting approach where the model was fitted to observed data (Chapter 2), a non-parametric model-free approach where the structure of data was directly explored (Chapter 3) and a purely model-based exploration, where the model was designed according to previously established information (Chapter 4) and later possible extensions were explored (Chapter 5).

Chapter 2 reconstructs the evolution of post-marital residence for 5 language families (Austronesian, Bantu, Indo-European, Pama-Nyungan and Uto-Aztecan) by utilizing methodology based on DNA evolution and language trees as a proxy for the genealogical relationship of societies. The chapter itself is based on previous works that reconstructed residence on a single tree (Jordan and Mace, 2007; Jordan et al., 2009; Fortunato and Jordan, 2010; Opie et al., 2014), extended with cross-cultural analysis and comparison of patterns of residence evolution across language groups. By backward simulating the evolution of post-marital residence on language trees, starting from the last-known residence value, the pattern of residence evolution, matrix of rates or probability of change in some time, is found. This was run on each individual trees and the patterns were compared, such as by fitting this pattern to residence data and trees of different language groups and comparing their likelihoods, or the probability of them occurring.

Our finding was that each language family follows their own specific pattern of residence evolution, which suggests that local effects play a much stronger role then global ones and that there is no strong general global pattern of residence evolution. While these results might not be immediately surprising, in fact, if strong evidence for the similar pattern in all 5 language families was found, this would suggest that the generally rejected theories of unilineal evolution (society is evolving in stages, see Mattison, 2011) are correct. The total lack of pattern is at least interesting as well. The reason for this is that there is a large body of evidence for an effect of certain factors, such as the type and sex differences in contributions to subsistence, warfare or the organizational level of society (see Chapter 1). Thus we would expect at least some similar patterns based on similar demographic histories, such as an agriculture-driven demographic expansion in Bantu and Indo-European language families. This chapter also pointed out several methodological deficiencies. A proper way to test for the existence of a global pattern would be to fit the model of residence change into the tree and data of all language families simultaneously. This would require estimation of a single set of parameters for all language trees. This is not however possible with current software. Even specification of states that are not present in data, to allow the possibility that the state might have existed in past, is not possible.

Being able to define more complex models means that one can test various scenarios directly, instead of indirect comparisons of results from separate analyses. Even in biology, where software that enables this kind of analyses exists and are steadily gaining popularity, such as BEAST2 (Bouckaert et al., 2014) or RevBayes (Höhna et al., 2016), their use as tools for complex modelling is still relatively underused in comparison to more common tasks such as phylogeny estimation. And while the models of language, trait and DNA evolution are virtually similar, adopting software made for DNA analyses to cultural data can still pose a challenge.

In Chapter 3, I analysed one of the major ethnographic databases, the Ethnographic Atlas (Murdock, 1967), to find out whether different types of post-marital residences are associated with different configurations of societal traits (i.e., the same values of variables in the Ethnographic Atlas) or if they share similar societal traits. This was done by utilizing hierarchical clustering to uncover the structure of societal data followed by finding the optimal number of clusters by minimizing the diversity of post-marital residences inside these clusters of societies so that in the ideal case each cluster represents societies with a single residence type. In addition, Multiple Covariance Analysis (MCA) was performed to uncover relationships between variables and remove potential spurious correlations, and additional clustering was done using these transformed variables.

In the end, the clustering on the non-transformed variables outperformed clustering on the variables transformed by MCA, with the non-MCA clustering having a significantly smaller number of clusters and generally lower values of cluster diversity, especially when penalization for the high number of clusters was added. The best clustering result had six clusters, all with significant portions of societies, with three of them almost exclusively formed by a single type of residence, two of them being patrilocal and one of them being matrilocal. Additionally, while not having low diversity, another cluster absorbed a significant portion of societies with a neolocal residence. It must be noted that the existence of patrilocal and matrilocal clusters with small diversity does not mean that these residences were not present in other clusters. This means that while there are particular conditions that uniquely predict matrilocality and patrilocality, there are a number of other conditions that make no such prediction. This is a significant discovery since it explains confusion over some variables, such as sex contribution to subsistence, which is correlated with residence in some areas, but not in others (see Korotayev (2001) or Ember (2011) for discussion). It also suggests that more complex models should be used and instead of explaining the existence of individual types of residences universally, residence should be treated in its specific context.

This was done in Chapter 4 and Chapter 5. Chapter 4 describes an agent-based model of warfare-induced change to matrilocality. The model was inspired mainly by the *Warfare Theory of Matrilocality* (Ember and Ember, 1971) and the *Migration Theory of Matrilocality*. The model simulates a number of interacting villages that form a society. This society is under attack by some other society, which could be simulated in a similar way but for simplicity, a constant warfare pressure was assumed. Villages on the border of the society, which are under the warfare pressure, are forced to change their residence from patrilocality to matrilocality to replenish the number of warriors so that the village would survive. The model then examines if, through marriages, the matrilocality will spread through a community and under what conditions the entire community will turn to matrilocality. The model displayed different types of stable behaviours, which could be categorized into several classes according to their demographic behaviour. While warfare was able to cause a change towards matrilocality for a wide range of parameters, matrilocality generally did not spread through the community, except when a large proportion of villages were under the warfare pressure. This changed when the effect of warfare was combined with the effect of matridominant labour. Even a small matrilocal pressure resulting from matridominant labour was able to dramatically increase the number of matrilocal villages outside of the warfare pressure and in many cases contribute to the fixation of matrilocality in the community. These results suggest that in the short term matrilocality can be found on or near conflict zones of two societies, but for the long-term fixation of matrilocality either a large portion of society must be affected by warfare or there must be presence of some other factors that, while insignificant by themselves, help in adoption of a particular post-marital residence.

Chapter 5 then explores a further possible extensions of the model, such as a network effect, the inclusion of relationship between societies to model internal warfare and warfare based on depletion of resources and their acquisition through pillaging. The chapter discusses both the advantages and disadvantages of these approaches regarding simulation of post-marital residence change.

Each of these four chapters provides significantly different points of view on the post-marital residence and cross-cultural approaches in anthropology in general. When combined, they paint an interesting picture of the search for global patterns of post-marital residence, which resulted in finding more complex localized ones. And while not often providing a direct answer, they might form an important starting point for further research. However, this work also showed a number of problems in computational anthropology and which need to be investigated further.

6.2 Problems in computational anthropology

6.2.1 Databases: completeness and convenience

There are numerous databases in anthropology, the most prominent ones being the Human Relations Area Files (HRAF)[1], the Ethnographic Atlas (Murdock, 1967), the Standard Cross Cultural Sample (Murdock and White, 1969) and probably many more. However, they often have significant problems. First of all, many databases have only paper form. While doing literature research, I have found several great books full of informative tables. To utilize this data, I would have to manually rewrite all this information into an electronic form. This is a significant barrier, especially for small teams or single person. This is not the only barrier that exists however. The Human Relations Area Files is available only to HRAF members and not to the public. And while the corrected Ethnographic Atlas (Gray, 1999) has an electronic form, it is not actively maintained, has no official page and the link from which I originally obtained the files is already dead[2]. I thus must count myself lucky that I was able to even obtain this version. Ethnologue[3], an important anthropological (or to be precise linguistic) database, instituted a paywall for high-income countries. Fortunately, at this time the Glottolog[4] was launched and serve as an effective replacement. In addition, even modern databases have significant problems. The D-place[5] (Kirby et al., 2016) provides web access to a number of anthropological databases. However, it does not provide a web API to search and download data programmatically. The data are contained on freely accessible github[6] and a custom python package is provided to provide access to them.

Compare these problems to the realm of DNA analysis with three huge databases: American GenBank, European ENA and Japanese DDBJ. These databases are actively maintained, provide web search for manual access, web API to access the information programmatically (which is then leveraged by several software packages). All these features are completely free and without registration. Users can also upload their own data and these three databases are synchronized. Additionally, a great number of

[1] http://hraf.yale.edu/
[2] http://intersci.ss.uci.edu/wiki/index.php/Ethnographic_Atlas
[3] https://www.ethnologue.com/
[4] https://glottolog.org/
[5] https://d-place.org/
[6] https://github.com/D-PLACE/dplace-data

other more specialized databases exist. All this makes the environment, together with software for DNA analysis and a number of step-by-step tutorials, very accessible to both beginners and seasoned scientists. While there are also disadvantages in this approach, I think that this can serve as an inspiration for future development and possibly even transformation of this field.

6.2.2 Clarity of anthropological theories

Classical anthropology produced a large amount of data and theories, but in a rather unorganized fashion. While this might not pose a problem when theories have only verbal form and are tested indirectly, a precise formulation of a problem is essential when theories are to be formally tested. This is easily demonstrated in Chapter 4 in which I was trying to turn "factors that might influence post-marital residence" into a mathematical model. Similarly, in the Ember and Divale debate on the relationship between warfare and residence (Ember and Ember, 1971; Divale, 1974; Ember, 1974; Divale, 1984) I was personally more biased towards Divale's explanation because it had a much clearer mechanistic formulation. His scenario started with migrating society into an already occupied environment, continued with conflict with an existing population over scarce resources and then described why and how matrilocality is developed, adopted and lost. This explanation provided necessary information on the inner working of particular required behaviour and thus did not require a great deal of additional research, although the model still had to be simplified due to a lack of information on several submodels. This is in fact another problem with many anthropological theories (or at least, regarding post-marital residence). Many theories suggest a relationship between various factors, but do not sufficiently explore these relationships. Second-order effects are almost never mentioned. For example, according to both Divale and Ember, warfare, further divided into internal and external, is suggested as an important factor that influences post-marital residence. However, neither theory attempts to sufficiently formulate what warfare is or what its functional role in population is and how the population reacts to it. Similarly, both authors note differences between patrilocality and matrilocality in the way they practice warfare and that in matrilocality internal warfare is almost absent. And while they formulate it as an effect of the distribution of males, and thus warriors, across villages, there was no attempt to quantify this effect and compare it to other peacekeeping mechanisms, such as alliances through marriages between village leaders. This is often discovered when the implicit assumption on the behaviour of the population needs to be simulated, which results in much greater complexity of the computational model (see Figure 6.1).

6.2.3 Acceptance of modelling approach

In anthropology, and social sciences in general, mathematical representation and computer modelling of society or culture are not always accepted without scepticism, at least among the more classically-oriented researchers. In fact, this is not a new thing (Rodin et al., 1978) and while even decades ago there were numerous mathematical and computational models (Dyke, 1981), even to this day a large part of anthropological literature largely ignores the computational progress on this field and concentrates on the historical description of societies or only verbally-defined models and theories. In fact, it seems that the field is split into two groups, with papers published in scientific journals utilizing computational methods and book-oriented authors preferring a more narrative approach. One common argument against computational methods is a lack of complexity of represented models (Dyke, 1981). However, while a verbally-defined theory can seem more complex, this is often dispelled once a more precise specification of relationship is required (as mentioned in the previous section). An advantage of the computational approach is its precision. Once simple models have been explored, and their behaviour understood, more complex models can be developed. Fortunately, the successful use of computational methods by Facebook, Google and others that managed to model various human behaviours had a transformational effect on many social sciences.

Compare this to biology, which is often called a "soft" science as well. At the start of the 20th century, biology had only a lukewarm relationship to mathematics. Even Darwin in his autobiography commented

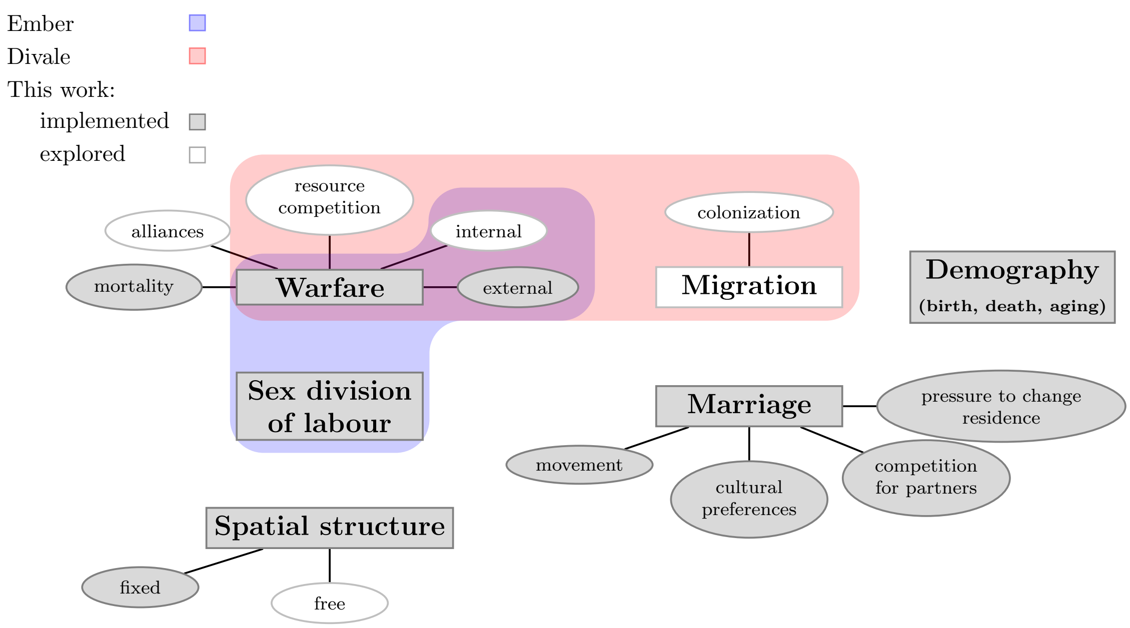


Figure 6.1: Comparison of concepts, factors or submodels represented in Ember's and Divale's theories and in the model implemented in Chapter 4. The coloured areas represent Ember's (light blue) and Divale's (light red) theories. Concepts that are directly implemented in the model from Chapter 4 are in grey, while those that were explored, but not implemented, are left uncoloured. As all the implicitly assumed concepts or suggested effect have to be explicitly modelled, the resulting model presented in Chapter 4 is significantly more complex than the original theories.

that he disliked mathematics in his youth, but later in life regretted that he had not understood it (Darwin, 1887). This relationship however significantly changed. The advances in studying population dynamics by Malthus (1798) and Verhulst (1845) were extended by Lotka (1920), which gave rise to ecological theory. At a similar time, the SIR (susceptible, infectious, resistant) model, a staple in disease modelling, was established (Kermack and McKendrick, 1927). And of course, R. A. Fisher not only contributed significantly to genetics (Piegorsch, 1990), but also greatly extended statistics, developing the maximum likelihood, statistical hypothesis inference testing, related p-values and analysis of variance (ANOVA) (Box, 1978). Nowadays, ecology books are often full of mathematical models instead of verbal ones and even field biologists are looking at integrating mathematical models and statistical analysis to help analyse and interpret their field data.

6.3 Future directions

This thesis should not be perceived as a final say on the problem of post-marital residence. In fact, it just scratches the surface of what it is possible to do with a computational approach in this field. Significant progress could be possible through improved and extended databases so that obtaining and processing a large amount of data is simple enough in with the language of choice (R, Python, Julia and others).

6.3.1 Language-tree based approach

With bigger and better databases that connect already known, or integrate new, information about societies, Chapter 2 could be done on much larger sample of trees, such as language families from Asia (Austroasiatic, Sino-Tibetan, Dravidian), Africa (Niger-Congo – only Bantu subfamily was represented here, Nilo-Saharan, Afroasiatic), North America (Oto-Manguean, Algic, Na-Dene, Mayan) and South America (Arawak, Carib, Quechuan, Tupian). Additionally, an epoch model (Bielejec et al., 2014) could be utilized. This allows two or more sets of rates to be used. Before some time-point, post-marital residence evolves according to the first set of rates and after the time-point according to the second set. This time point could be some important historic event, such as the development of agriculture and its non-genealogical spread. More complex models could allow different rates of residence evolution for a specific branch of a tree. However, this might not be entirely possible with just encoded residence type. Generally, these models were developed on DNA, which is represented as a long string of states (bases), which naturally can hold more information. Fortunato and Jordan (2010) tried to alleviate this by coding residence using three coding positions, two for the primary (prevalent) type of residence and a single state for a secondary (less common, but possible) type of residence. While this technique has its own problems, since it imposes a certain structure of the residence .e.g., primary matrilocal residence with position 1 and 2 is evolutionary different from primary matrilocal residence with positions 1 and 3, a similar approach could be used to encode more evolutionary information in residence states. Still, given the scarcity of detailed information in ethnographies, this might be possible only for a limited set of data.

Before these methods can be widely used, a robust investigation of relationships between languages and residence should be performed. In this work, language trees in their evolutionary time were used. Some authors however suggest the use of dated trees, where the branch-time would be in years. This was not done in this work due to problems of a technical nature. To take this possible discrepancy into account, we tried to test for the relationship between branch length and residence at least indirectly by utilizing branch transformations. And while we found some evidence that the evolutionary time might be valid, this is by no means a sufficient exploration of this problem.

6.3.2 Data-mining approach

Similarly, better and easily accessible databases are an invitation for data-mining procedures. These techniques, instead of testing hypotheses gained by studying the literature or working in the field, can discover unexpected patterns in data. Chapter 3 is just one such example. The field of data-mining is a growing one with many well-known techniques and thus utilizing them should not be problematic.

My approach relied on using a clustering algorithm to recover the number of clusters, which were then described according to the residence. I have however not fully exhausted the description of these results. A deeper analysis would be required to gather all the differences between variables of interest and analyse their impact, especially if a larger number of clusters is used.

A similar, yet significantly different, approach would be to look at this problem as a classification problem and utilize machine learning to be able to classify societies based on some readily available variables. If this would be possible with a very low error rate, a classifier could be used to predict residence in societies where this information is not available. If a decision tree was used to build such classification, the rules of the decision tree would be informative as well.

6.3.3 Modelling approach

The model constructed in Chapter 4 is not perfect, it is a very simplified implementation of Divale's and Ember's theories. A number of simplifications were introduced mainly due to lack of mechanistic knowledge of various subsystems, such as warfare or how alliances are formed. This could inspire anthropologists to study these systems in detail so that mechanistic models can be developed. These models can then be used, in their variations pertaining to specific applications, as a part of other models. This approach was done with the demographic model in Chapter 4. Basic population dynamics is a well-known problem and has been relentlessly studied since the eighteen century (Malthus, 1798). Since then, mathematical representations that are robust enough to cover the vast majority of cases, but simple enough to be easily understood and integrated into other models, have been were developed. A well-studied and understood simplified example is an important prerequisite for a more complex scenario and thus works like Turchin and Korotayev (2006), Kohler et al. (2009) or Billari et al. (2007) should be more prominent.

However, even now the model can be extended in numerous ways. Currently, the submodel for marriages is quite restrictive and individuals will always end up marrying, if possible. I already developed conditions of no-marriage which lessen this requirement, it was however abandoned due to lack of knowledge about the role of age in marriage. A similar fate is shared by age-fertility rates and age-specific warfare effectivity. When the age-related effect is known, the cohort structure of the model can be broken up, allowing marriage between individuals of different age and even polygamy. By studying warfare and alliance theory, the internal warfare could be introduced and instead of using a constant warfare pressure, the enemy community could be explicitly modelled. However, it should be noted that the total running time of a model is already substantial due to the sheer number of parameter combinations, so that a cloud computing solution had to be employed. By introducing new parameters, it might be computationally challenging to fully explore model behaviour.

6.3.4 Anthropological approach

While I am not an anthropologist, I have made my best effort to study and understand the problems of anthropological research and post-marital residence specifically. However, I am a computational scientist and thus there are a lot of areas that I might have missed during my research. Many results that do not seem special to me might be intriguing to anthropologists due to a much higher expertise of the field. I can thus only emphasize the interesting opportunities that might arise from future collaboration.

The lack of a global pattern of residence evolution is not surprising, in fact, some evidence for this stems for a different relationship between residence and division of labour by sex based on particular geographical area (Ember and Ember, 1971) and the opposite would suggest that society develops in stages, i.e., unilinear evolution. And while the development of some structures might be dependent on the presence of others, post-marital residence in its core is just a differential sex dispersion. What was however surprising is that all tested language groups differed significantly from each other across all their residence states and thus not a single, but multiple factors must play a significant role. This was essentially confirmed in the following chapter. The individual residence states can exist under significantly different conditions. This essentially means that these residence states might fulfil a different functional role in society and thus they might as well be labelled differently. However, a combined computational and anthropological approach is required here to precisely define these conditions. I am personally very intrigued by this finding and I am curious about where it might take us. When these conditions are described, they can be explicitly modelled using an agent-based approach to test the validity of hypotheses about the function of residence.

6.4 Conclusion

This thesis presented a computational perspective on the problem of the study of post-marital residence. The post-marital residence was studied from three different angles, using an evolutionary approach with language trees, data-mining approach in clustering of the Ethnographic Atlas and a simulation approach with an agent-based model of warfare-induced residence change. While the results of individual chapters were not definitive, together they form a strong statement regarding how various factors influence a change of post-marital residence. Rather than a conclusive answer, this work should be perceived as a proof of concept and invitation for collaboration between classical anthropology and computational-based approaches.

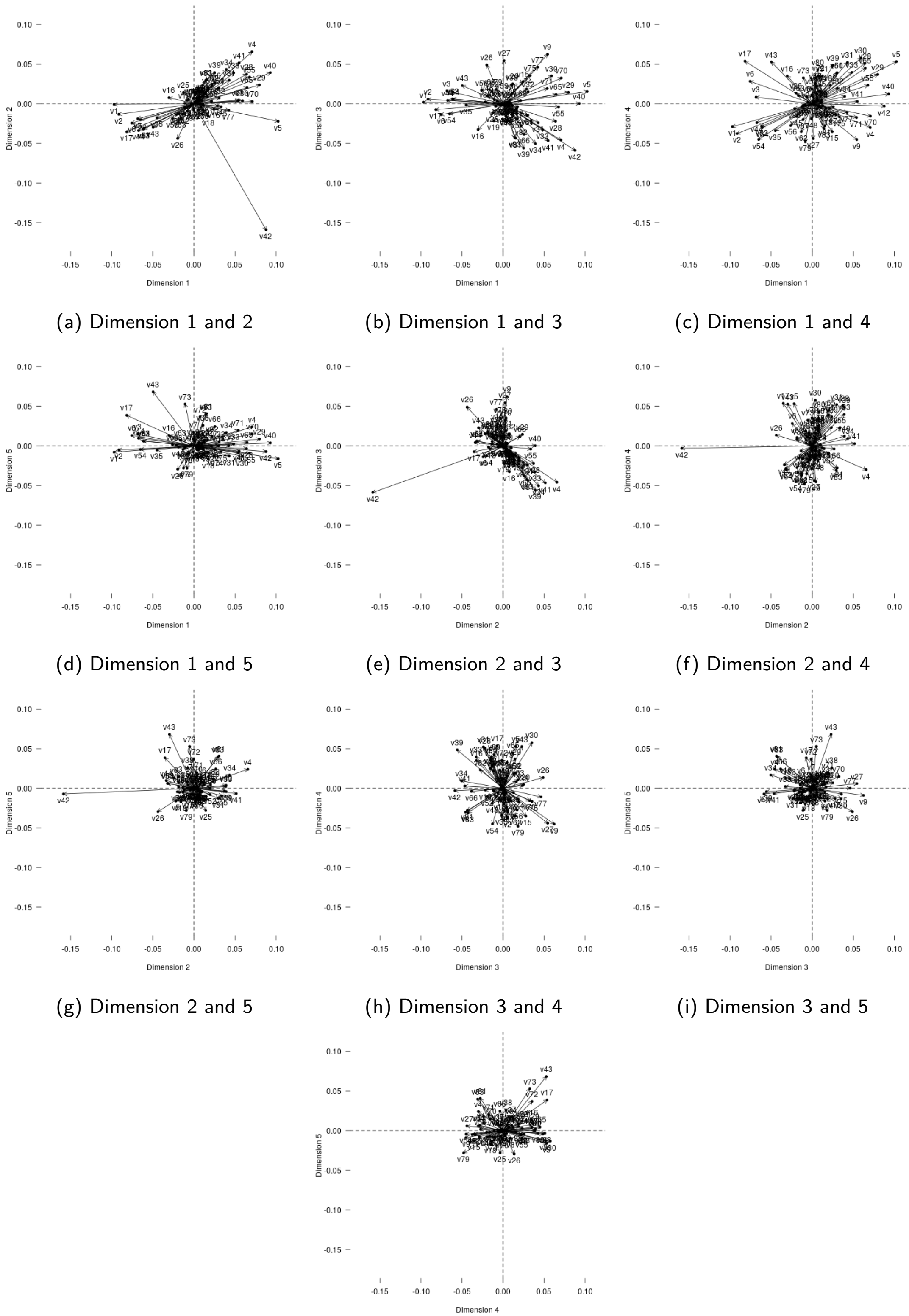
A. Hierarchical Clustering of the Ethnographic Atlas

A.1 Multiple Correspondence Analysis of Ethnographic Atlas

Most variables are not strongly associated with any dimension except for variable v42 (the prevalent type of subsistence economy) (Figure A.1), which is associated with dimension 2. Other than that, there are a number of less determining relationships. Somewhat notable is a prevalence of other subsistence variables, such as v1 (gathering) and v2 (hunting) correlated negatively and v4 (animal husbandry) and v5 (agriculture) correlated positively with dimension 1. Given that v1–v5 are ordinal variables, it is interesting that these show on orthogonal dimensions. Variable v42 thus codes some additional information that is not fully captured by v1–v5.

The positive association of dimension with variable and also association between variables can be more clearly seen on Figure A.2, which describes correlations between variables and dimensions. It is clearly visible here that while very similar on dimension 1 to variable v4 (e.g., Figure A.2c), variable v42 carries significant information in dimension 2 (e.g., Figure A.2a) and except the relationship between these two variables and v1, v2 and v5 in dimension 1, there is very little significant association between other variables and dimensions. It should however be noted that even the strongest correlations are very weak.

We can view associations of societies and dimensions using Figure A.3 in a similar way to the relationship between variables (Figure A.1). Several Mesoamerican societies (Tepehuan, Mixtec, Otomi, possibly Chitimach, Jacaltec) seem to form a group in dimension 1 together with Brazilian Aueto and several pastoral societies (Hadendowa, Karamojong and Uzbek) seems to be more strongly associated with dimension 4.



(a) Dimension 1 and 2

(b) Dimension 1 and 3

(c) Dimension 1 and 4

(d) Dimension 1 and 5

(e) Dimension 2 and 3

(f) Dimension 2 and 4

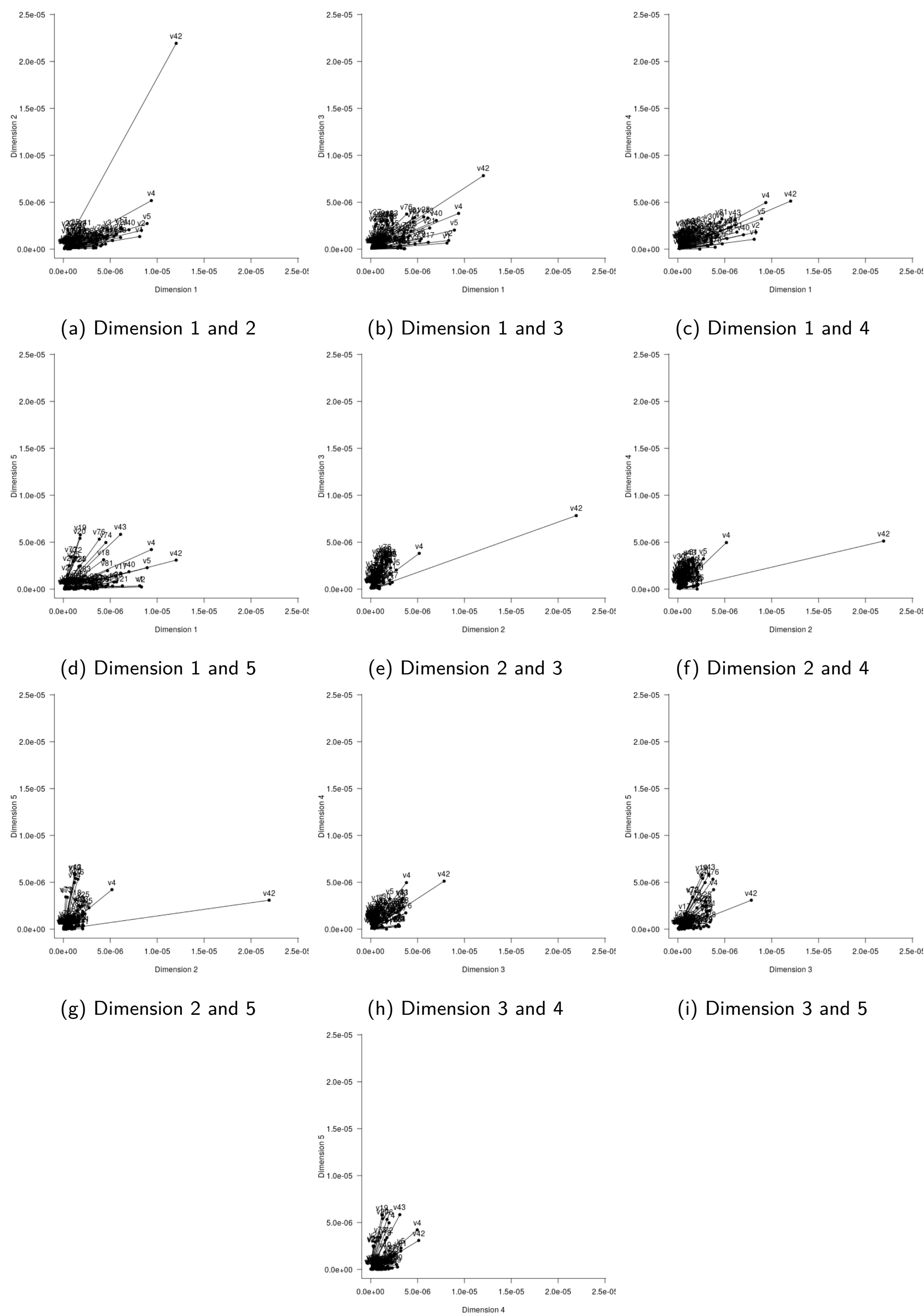
(g) Dimension 2 and 5

(h) Dimension 3 and 4

(i) Dimension 3 and 5

(j) Dimension 1 and 4

Figure A.1: Two dimensional graphs of loadings (relationships between variables and dimensions) for the first 5 dimensions. Most variables are not strongly connected with any dimension, except for variable v42 (the type of subsistence economy), which is strongly connected with dimension 2.



(a) Dimension 1 and 2

(b) Dimension 1 and 3

(c) Dimension 1 and 4

(d) Dimension 1 and 5

(e) Dimension 2 and 3

(f) Dimension 2 and 4

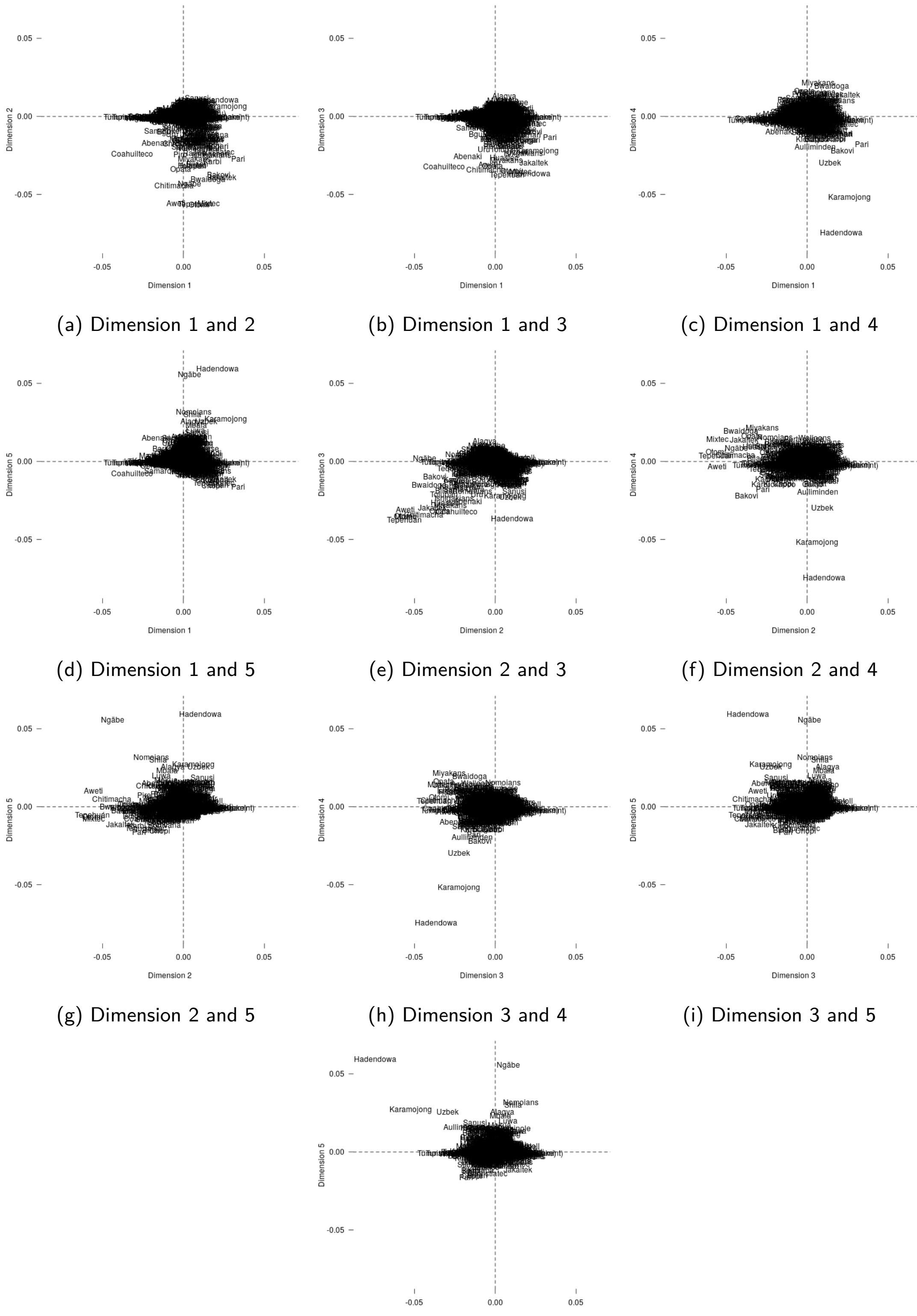
(g) Dimension 2 and 5

(h) Dimension 3 and 4

(i) Dimension 3 and 5

(j) Dimension 1 and 4

Figure A.2: Graphs of correlations between variables and dimensions. Variable v42 (the prevalent type of subsistence) seems to be correlated with dimension 2, however even this strongest correlation is insignificant ($r = 3 \cdot 10^{-5}$).



(a) Dimension 1 and 2 (b) Dimension 1 and 3 (c) Dimension 1 and 4

(d) Dimension 1 and 5 (e) Dimension 2 and 3 (f) Dimension 2 and 4

(g) Dimension 2 and 5 (h) Dimension 3 and 4 (i) Dimension 3 and 5

(j) Dimension 1 and 4

Figure A.3: Graph of associations between societies and the first 5 dimensions extracted by MCA. Only two groups of societies are associated with dimension: Mesoamerican societies (Tepehuan, Mixtec, Otomi, Chitimach and Jacaltec) together with Brazilian Aueto are associated with dimension 1 and several pastoral societies (Hadendowa, Karamojong and Uzbek) are associated with dimension 4.

A.2 Comparison of variable distribution from obtained clusters

A.2.1 6 clusters from non-squared Ward's method

Table A.1 shows a full list of variables that were grouped into categories Table 3.7. Only a few vaiables seem to be not relevant (40% difference): v50 (sex differences in gathering), v61 (age and occupational specialization in gathering), v65 (age and occupational specialization in agriculture) and v87 (shape of roof of secondary or alternative house type), most variables have different distribution in all six clusters.

Table A.1: Comparison of distribution across all variables and 6 clusters from non-squared Ward's method, see Table 3.7 for grouped variables according to class.

Variable	Same	Not enough evidence	Different	Different (%)	Class
v1	1	0	4	0.80	Subsistence
v2	1	0	4	0.80	Subsistence
v3	0	0	5	1.00	Subsistence
v4	0	0	5	1.00	Subsistence
v5	0	0	5	1.00	Subsistence
v6	0	0	5	1.00	Marriage
v7	0	1	4	0.80	Marriage
v8	0	0	5	1.00	Marriage
v9	0	0	5	1.00	Marriage
v15	0	0	5	1.00	Marriage
v16	0	1	4	0.80	Marriage
v17	0	0	5	1.00	Descent
v18	1	0	4	0.80	Descent
v19	1	0	4	0.80	Descent
v20	0	0	5	1.00	Descent
v21	0	0	5	1.00	Descent
v23	0	0	5	1.00	Marriage
v24	0	0	5	1.00	Marriage
v25	0	0	5	1.00	Marriage
v26	0	0	5	1.00	Marriage
v27	0	0	5	1.00	Descent
v28	0	0	5	1.00	Subsistence
v29	0	0	5	1.00	Subsistence
v30	0	0	5	1.00	Settlement pattern and size
v31	2	0	3	0.60	Settlement pattern and size
v32	1	0	4	0.80	Political organisation
v33	0	0	5	1.00	Political organisation
v34	0	0	5	1.00	Belief and religion
v35	2	0	3	0.60	Games
v36	2	0	3	0.60	Sex related taboos and traditions
v37	0	0	5	1.00	Sex related taboos and traditions
v38	1	0	4	0.80	Sex related taboos and traditions
v39	0	0	5	1.00	Subsistence
v40	0	0	5	1.00	Subsistence

v41	0	0	5	1.00	Subsistence
v42	0	0	5	1.00	Subsistence
v43	0	0	5	1.00	Descent
v44	0	0	5	1.00	Sex differences
v45	2	0	3	0.60	Sex differences
v46	0	1	4	0.80	Sex differences
v47	1	0	4	0.80	Sex differences
v48	0	1	4	0.80	Sex differences
v49	2	0	3	0.60	Sex differences
v50	3	0	2	0.40	Sex differences
v51	1	0	4	0.80	Sex differences
v52	0	1	4	0.80	Sex differences
v53	0	0	5	1.00	Sex differences
v54	0	1	4	0.80	Sex differences
v55	0	0	5	1.00	Age and occupational specialisation
v56	1	0	4	0.80	Age and occupational specialisation
v57	0	1	4	0.80	Age and occupational specialisation
v58	1	0	4	0.80	Age and occupational specialisation
v59	0	1	4	0.80	Age and occupational specialisation
v61	3	0	2	0.40	Age and occupational specialisation
v62	0	0	5	1.00	Age and occupational specialisation
v63	1	0	4	0.80	Age and occupational specialisation
v64	0	0	5	1.00	Age and occupational specialisation
v65	2	1	2	0.40	Age and occupational specialisation
v66	1	0	4	0.80	Class stratification and slavery
v68	0	0	5	1.00	Class stratification and slavery
v70	0	0	5	1.00	Class stratification and slavery
v71	0	0	5	1.00	Class stratification and slavery
v72	0	0	5	1.00	Political organisation
v73	0	0	5	1.00	Political organisation
v74	0	0	5	1.00	Inheritance of property
v75	0	0	5	1.00	Inheritance of property
v76	0	0	5	1.00	Inheritance of property
v77	0	1	4	0.80	Inheritance of property
v78	2	0	3	0.60	Sex related taboos and traditions
v79	0	0	5	1.00	Housing
v80	0	0	5	1.00	Housing
v81	0	0	5	1.00	Housing
v82	0	0	5	1.00	Housing
v83	0	1	4	0.80	Housing
v84	2	0	3	0.60	Housing
v85	1	0	4	0.80	Housing
v86	2	0	3	0.60	Housing
v87	2	1	2	0.40	Housing
v88	1	0	4	0.80	Housing
v90	2	0	3	0.60	Political organisation
v94	2	0	3	0.60	Political organisation
v112	1	0	4	0.80	Belief and religion

Table A.2: Comparison between distributions of variables across all bifurcations according the non-squared Ward's method with 13 clusters. The 83 variables were categorized into 13 underlying classes. The columns show how many times the distribution of variables of certain class were significantly different or the same based on AICc values of a Bayesian multinomial test.

Class	Same	Not enough evidence	Different	Different (%)
Age and occupational specialisation	33	7	80	67
Belief and religion	5	1	18	75
Class stratification and slavery	10	0	38	79
Descent	9	0	75	89
Games	5	1	6	50
Housing	42	9	69	57
Inheritance of property	10	3	35	73
Marriage	25	2	93	78
Political organisation	25	1	46	64
Settlement pattern and size	9	0	15	62
Sex differences	34	12	86	65
Sex related taboos and traditions	20	1	27	56
Subsistence	23	2	107	81

A.2.2 13 clusters from non-squared Ward's method

While most variable distribution were significantly different across all 6 clusters, this significantly drops when 13 clusters are used (Table A.2, see Table A.3 for full list of variables). Only the subsistence and descent are still highly relevant, but less so than previously (80-90%). Other important (70-80%) classes of variables includes class stratification and slavery, marriage, belief and religion and inheritance of property. As previously, the least important category are games, but are now joined by sex-related taboos and traditions and housing as well.

Table A.3: Comparison of distribution across all variables and 13 clusters from non-squared Ward's method, see Table A.2 for grouped variables according to class.

Variable	Same	Not enough evidence	Different	Different (%)	Class
v1	3	0	9	0.75	Subsistence
v2	3	0	9	0.75	Subsistence
v3	1	0	11	0.92	Subsistence
v4	1	1	10	0.83	Subsistence
v5	4	0	8	0.67	Subsistence
v6	0	0	12	1.00	Marriage
v7	3	1	8	0.67	Marriage
v8	1	0	11	0.92	Marriage
v9	2	0	10	0.83	Marriage
v15	0	0	12	1.00	Marriage
v16	1	1	10	0.83	Marriage
v17	0	0	12	1.00	Descent
v18	1	0	11	0.92	Descent

v19	4	0	8	0.67	Descent
v20	3	0	9	0.75	Descent
v21	1	0	11	0.92	Descent
v23	4	0	8	0.67	Marriage
v24	3	0	9	0.75	Marriage
v25	6	0	6	0.50	Marriage
v26	5	0	7	0.58	Marriage
v27	0	0	12	1.00	Descent
v28	2	0	10	0.83	Subsistence
v29	2	0	10	0.83	Subsistence
v30	2	0	10	0.83	Settlement pattern and size
v31	7	0	5	0.42	Settlement pattern and size
v32	3	0	9	0.75	Political organisation
v33	3	1	8	0.67	Political organisation
v34	2	0	10	0.83	Belief and religion
v35	5	1	6	0.50	Games
v36	7	1	4	0.33	Sex related taboos and traditions
v37	5	0	7	0.58	Sex related taboos and traditions
v38	3	0	9	0.75	Sex related taboos and traditions
v39	5	0	7	0.58	Subsistence
v40	0	0	12	1.00	Subsistence
v41	2	0	10	0.83	Subsistence
v42	0	1	11	0.92	Subsistence
v43	0	0	12	1.00	Descent
v44	4	0	8	0.67	Sex differences
v45	3	1	8	0.67	Sex differences
v46	5	1	6	0.50	Sex differences
v47	2	1	9	0.75	Sex differences
v48	2	2	8	0.67	Sex differences
v49	6	0	6	0.50	Sex differences
v50	5	0	7	0.58	Sex differences
v51	5	0	7	0.58	Sex differences
v52	0	4	8	0.67	Sex differences
v53	1	1	10	0.83	Sex differences
v54	1	2	9	0.75	Sex differences
v55	2	1	9	0.75	Age and occupational specialisation
v56	3	0	9	0.75	Age and occupational specialisation
v57	3	1	8	0.67	Age and occupational specialisation
v58	1	1	10	0.83	Age and occupational specialisation
v59	1	1	10	0.83	Age and occupational specialisation
v61	6	0	6	0.50	Age and occupational specialisation
v62	3	1	8	0.67	Age and occupational specialisation
v63	3	0	9	0.75	Age and occupational specialisation
v64	3	0	9	0.75	Age and occupational specialisation
v65	8	2	2	0.17	Age and occupational specialisation
v66	2	0	10	0.83	Class stratification and slavery
v68	4	0	8	0.67	Class stratification and slavery
v70	2	0	10	0.83	Class stratification and slavery
v71	2	0	10	0.83	Class stratification and slavery
v72	1	0	11	0.92	Political organisation
v73	1	0	11	0.92	Political organisation

v74	1	1	10	0.83	Inheritance of property
v75	2	1	9	0.75	Inheritance of property
v76	2	0	10	0.83	Inheritance of property
v77	5	1	6	0.50	Inheritance of property
v78	5	0	7	0.58	Sex related taboos and traditions
v79	1	1	10	0.83	Housing
v80	1	1	10	0.83	Housing
v81	2	0	10	0.83	Housing
v82	2	0	10	0.83	Housing
v83	2	1	9	0.75	Housing
v84	7	1	4	0.33	Housing
v85	5	1	6	0.50	Housing
v86	7	2	3	0.25	Housing
v87	8	1	3	0.25	Housing
v88	7	1	4	0.33	Housing
v90	8	0	4	0.33	Political organisation
v94	9	0	3	0.25	Political organisation
v112	3	1	8	0.67	Belief and religion

Figure A.5 and Table A.4 show the effect of a large number of clusters on distribution of selected variables. Clusters are more “specialized” than before, with a much larger proportion of the most common variable. Cluster 1, 2 and 13 are hunter-gatherers, with cluster 13 formed almost predominantly by fishing societies. Cluster 9 is yet again a combination of complex agriculturalists with pastoral societies. Clusters 8 and 12 are simple horticulturalists, clusters 3, 4 and 6 simple farmers, clusters 5, 7, 10 are mixed clusters of simple and complex farmers, while cluster 11 has the most developed societies reaching the highest population densities.

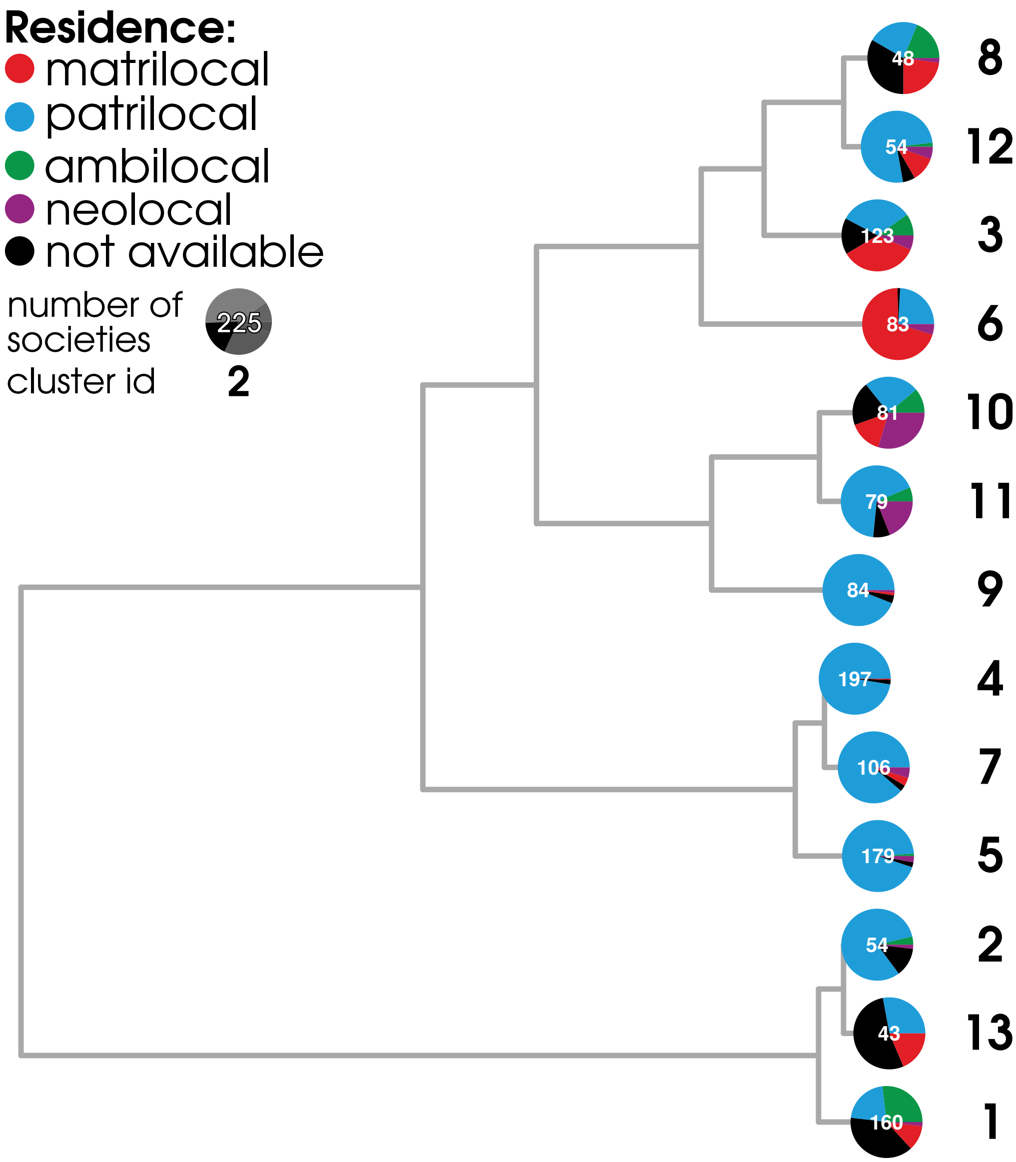


Figure A.4: Tree constructed by clustering data from the Ethnographic Atlas using the non-squared Ward's method and extracting 13 clusters. The pie charts represent societies and a post-marital residence composition of each cluster, with red representing matrilocality, blue patrilocality, green ambilocality, purple neolocality and black standing for unknown data. The number inside each pie chart is the number of societies in each cluster and the number next to the pie-chart is the ID of the cluster.

Table A.4: Typical value of chosen variables for each of the 13 final clusters. For each variable and each cluster, the most common value was taken after excluding unknown values and the percentage frequency of this value, including unknown values, is reported. For a full representation of variable distributions, see Figure A.5.

Cluster	Intensity of agriculture (v28)	Settlement pattern and size (v30)	Mean size of local communities (v31)	Dominant mode of subsistence (v42)
1	absent (86%)	seminomadic (70%)	less than 50 (36%)	gathering (40%)
2	absent (98%)	seminomadic (41%)	50 to 99 (30%)	gathering (37%)
3	extensive or shifting (65%)	compact and permanent (38%)	less than 50 (19%)	extensive agriculture (45%)
4	extensive or shifting (86%)	compact and permanent (58%)	100 to 199 (9%)	extensive agriculture (83%)
5	intensive agriculture (37%)	dispersed homesteads (31%)	100 to 199 (7%)	intensive agriculture (40%)
6	extensive or shifting (84%)	compact and permanent (53%)	50 to 99 (11%)	extensive agriculture (80%)
7	intensive agriculture (44%)	compact and permanent (45%)	400 to 1000 (6%)	intensive agriculture (46%)
8	horticulture (81%)	compact and permanent (52%)	200 to 399 (19%)	extensive agriculture (56%)
9	intensive agriculture with irrigation (44%)	compact and permanent (30%)	cities with popopulation over 50 000 (11%)	pastoralism (54%)
10	extensive or shifting (35%)	compact and permanent (57%)	400 to 1000 (16%)	intensive agriculture (42%)
11	intensive agriculture (59%)	compact and permanent (72%)	cities with popopulation over 50 000 (57%)	intensive agriculture (87%)
12	horticulture (89%)	compact and permanent (59%)	50 to 99 (19%)	extensive agriculture (81%)
13	absent (100%)	semisedentary (40%)	less than 50 (21%)	fishing (79%)

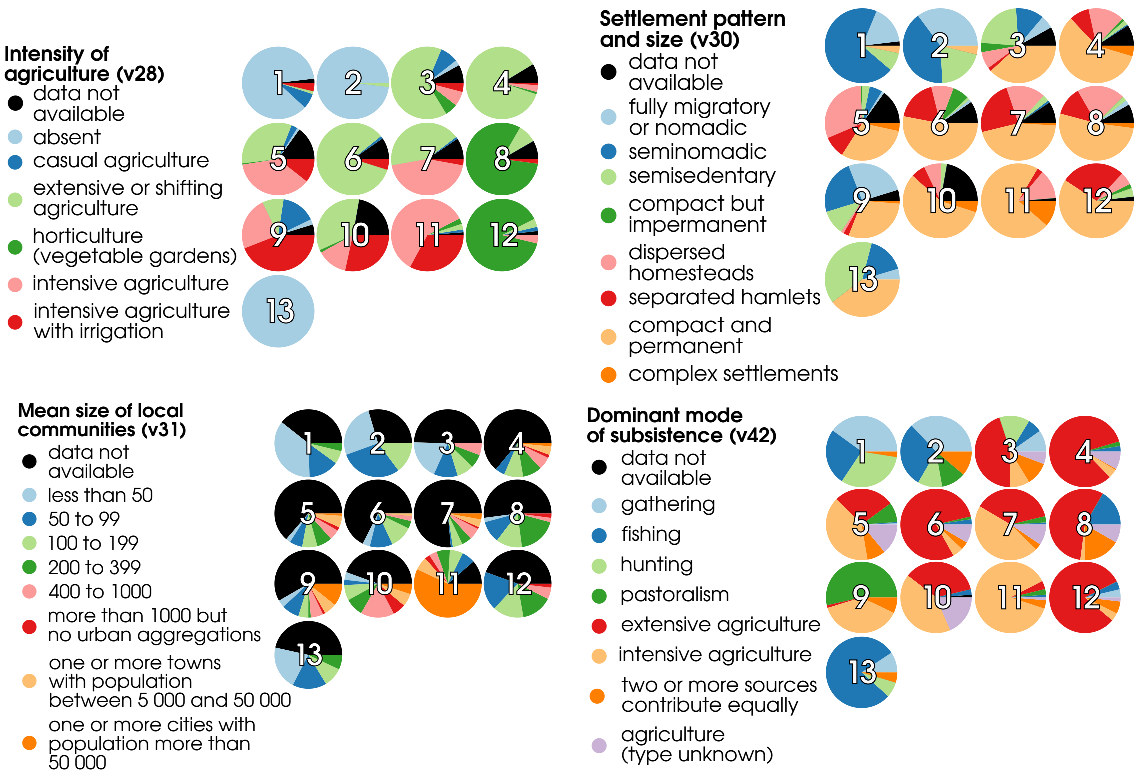


Figure A.5: Distribution of values of four chosen variables for each final cluster from non-squared Ward's method. The four variables: Intensity of Agriculture (v28), Settlement pattern and size (v30), mean size of local communities (v31) and the Dominant mode of subsistence (v42) were chosen for their representation of classical classification of societies into simple and complex hunter-gatherers, simple and complex farmers and pastoralists.

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STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Jiří Moravec

Name/Title of Principal Supervisor: Professor Murray P. Cox

Name of Published Research Output and full reference:
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Fiona M. Jordan, Robert M. Ross, Russell Gray, Stephen Marsland,
Murray P. Cox
Evolution and Human Behavior,
2018

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See the section 2.1.1. Author contributions in chapter 2

Candidate's Signature — Date: 24. September 2018

Principal Supervisor's signature — Date: 24. September 2018

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