

Modelling the evolution of socio-political complexity

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Abstract

The level of organisation required to maintain cohesion in the vast societies we live in today is unprecedented in our past. In this thesis I look into why human societies began to shift from the small-scale groups which characterises the vast majority of human past, into the large-scale entities most of us currently live in. Several ideas have been proposed to explain why many different features of social complexity began to coalesce together in some areas of the world before others, each with some level of support from the archaeological record. In this thesis I have taken a different approach. I rigorously test one hypothesis for its logical consistency before applying it to archaeological data by formalising it as an agent-based model. The hypothesis described by Robert Carneiro (1970, 2012a) suggests that the more limited population movement is through environmental, resource, or social circumscription, the more likely complex societies are to form. By constructing agent-based models from this hypothesis I can show the conditions under which this statement is true, and have identified several areas where assumptions were not made explicit in the original hypothesis. By adapting the models to correspond with the conditions of the Valley of Oaxaca in highland Mexico, I show the extent to which the circumscription theory may explain the emergence of social complexity there and where the gaps in our knowledge lie. In creating and testing an agent-based model of the circumscription hypothesis I have shown how agent-based models may be used in archaeology to deepen our understanding of verbal theories and identified conditions which could have intensified the emergence of complex societies around the world.

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“You are here to learn the subtle science and exact art of potion-making.”
Severus Snape, in *Harry Potter and the Philosopher’s Stone* (J. K. Rowling, 1997).

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“For every task that must be done, there is an element of fun. Find the fun, and SNAP! The job’s a game!” Mary Poppins (Disney, 1964)

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"Words are, in my not so humble opinion, our most inexhaustible source of magic, capable of both inflicting injury and remedying it." Albus Dumbledore, in *Harry Potter and the Deathly Hallows, Part II* (2011)

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Overview

This thesis is written in sequential order: each chapter will provide information and insights to set the background of the following chapters. In Chapter 1, I introduce the topic of social complexity. This is the broadest chapter, covering research from across theoretical and geographical landscapes. The theoretical basis for the models constructed in Chapters 3, 4, and 5; and archaeological basis of Chapter 5, are embedded in the discussion here.

In Chapter 2, I continue to cover the background of Chapters 3, 4, and 5 but with a much more specific focus on the role of formal models in archaeological research. I discuss the benefits of making our own inherent biases and assumptions explicit using tools such as agent-based modelling. The models in the following chapters are built following the principles laid out in Chapter 2.

In Chapters 3, 4, and 5, I discuss three agent-based models designed to test the internal logic, consistency, implicit assumptions, and relevance of the circumscription theory as a possible explanation for the initial emergence of social complexity in human societies. In Chapter 3 I test the core of the circumscription theory in an abstract model by focusing only on the effect of environmental and resource barriers. The model in Chapter 4 builds on the model discussed in Chapter 3 to include the effect of social circumscription, both in isolation and in combination with the environmental and resource circumscription tested in Chapter 3.

To test the relevance of the circumscription theory our in own world, in Chapter 5 I link the abstract models of the previous chapters with the Valley of Oaxaca in Mexico. In this chapter, I compare evidence from the archaeological record for the initial emergence of social complexity with the formation of complex societies in a model developed from the previous two chapters.

I conclude the thesis in Chapter 6 with the overall findings of Chapters 3 to 5, and benefits of using agent-based models as a method in archaeological research.

Chapter 1: What is social complexity and why did it emerge in some human societies?



Abstract

Human societies have not always had the extensive institutions, territories, and population sizes that we see today. The time, location, and reasons for the emergence of societies of increasing social complexity have long been topics of archaeological interest. In this chapter I discuss how different features of social complexity may be identified in the archaeological record and how multiple lines of evidence may be interpreted to infer what societies in the past may have been like. I then discuss different ideas for why social complexity may have emerged, with a focus on the circumscription theory proposed by Robert Carneiro. This chapter provides the theoretical foundation for the agent-based models presented in Chapters 3, 4, and 5.

1.1 Introduction

Humans have lived in small-scale groups for the majority of our past as a species. This is a surprising statement given the patchwork of immense human societies spanning the world today. Our population is larger than at any time previously (Nielsen, 2016). There is hardly a corner of the globe (or even beyond, into the Solar System) that people have not had an impact on (Cazalis, Loreau and Henderson, 2018; Goudi, 2019). People have developed all manner of institutions that govern our everyday lives to survive in such unprecedented social and environmental conditions. How did small-scale, mobile, hunter-gatherer human groups become the cities and nations we live in today? Why did people choose to gather in permanent settlements, live by communal rules, and sometimes decide to conquer their neighbours? These are important questions to ask for us to understand the societies we live in now. In order to do so, we need to look into the past to see when, where, how, and why human groups started to change into large-scale societies. To be able to see these changes in social complexity in the past, we need to know what to look for.

Social complexity is a nebulous concept. Every aspect of life as a human is complex in its own way. Groups of people with a highly complicated set of religious beliefs may or may not also be part of a society with complicated organisational or secular features. A trade network transporting materials thousands of miles from their origin may occur merely through a chain of neighbours exchanging gifts, without an agreed end destination for those objects. There are as many ways to understand social complexity as questions to ask about it. However, as an underlying theme, we are looking for evidence of people cooperating on a large scale. The greater the number of indicators of social complexity from different aspects of a society, the more complex a society is assumed to be. Deciding what those indicators are and how much can be inferred from them is complicated by the nature of human societies and the fragmentary condition of evidence from the past.

1.2 What is social complexity?

There is a wide range of societies across the world. Anthropologists from the last century have seen this variation and attempted to classify different societies

into groups or stages (Carneiro, 1987). Simple categories include differentiating between 'bands', 'tribes', 'chiefdoms', and 'states' (as promoted by Service, 1975), with the assumption that societies increase in complexity in a linear fashion along these stages (Carneiro, 2003). A backlash against this argued that restricting all societies to within a linear scale such as this ignores the vast range of characteristics exhibited by societies within those discrete boxes and implies an inherently false idea of progression where the more 'complex' societies are considered better (Trigger, 1985; Crumley, 1995; Carneiro, 2003; Yoffee, 2005; Johnson, 2010). The implied progression from one stage to the next as inevitable also avoids the difficult question of why societies should change at all. In a 'Darwinian' sense, evolution is not directed and can result in a branching tree of change with selection pressures resulting in 'descent with modification' (Shennan, 2002; Richerson and Boyd, 2005; Mesoudi, 2011, 2016).

The terms used by Service and others like him are still prevalent in research on human societies today. Work has been done to create finer scales within those broad classifications (such as distinguishing between the 'simple' chiefdom of the Chumash of the Santa Barbara Channel region (Arnold, 1992), compared to the 'complex' chiefdom of Cahokia (Cobb, 2003)); to define what exactly puts a society in one category over another (such as through assigning levels of settlement hierarchy (Spencer and Redmond, 2004)); and to highlight the flexibility of those stages (societies can cycle between those, or skip through them (Anderson, 1996; Gavrillets, Anderson and Turchin, 2010; Currie *et al.*, 2010). This section will briefly cover the traits which can be used to determine the levels of social complexity shown by different societies.

There is a long history of using the presence or absence of different traits in a society to indicate its level of complexity relative to others. In the 1950s, Vere Gordon Childe attempted to distinguish urban from pre-urban societies based on ten classifications (see Table 1.1) (Childe, 1950). Childe's ten classifications focus primarily on the economic features, with the assumption that all of ten must occur in unison in order for people to be classified as living an urban lifestyle. It is now known that societies can exhibit some of these traits without others (Flannery, 1994), but that there is a pattern in the order in which they appear. Recent work has built on the urbanisation classifications suggested by

Childe to assemble more general traits of social complexity into Guttman scales (also known as cumulative scaling, where elements can be ordered such that the presence of certain traits predict the presence of others) (Carneiro, 1962; Peregrine, 2004). This measure does not assume that all traits must occur in unison, but shows which are likely to occur (or be required) before the next trait can also appear. Peregrine (2004) shows that some traits consistently occur before others among societies randomly selected from the Human Relations Area Files (HRAF) database. For example, agriculture can be present in societies with very few other traits of social complexity, while writing and money tend only to appear in societies where all other traits are also present (Peregrine, 2004, p147). A measure of social complexity, used as a shorthand label for comparing different societies, can be derived from this scale of traits. Where these traits cluster into regularly re-occurring groups, the presence or absence of groups of traits may provide broad classifications of different levels of social complexity (Peregrine, 2004, p148- 9; 2007, p78).

Table 1.1 The list of traits suggested by Gordon V. Childe (1950) to describe urban societies. The list includes 5 primary and 5 secondary characteristics. These traits tend to appear together in the archaeological record and it was assumed that a shift from pre-urban to urban societies took the rapid form of a revolution. It is now known that these traits may appear independently over time (Flannery, 1994), although it has been suggested by Spencer (2009) that the shift from chiefdom-level to state-level societies (as two adaptive peaks) may have required fast changes in polity organisation. Spencer (2009) and Abrutyn and Lawrence (2010) argue that this is due to selection pressures acting on societies to efficiently distribute resources and manage the population (see Section 1.4 for further discussion).

Primary characteristics	Secondary characteristics
Size and density of cities	Monumental public works
Full-time specialisation of labour	Long-distance trade
Concentration of surplus (fuels political economy)	Standardized art and aesthetics
Class-structured society (not ranked, but stratified)	Writing
State organisation (transcends kinship – unrelated)	Arithmetic, geometry, astronomy

By extension, the presence of one trait may indicate the likely presence of others. Turchin *et al.*, (2017) show that the population, territory size, capital population and the levels of hierarchy (in administrative, military, religious, and settlement levels) of a polity were most strongly correlated in a principle-components analysis of multiple complexity variables. To note: the term ‘polity’ is used in this thesis to refer to a unit of people who may be mobilised to act in unison for political purposes, although the term is much debated with other definitions focusing on the territoriality of groups rather than on relationships between people (Tomaszewski and Smith, 2011). This supports earlier work done suggesting that settlement hierarchy (the ranking of settlements based on the distribution of power within a polity) may be used as a proxy for the level of social complexity (Spencer and Redmond, 2004). Without taking the measure too rigidly, the more levels of settlement hierarchy, the larger and more complex the polity can be assumed to be. The relative focal importance of settlements, based on their size and the administrative features present, can be indicated by

rank-size analysis of settlements over time (Drennan and Peterson, 2004; Duffy, 2015; Palmisano, 2017).

Categorising societies based on the incidence of different traits of social complexity is a useful way to describe and compare societies from different backgrounds, but should be used only with the full awareness that there are many different ways to potentially measure social complexity, and none should imply an inevitable march of progression or ordering of societies into morally 'superior' and 'inferior'. Use of the term 'social complexity' in this thesis is intended to imply the collection of all measures discussed here. The terms 'chiefdom' and 'state' are used as a short-hand for relative scale of social complexity and are not meant to rigidly divide societies into arbitrary classifications.

1.3 How can we measure social complexity?

As difficult as it already is to define social complexity in a useful way, it becomes more difficult when the data available are fragmentary. This section will cover the main characteristics of social complexity which can be identified within the constraints of the archaeological record.

The archaeological record consists of the material remains of human actions from the past which have preserved long enough for them to be recovered, together with the environmental setting at the time. The types of materials which preserve are severely biased to the most durable (such as stone and ceramics) while other more organic remains (such as food, paper, and clothing) will often perish unless under extreme circumstances (extremely arid, waterlogged or frozen conditions, or through charring) (Renfrew and Bahn, 2015). Older materials are more likely to perish or become damaged over time, thus making interpretation of older remains less reliable.

Interpreting the fragments which have preserved is a continuous challenge in archaeology (Gilchrist, 1999; Hodder and Hutson, 2003; Johnson, 2010). It is easy for us as creative, story-telling humans to imagine the past only as a different version of our present. This problem is particularly accentuated when the material remains are particularly old or do not relate to objects, beliefs, or

behaviours that we have today. The archaeologist must therefore question their interpretations at all times and use as many lines of evidence as possible to understand the people of the past. This applies to the interpretation of archaeological evidence for social complexity as well as any other area of human life. The following sections examine the evidence for key traits of social complexity and discuss how these alone may be problematic. The section will conclude with a justification for the measures of social complexity used in the rest of this thesis.

1.3.1 Size

Size is an important indicator of the level of social complexity. A large population size implies the need for extensive communication to coordinate the group as a cohesive whole. To accurately measure the scale of a society it is important to be able to identify how many people considered themselves to be part of it. The archaeological record does not preserve the thoughts of people in the past, but we can find evidence of their affiliations or shared cultural practices through their material remains. As examples: stone handaxes of the Acheulean type retained a similar tear-drop shape for thousands of years (c. 1.6mya to less than 200kya) and across continents (Lycett, 2008); the Bell Beaker culture is unified by remarkably consistent pottery vessel shape and decoration across Europe between 2750-2500 BCE (Olalde *et al.*, 2018); and, in Neolithic Europe (around 5000-4000 BCE), a type of stone only found in the Alps was knapped and smoothed into polished stone handaxes, then spread across Europe up to 1700km away from the original source of stone (Petréquin *et al.*, 2011). However, similarity in one type of artefact across wide areas may simply signal sufficient interaction between neighbouring peoples to exchange a gift or imitate a style, not a shared social identity. This becomes even more difficult to measure if the groups being analysed are smaller and with continuously shifting boundaries.

A more reliable measure of shared polity identity can be taken from artefacts which were made deliberately to identify that polity. This can include textual information, such as the king lists of ancient Egypt and Maya in Mexico (Bronk Ramsey *et al.*, 2010; Folan *et al.*, 1995). In the absence of writing this can apply to any items or architecture created with the intention of communicating power

and allegiance, such as the monumental Huacas del Sol and de la Luna in the Moche Valley in Peru as clear markers of Moche elite prominence (DeMarrias, Castillo and Earle, 1996). In this case identifying monumental architecture in combination with shared artefact styles may indicate the scale of the society.

1.3.2 Power differentiation

The gulf between those with greater or lesser access to resources may be another indicator of the overall complexity of a society. The assumption here is that if people in a society are able to access and accumulate resources or valuable goods, there must be a form of more extensive trade network with other groups of people or the capability to support specialist craftspeople within the society itself. If some people within that society hoard more material wealth than others, we may assume that they held a more venerable position or were able to wield more power over others. At the extreme end of this are autocrats who can use their power to display huge wealth. Objects may be given prestigious value due to the inherent properties of the material (being a rare or particularly distinctive material, such as jade or gold), the difficulty of crafting it, or the distance it has travelled (Hayden, 1998; Helms 1993). The archaeological record holds evidence for some of the earliest people who gained or were granted power to access more prestigious items than others. Evidence for restricted access to prestige items extends even as far back in the past as the Upper Palaeolithic (c.10,000-50,000ya) before farming became the main method for subsistence provision. Elaborate burials at the site of Sungir in western Russia, dated to 26-27kya, suggest a differentiation of status between individuals. The individuals here were interred with, among other artefacts, a mass of carved mammoth ivory beads which would have taken thousands of hours to create (Dobrovolskaya, Richards and Trinkaus, 2012). It is worth noting that the burials included the body of an early adolescent and late juvenile (Dobrovolskaya, Richards and Trinkaus, 2012). This is important because younger individuals would not have had long to build up their own status within their lifetimes, which implies a hereditary element (Marcus, 2008, p257). However distinctive these burials, there is little evidence indicating why these individuals were distinguished over others or that they had direct influence over other people. As has been argued before, there is more than one form of power (Flannery, 1972; Crumley, 1995, 2005) and a person's status in a burial context

may have little bearing on their status in life. Prestige burial goods alone are therefore only one indicator of social complexity.

Instead of seeking to identify an individual's power over other individuals in the archaeological record, it may be more useful to look at the scale of that power. When power extends beyond that of an individual within a group to include additional groups of people, this can be considered good evidence for the increase in social complexity. An important archaeological marker for this is settlement hierarchy, where one or a few settlements (permanent residential locations) have a level of control over others. In an economic sense, increasingly larger, central settlements will need support from surrounding areas to maintain the population (Smith, 2004). Those settlements which are larger in size (by population and area covered), and show evidence of an administrative role in organising the polity (usually signified by the presence of non-residential buildings) tend to be considered higher in a settlement hierarchy (Marcus, 2008). Larger settlements which contain more non-residential architecture can indicate higher levels of authority in the polity (Spencer and Redmond, 2003). Methods to estimate the population size of a settlement rely on estimating the number of people living there from the number, size, and structure of preserved residential buildings, and the extent of archaeological remains in general (Kirch and Rallu, 2007). An early example is the site of Erlitou in ancient China (c.1900-1500 BCE), with evidence of specialised bronze foundries and monumental architecture up to 1,000m across (Yang, 2004; Bagley, 1999). The presence of sites which are comparatively larger and with greater internal differentiation than other contemporary sites is itself a useful indicator of social complexity, because it may be assumed that those sites required more complex organisational systems to supply the population with food, resources, and labour to make these features possible.

1.3.3 Organisation

Another important aspect of social complexity is the organisational skills required to keep a polity cohesive (Flannery, 1972). It may therefore be possible to interpret complexity of social organisation by the levels of organisation required to achieve the material remains seen in the archaeological record. Monumental architecture, such as the stone monument at Göbekli Tepe in the

Middle East (9,000 BCE), is an example of this, requiring the mobilisation of labour, raw materials, and coordination of construction (Schmidt, 2006, cited in Marchs, 2008 and Wengrow and Graeber, 2015). The specialised labour required to harvest lacquer sap and craft ornate objects by the Jōmon people of Japan, who existed between around 10,000-500 BCE, is another (Pearson, 2007, Matsui and Kanehara, 2006). These craftspeople may have depended on others for subsistence needs while they worked. But this indicator alone may be misleading. Both of these examples are from people who depended on hunting and foraging for a large portion of their diet and show very few other indicators of social complexity. Where craft specialisation is combined with other markers of social complexity, such as a prestige goods economy between elites, we can begin to infer more about the society. For example, the pyramids and burial goods of the Old Kingdom pharaohs in Egypt indicate a society which is able to mobilise labour on a large scale and support craft specialists to achieve the ends of the privileged few in the upper echelons of power (Kemp, 2006). All of these aspects together indicate a society of greater scale and social complexity than the hunter-foraging societies before.

An additional marker of social complexity comes in the form of military specialisation (D'Altroy, 1985). As with craft specialisation, maintaining, mobilising and equipping soldiers requires labour and subsistence. But military specialists also indicate the level of social complexity more directly. If a polity had dedicated resources to warfare, it may be assumed that they were engaged in conflict, which requires that people identify themselves as belonging to different sides. The scale of the military indicates the scale of the conflict, and therefore the scale of the opposing polities. Archaeological evidence for battles is very rarely found. But other evidence, such as weapons, defensive walls, hill-top locations of settlements, and written records may survive. In the Valley of Oaxaca, Mexico, it is clear that violence escalates with increasing social complexity. The presence of burned daub at settlements, foundation of defensive settlements such as Monte Albán, and propagandistic depictions of tortured captives, glyphs recording the settlements conquered and a skull rack of the remains of conquered people, signify the military gains of the Zapotec society (Spencer and Redmond, 2003, 2004; Marcus and Flannery, 1996). However, a society can continue to grow in population and internal

specialisation without prioritising military conquest, as the Zapotec people did after the initial conquest of surrounding areas (Feinman *et al.*, 1985; Balkansky 1998; Blanton *et al.*, 1982). Combining evidence for military specialisation with evidence for the spread of a polity (based on material culture) and internal differentiation of roles into leaders or other specialists will provide a more reliable measure of social complexity.

1.3.4 The measure of social complexity used in this thesis

The sections above (1.3.1 to 1.3.3) show that there are multiple measures which can be used to label one society as more complex than another, which cannot be reconciled into one simple linear trajectory (Drennan, Peterson and Fox, 2010). However, looking at multiple traits in combination can be informative. An accurate measure of settlement hierarchy will require information about the size of the polity, the concentration of power within the polity, and the level of internal specialisation of roles to distinguish settlements with more control than others. All of these features are considered in determining the settlement hierarchy of a polity. As a coarse measure, it can be assumed that the greater the social complexity of a polity, the greater the number of levels of settlement hierarchy it will contain (Spencer and Redmond, 2004). In addition, proportion of settlements ranked at different levels of settlement hierarchy may be plotted as a rank-size graph, if we assume that the larger the settlement the more likely it is to have power over other settlements. A polity where the majority of resources and people are concentrated in a few settlements will produce a concave, or primate, rank-size shape, whereas a polity where resources and people are more evenly distributed will produce a more convex shape. If power is located in settlements with a greater proportion of resources and people, we may therefore assume that a polity with a primate rank-size graph have greater differentiation of settlement hierarchy (Drennan and Peterson, 2004; Crema, 2014). For the purposes of testing hypotheses concerning the emergence of social complexity at the polity-level (not the emergence of individual-level inequality within societies), I will use a measure of settlement hierarchy in this thesis. A measure of settlement hierarchy has the dual advantage of being detectable in the archaeological record (through the comparison of settlements) and of reflecting other measures of social complexity (including: wealth concentration, extent of influence, and the internal

specialisation of roles). It is therefore a relatively simple measure which can be used to compare societies across time and place. In Chapter 5 (Section 5.2.1), I discuss the settlement hierarchy and associated social complexity of the Valley of Oaxaca in Mexico in particular. In Chapter 2, I discuss the more specific assumptions made in this thesis.

1.4 What causes social complexity to increase?

The work done to identify different levels of social complexity through the great variety of features of human societies is important to be able to describe any changes in social complexity over time. Using the markers identified above, it may be possible to trace the increase, plateau, and eventual collapse of many societies where archaeological remains for the relevant time span have been uncovered. However, describing social complexity does not explain how or why societies may have changed.

Theories for the initial emergence of social complexity have tended to focus on single factors considered to be the main drivers of change. Main drivers have variously been attributed to: population pressure and agriculture (Boserup, 1965), technological innovations (Wittfogel, 1957; Johnson and Earle, 2000; Earle, 2002), warfare and conflict (Carneiro, 1970; Goldman, 1955), trade (Rathje, 1971; Helms, 1988, 1993; Sherman *et al.*, 2010), and elite ideology and religion (Mann, 1986; Marcus and Flannery, 2004). A focus on single factors such as these may be misleading. Flannery (1972) argues that instead of creating an over-simplified linear model of complexity increase, we should look for the circular connections between multiple variables. An analysis of 289 cultures from the Atlas of Cultural Evolution shows how population pressure, reliance on agriculture and technological specialisation can be interlinked in the evolution of cultural complexity, even when controlling for change over time (Peregrine, 2003, pp23-30).

One strength of these prime mover theories is that they can focus on explanations for the increase in social complexity at the individual level. All of the above explanations can be directly linked to the decisions made by individuals which have consequences for the society as a whole (whether originally intended by the individual or not). For example, archaeological

theories informed by ethnography classically assign great importance to the role of charismatic individuals in corralling groups of people together, as attested to by descriptions for chieftdom and state formation from ethnographic and historical records (Flannery and Marcus, 2012). However, focusing exclusively on individual agency and the role of cultural factors may mask more general theoretical explanations for the emergence of social complexity. The decisions that people are able to consider and act upon are constrained by the wider cultural context in which they live, but that cultural context is also formed from the accumulation of individual actions (c.f. Bourdieu, 1977; Giddens, 1984). Much like processes in biological evolution where individual actions (such as reproduction or death) can result in broader evolutionary trends of speciation or extinction, individual actions within human cultures can change societies as a whole over time. Theories and methods developed to understand the complex interactions between micro- and macro-levels in biological processes of change may therefore be applicable to understanding cultural change as well (Mesoudi, 2016). For example, phylogenetic methods have been applied to test for the presence of, and transition between, stages of social complexity, thus combining the heritability of traits with broad scale patterns over time (Currie, *et al.*, 2010; Currie and Mace, 2011). However, this is a macro-evolutionary method to describe the changes in social complexity in broad strokes and does not test for the individual-level mechanisms underlying any changes in social complexity over time.

The application of evolutionary theory to human societies can be extended beyond describing the patterns of change to explain why these changes may have occurred. Work has already been done in attempting to explain why chiefdoms and states form despite the costs incurred in both establishing and maintaining a new system (Marcus, 1998). New societies can often be short-lived, especially where no precedent for a more complex form of organisation exists. A variety of different types of organisation may be developed over time as people experiment with different methods of organisation and types of power and control (Wright, 1977). Societies may cycle with oscillating levels of complexity without ever shifting to state-level organisation (Marcus, 1998; Wright, 2006). A shift to a state-level society requires organisation structures which can sustain management of large populations of people and the

mobilisation of correspondingly large amounts of resources. Societies which cannot sustain the administrative burden may fragment into smaller, more manageable sections. Authority in a smaller, chiefdom-type society will tend to be almost exclusively centralised so that the leader can exert direct influence on all other members of the society. This is only possible in societies small enough for the chief to have a direct presence at all times. A state-level society, on the other hand, is characterised by a larger size (of population and territory) and the delegation of power beyond the central authority to ensure that all extremities of the polity are maintained (Spencer, 2014). The main question here is therefore under what circumstances the leader of a chiefdom would consent to divide their power. Spencer (1998, 2014) argues that this situation will arise through the territorial expansion of the polity, which will rapidly increase access to further labour and resources (Spencer, 1998, 2014). A critical threshold is reached when the chiefdom grows beyond the range which can be successfully administered by a central authority. The chief must then either delegate power and increase internal specialisation (as bureaucratic roles) to extend the range of control, or allow the polity to fragment and result in a cycling of complexity at the chiefdom level (Marcus, 1998; Anderson, 1996; Wright, 1977). The transition between 'chiefdom' and 'state' may be a phase of lower adaptive fitness (an 'adaptive valley') that could prevent many chiefdoms from transitioning to state-level organisation Spencer (2009). This process has been described in the archaeological record (Spencer, 2010) and as a dynamic mathematical model (Spencer, 1998).

A society with state-level social organisation may reach a higher adaptive peak (where the society is able to out-compete other neighbouring societies for resources or territory) than a chiefdom-level society through larger labour and defensive force (Turchin and Gavrillets, 2009; Turchin *et al.*, 2013) as well as access to a wider variety of land and resources to mitigate risk. The main premise is that groups which can mobilise larger numbers of people effectively will out-compete smaller groups with less robust structures in a social arms race (Johnson and Earle, 2000). Neighbouring societies must then increase in social complexity in order to compete, causing a proliferation of secondary state formation (Balkansky, 2006). Turchin *et al.*, (2013) tested whether increasing intensity of military activity resulted in the selection of ultrasocial traits (features

of a society which enable large numbers of people to cooperate more effectively, such as bureaucracy or unifying religion) by comparing an agent-based model with data from across the Afro-Eurasian landmass spanning 3000 years in the past. They found that the presence of military technologies does have a significant effect on the selection for ultrasocial traits in societies across the Afro-Eurasian landmass, implying the importance of warfare in the evolution of social complexity. Although group selection is a much debated concept, research which uses the concept of multilevel selection (Turchin, 2010; Boyd and Richerson, 2010; Martinez and Esposito, 2014) has the advantage of bridging between different levels of selection to explain the proliferation of traits in a more nuanced way than focusing on a single level.

In all cases however, there is the risk of fragmentation into smaller, simpler societies. As Currie and Mace (2011) show, societies are much more likely to increase in complexity by incremental steps, but that a polity may fragment into any of the previous stages of social complexity. The approaches to explaining societal change suggest that there may be different costs and benefits to different forms of society, depending on the social context. Ever larger and more complex societies may not be needed if there are no other societies to compete with.

The other question that arises from investigating why societies can increase in complexity is why people would accept becoming subordinate under a leader. The emergence of leadership in an evolutionary context has been researched extensively and can be applied to human societies. The basic idea of reproductive skew, whereby some individuals in a group have greater access to resources and reproductive opportunities than others within a group, may be relevant in explaining despotism in human groups. Those with less access may still stay because the benefits from limited access to resources or group defence still outweigh the costs of being independent (Summers, 2005; Buston *et al.*, 2009). Bell and Winterhalder (2014) developed mathematical models to test the optimal concessions that a leader would need to make to maintain a subordinate population without driving them away. Complementing this, Hooper, Kaplan and Boone (2010) used mathematical models to test under what conditions subordinates would accept a leader based on the relative gains of cooperation and costs of sanctioning defectors in the group. Building on insights

from Hooper, Kaplan and Boone (2010), Powers and Lehmann (2014) built models confirming that hierarchical social organisation can emerge without coercion by elites, when it is beneficial for members of a group to have the extra organisational capabilities. For example, in organising more advanced agricultural technology to extract more resources.

The strength of this research is that it provides a mathematical basis to compare hypotheses of leadership formation using archaeological and ethnographic data. Kohler *et al.*, (2012) constructed an agent-based model based on Hooper, Kaplan and Boone (2010) to test whether leadership in small-scale Pueblo societies could have formed without elite coercion. Others have investigated the extent to which the Ideal Free or Ideal Despotism Distributions modelled by Bell and Winterhalder (2014) apply to real-world examples (Jazwa, Kennett and Winterhalder, 2015; Kennett and Winterhalder, 2008; Kennett and Conlee, 2002; Kennett *et al.*, 2009). These studies are useful to ground-truth the abstract mathematical models, but further work is needed to apply them more generally and determine whether the patterns are universal.

Research into the changing internal structure of societies helps explain the proliferation of increasingly complex societies, but not why the process should proceed more quickly in some places compared to others. Why did state-level societies appear for the first time in some areas of the world, but not others? Why should people be in conflict with each other at all, and why should that conflict escalate into the founding of whole new social structures? One explanation has been put forward by Robert Carneiro, who suggests that population growth and limitations to free movement may result in increasing competition over limited resources, thereby initiating the conflict cycle between increasingly complex societies described above. This process is described as the 'circumscription theory' and is discussed further in Section 1.5.

1.5 Circumscription theory

The circumscription theory, as described by Carneiro (1970, 1988, 2012a, 2012b), suggests that limitations to population movement will intensify conflict between societies, leading to conquest warfare and the establishment of increasingly complex societies. Groups of people will become subordinate to

others when their options for moving away are more costly than being subjugated by the conquering polity (see Section 1.4 for the discussion on accepting despotic leadership and selection for more complex societies).

Carneiro argues that circumscribing conditions come in three main forms: environmental, where geographical barriers present a physical barrier to movement; resource, where people attempt to gain access to limited resources and end up concentrated in resource-rich areas; and social, where surrounding areas are already claimed as territory belonging to rival groups (Carneiro, 1970, 1988, 2012a). These three sources of circumscription all result in limitations to population movement and subsequent competition over resources between people (see Figure 1.1). These different barriers to population movement are not always insurmountable. An environmental barrier of ocean water, for example, might only be a barrier to those people who lack the boats or navigation skills to cross it. Areas of high subsistence resource concentration may be extended through agricultural intensification. The hard boundary of a territory with a neighbouring society might only last as long as the fence delineating it. An assessment of the level of circumscription experienced by any population in the past therefore requires an understanding of the conditions at the time, as far as the available evidence will allow.

Of the three circumscription conditions, Carneiro argues that environmental circumscription will have the strongest influence as it has greater potential to make tighter conditions for people than resource or social circumscription. However, resource circumscription could potentially have a more significant effect in areas where there is a stark difference in the resources of neighbouring areas or the resources are particularly desirable, leading to the clustering of settlements and conflict over access. Social circumscription may also have an important effect in areas where population size can escalate rapidly, typically in areas which are rich in subsistence resources. Social circumscription can arise without resource circumscription, but as always, it is a matter of degree and more food will allow a faster rate of population increase.

Attempts have been made to apply the circumscription theory to areas where societies increased in social complexity, with mixed results. Descriptions of societal change over time can uncover fine-scale details about the events and

environmental conditions of particular areas in the past, including past agricultural productivity (Currie, et al, 2015; Zinkina, Korotayev and Alexey, 2016). However, verbal applications of the circumscription theory are framed by the standpoint of the author as it is very easy to argue either for or against the effect of circumscription through biases in data presentation or collection (e.g. Kirch, 1988; Hauer, 1998; Deflem, 1999; Vaneeckhout, 2008; Gibson, 2012; McCoy *et al.*, 2014). So, while detailed information is much needed to be able to accurately assess the impact of experienced circumscription on polity change, verbal descriptions alone cannot conclusively support or reject the theory. The discussion below will assess whether there may be support for the circumscription hypothesis from archaeological evidence for the emergence of social complexity.

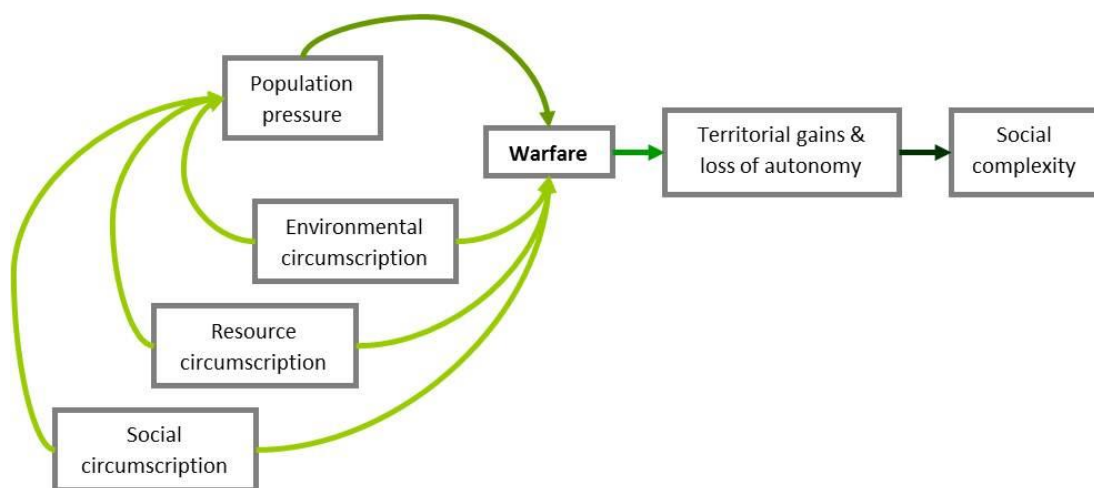


Figure 1.1 Summary of the circumscription hypothesis, as argued for by Carneiro (1970, 2012a). Central to the hypothesis is the role of warfare. Population pressure (limits on resource availability for the number of people with access to those resources) can result in a higher incidence of warfare. Environmental, resource, or social circumscription may accentuate the effect of population pressure, but may still exert pressure on a population before carrying capacity is reached by reducing the options to move. An increase in warfare may therefore occur before population pressure is noticeable. Circumscription of any sort can result in limited dispersal, and therefore conflict with neighbouring people, without necessarily being related to population pressure. The link between warfare and social complexity is based on the assumption that the conflict caused by population pressure or circumscribed conditions will result in the conquering of one group of people over another, thus increasing the size of one polity (in population and territory size) and causing the loss of

autonomy of the other. The larger groups will have more power to then defeat other neighbouring groups, and continue increasing in size (Marcus and Flannery, 1996). This hypothesis assumes that the mechanisms to organise ever-larger groups of people will be developed as they are needed.

1.5.1 Archaeological evidence

Is there any evidence that social complexity formation is associated with any of these three types of circumscription? And does one type lead to a faster accumulation and/or higher level of social complexity than others? This section will discuss a small number of instances where social complexity is associated with circumscribed population movement, with a focus on cases where an increase in social complexity was unprecedented in that region without external contact from other more complex societies. These may be considered good test areas because the societies here changed in complexity without any apparent external pressure from other more complex societies to do so (Marcus, 2008). Any circumscribing conditions may therefore have been relevant. The aim here is not to determine whether circumscribing conditions *must* result in the emergence of social complexity or whether social complexity can *only* have appeared where circumscription had an effect. Carneiro (2012a, 2012b) argues that circumscribing conditions would merely amplify, not guarantee, the formation of social complexity. Instead, I discuss a few examples where social complexity did form where environmental, resource, or social circumscription may have had an impact. This is to assess whether there is any support for the circumscription hypothesis in the archaeological record, and whether it could therefore be a more generally applicable universal theory for the emergence of social complexity in other situations, as Carneiro (2012a, 2012b) suggests.

1.5.2 If there is environmental circumscription, is there also evidence of polity formation?

There are two notable examples where environmental circumscription and polity formation are closely associated. The first is the Nile Valley in Egypt. The second is the Valley of Oaxaca in Mexico. Both areas are heavily environmentally circumscribed, by desert and mountains respectively (Carneiro, 2012a). Both had a large enough resource base to support growing populations.

Both are also areas where societies increased in social complexity faster and to a higher level than any surrounding areas (Spencer, 2010; Carneiro, 1970, 2012a). Hierakonpolis became a state-level society (with four levels of settlement hierarchy) in Upper Egypt between c.3,400-3,200 BCE (Hoffman, Hamrourh and Allen, 1986; Sandeford, 2018). The Zapotecs did likewise in highland Mexico between around 300 BCE – 200 CE (Spencer, 2003, 2010; Spencer and Redmond, 2003, 2004). These two cases suggest that environmental circumscription could have had an important effect on the formation of social complexity.

There has been much research done in the Valley of Oaxaca to understand how and why the Zapotec society grew. Data collected from this region are relatively temporally and spatially complete (Blanton *et al.*, 1982; Kowalewski *et al.*, 1989a, 1989b; Marcus and Flannery, 1996; see Chapter 5, Section 5.2), and include environmental information which classifies the valley floor by potential for resource productivity (Kirkby, 1973; Nicholas, 1989; Chapter 5, Figure 5.4). Although there is good archaeological and environmental data, the circumscription hypothesis has not been directly tested here any further than the suggestion that the mountainous border may have had an important effect on societies there. It has been argued that population pressure was also not a concern in the Valley of Oaxaca for the duration of the initial emergence of social complexity in the valley (Feinman and Nicholas, 1990, p96). However, population pressure is loose concept which may be defined in different ways and may be felt before carrying capacity is reached. I discuss the assumptions of population pressure as related to the circumscription hypothesis further in Chapter 4 (Sections 4.3.1 and 4.3.2).

Even though the effect of population pressure may be contested, the importance of warfare (the main mechanism of the hypothesis to increase social complexity) may be attested to by archaeological data for the burning of buildings, depictions of conquered rivals, and conquest of neighbouring valleys by residents of the Valley of Oaxaca (Spencer, 1998, 2010; Redmond and Spencer, 2012; see Chapter 5, Section 5.2.2). This supports the circumscription hypothesis, insofar as social complexity formed in an environment which was highly circumscribed by surrounding mountains (see Chapter 5, Figure 5.1) where conflict between polities was rife. However, the degree to which the

incidence of warfare is related to environmental conditions is not clear from the archaeological evidence alone. The strength of archaeological data is in identifying long-term patterns of change over time, but at the expense of a fine-scale understanding of the individual processes which resulted in those patterns.

The extreme cases of environmental circumscription, combined with sufficient resources to allow large population growth, seen in Egypt and Oaxaca, are quite rare around the world. Other areas of indigenous social complexity formation tend to show a greater mix of environmental and resource circumscription. Even within the Nile Valley, it can be argued that the huge potential resources from the Nile could have had a significant impact on complexity formation there (a concentration of resources which is not seen in the Valley of Oaxaca) (Carneiro, 2012a). Coastal Peru, the Indus Valley in Pakistan, and riverine valleys in China and Mesopotamia, all show evidence of indigenous social complexity, and all have a combination of environmental circumscription (by mountains and/ or deserts) and resource circumscription (with resources highly centred on the rivers or coast) (Carneiro, 2012a, 2012b; Yi, 2012). Although the environmental barriers are less extreme in these areas compared to Egypt and Oaxaca, there would still have been some limitation to population movement (Carneiro, 2012a).

Areas which are rich enough in resources to sustain large scale population growth include lowland Mexico, where the Olmec (VanDerwarker, 2006; Coe and Diehl, 1980) and Maya (Marcus, 2003, 2008; Estrada-Belli, 2010) societies formed; along the Mississippi River in North America, where societies including Cahokia and Moundville formed (Cobb, 2003); and along the Amazon River, where societies including the Omagua and Tapajós formed (Carneiro, 2012a, p24). Evidence for monumental architecture, crafts specialisation, and large central settlements from these areas suggests the presence of social complexity. Whether these societies can be classified as 'states' prior to contact with other more complex societies is largely down to fine-scale discussions of the definition of a state and interpretation of the available archaeological evidence (c.f. Spencer and Redmond, 2004). Carneiro (2012a, p24) argues that these societies were slower to form the high levels of social complexity seen in

regions which had a greater extent of environmental circumscription because population movement was less constrained.

1.5.3 Is it possible to have social circumscription in areas without high resource concentration?

This question is much harder to answer given the archaeological evidence available. None of the areas of primary state formation show evidence only for social circumscription without environmental or resource circumscription (Carneiro, 2012a, 2012b; Sandeford, 2018). One area where social complexity arose later in time without drastic resource or environmental circumscription may be the Eurasian steppe (Carneiro, 2012b). In this case, there was room to move in a relatively uniform environment over vast areas. Carneiro argues that despite the lack of extreme environmental or resource circumscription, warfare, the mechanism for social complexity formation, was still present and therefore still had an effect. However, evidence presented by Honeychurch (2013) suggests that the Xiongnu state in Mongolia formed without evidence for warfare, but with considerations of the environment. A mountainous ridge system and arid grassland extend within Mongolia, and the Gobi desert presents an additional barrier to the south. The limiting environmental conditions are in addition to altercations with contemporary Qin and Han states to the southeast in China (Honeychurch, 2013). This example shows how vague the circumscription hypothesis is without clear definitions of what constitutes a 'circumscribed' area and what the role of warfare is in the formation of social complexity.

1.5.4 What can be concluded about the potential of the circumscription hypothesis to explain social complexity formation?

These examples show how environmental, resource, or social circumscription could have contributed to the rise of social complexity in certain areas of the world. I have not gone into detail about areas which may have these conditions but never developed social complexity, or areas where social complexity formed without these conditions being noticeably present. The purpose of this section was to determine whether there are commonalities in circumscribing conditions between the examples of social complexity formation around the world. The

examples presented here, although not exhaustive, suggest that circumscription is worth investigating further. There are details of each of the scenarios which have not been discussed at length, and there may be other commonalities and mechanisms leading to the formation of social complexity which override any similarities in circumscribed conditions (such as the role of ideology, or charismatic leaders, or other environmental conditions visible on a finer scale). In this thesis I focus on the circumscription hypothesis to see whether it *could* be a universal factor that Carneiro suggests it is. In Chapters 3, 4, and 5, I dissect the assumptions of the circumscription hypothesis in detail to determine whether the hypothesis itself is logically consistent and whether it may apply to an example of social complexity formation in the way that Carneiro has predicted.

1.5.5 Limitations of the circumscription hypothesis

Despite the work that has been done to test the predictions of the circumscription hypothesis using the archaeological data and in the construction of mathematical models, there remain areas for further clarification. While there are several examples around the world of areas which show evidence of the development of higher levels of social complexity within circumscribed conditions (Carneiro 1970, 1987, 1988, 1998, 2012a, 2012b), there is very little detail on what precisely makes an area circumscribed, by geography, resources, or rival societies (Schacht, 1988; Marcus, 2012; Peregrine, 2012). In the following chapters I discuss the assumptions (both implicit and explicit) of the circumscription hypothesis in detail. By doing so, I can then test whether the predicted emergence of social complexity in circumscribing conditions can be supported.

There is another side to the formation of social complexity that is not addressed as part of the circumscription hypothesis. The circumscription hypothesis rests on the assumption that warfare between rival groups is required for larger polities to emerge. But there is little mention of the mechanisms by which those groups should become integrated in organisational structure (Flannery, 1972; Crumley, 1995; Bondarenko, Grinin and Korotayev, *et al.*, 2002; Bondarenko, 2007, 2014), or how a polity is able to reorganise itself to unify ever larger populations dispersed over greater areas (c.f. Spencer, 2009; Wright, 2006).

Carneiro (2012a) does reformulate the hypothesis to include the role of charismatic individuals in cajoling disparate groups together. But this does not answer the question of how a polity can persist beyond the lifetime of the leader (Routledge, 2014). Others have looked into this more closely and there has been much writing about the role of different factors allowing the persistence and reformulation of social complexity over time. These include the role of: ideology (Claessen, 1989, 2010; Yoffee, 2005; DeMarrais, 1996); the economy (Friedman and Rowlands, 1977; Brumfiel and Earle, 1987; D'Altroy and Earle, 1985; Earle, 2002, Barker, 2008; Bernbeck, 2008 ; Levine, et al, 2013; Martin, 2010); technology (Wittfogel, 1957; Johnson and Earle, 2000; Kennett, *et al.*, 2013; Cederman and Girardin, 2010; Turchin, *et al.*, 2013; Carneiro, 1974); and, the emergence of collective action and leaders through evolutionary processes (e.g. Vehrencamp, 1983; Summers, 2005; Corning and Szathmary, 2015; Gavrillets, 2015; Glowacki and von Rueden, 2015; Richerson, *et al.*, 2015). However, these areas require further investigation that is beyond the scope of this thesis.

1.6 Agent-based modelling

Evidence in support of the circumscription hypothesis is limited by the nature of the archaeological record and compounded by the imprecise assumptions of the verbal hypothesis. We must therefore turn to new tools to test it. One such tool is agent-based modelling, which is increasingly being applied to archaeological research questions (Lake, 2014, 2015).

Agent-based models are a form of computational simulation whereby the agents or individuals in the model can be programmed to choose their next action based on the conditions they experience in the model. Agents are defined as anything which will take actions in the model, typically people or groups of people for archaeological purposes. Patterns which were not explicitly coded for can emerge from the model as a result of these decisions which can be compared with the emergent patterns of the archaeological record (Kohler and Gumerman, 2000; Lake, 2014). Detailed models have been constructed to simulate the environment and population movement of the Kayenta Anasazi to test whether climate change caused the abandonment of the Long House

Valley in Arizona (Axtell, et al, 2002) among other examples of both local (Altaweel and Wu, 2010) and global (Mithen and Reed, 2002) scale agent-based models to test hypotheses about processes in the past (Lake, 2014, 2015).

I will therefore use agent-based models to test the hypothesis that circumscription influenced the location and rate of the formation of complex societies at a local scale. It is predicted that higher levels of circumscription will increase the likelihood and the rate at which complexity emerges, and therefore, in considering a specific case study, that the mountainous region of the Valley of Oaxaca made complex societies more likely to form there. The methods used to formalise and test the circumscription hypothesis will be discussed in detail in Chapter 2.

1.7 Aim of this thesis

This thesis will investigate whether circumscribed conditions could have contributed to the initial emergence of social complexity in the past by using agent-based models to formalise the verbal hypothesis proposed by Carneiro. It is predicted that environmental, resource, and social circumscription will increase the rate of social complexity formation by limiting population movement. Those conditions which present the strongest barriers to free movement are predicted to create the strongest effect. This will be done in three stages of simulation building and testing: testing two core parts of the circumscription hypothesis in abstract modelling environments, and adapting the model to compare model output with archaeological data from the Valley of Oaxaca. Testing the hypothesis using formal modelling techniques and comparing model outputs with archaeological data will help to show whether circumscribing conditions could have contributed to the emergence of social complexity at different times around the world.

Chapter 2: How can agent-based models be used as an archaeological tool to investigate the emergence of social complexity?



Abstract

Every human being will interpret the world around them with their own assumptions and biases. This includes scientists and scholars, and is as true in archaeology as any other discipline. In this chapter I discuss how we can use agent-based models to make our assumptions explicit in such a way that they can be understood and scrutinised by others. In Chapter 1, I introduced the circumscription theory in relation to the initial emergence of social complexity. In this chapter, I build on this theoretical background and discuss how the circumscription theory, and other similar ideas explaining the emergence of social complexity, may be tested using formal models. This chapter forms the basis of the methods employed in Chapters 3, 4, and 5.

2.1 Introduction: formal models

Every human being is a modeller (Epstein, 2008). The volume of information that our senses are bombarded with every day means that in order to function effectively, we must simplify that information. In simplifying it, whether consciously done or not, we are building our own model of reality. This is as true in scientific disciplines as in any other area of life. Every one of us will hold on to assumptions that we are not aware of when interpreting data, deciding what experiments to run, or pondering over research ideas (for examples, see Saini, 2017). In order to do research which is as unaffected by our assumptions as possible we must attempt to identify what these assumptions are, both for ourselves and to others. Formalising hypotheses through mathematical equations or computational models is one way to do so.

There are two main advantages to building formal models. Firstly, the unflinching logical nature of mathematics and computer code can be used to test the internal consistency of an idea or hypothesis. To solve the equation, or to write a working model, will require distilling an idea down to its essential parts and stating the connections between them. This in itself can reveal problems or previously unspecified assumptions with the original idea, so starting a dialectic (back-and-forth) relationship between the model and theory. This can be a worth-while exercise to solidify a hypothesis (see Chapter 3, Section 3.6.1). Recording thought experiments in this way will ensure that any researcher will be able to follow the argument and unpick problems. This leads on to the second main advantage, which is that formal models are a written version of thoughts which others can decipher.

Formal models can take many forms, depending on the purposes of the researcher. Two types will be discussed briefly here: mathematical equation modelling and agent-based modelling (ABM). Both are useful but, like any tool, will fit some purposes better than others. In mathematical equation modelling, a whole argument can be distilled into a set of equations. This has the distinct advantage of simplicity and clarity, and the prospect of a solvable answer to the equations. For example, Spencer (1998) constructed a mathematical model to explain state formation based on a predator-prey relationship in biology. The equation very concisely shows how increasing territory (and therefore

resources) will coevolve with increasing bureaucracy in order to manage those resources. Societies which fail to manage those resources will collapse, initiating a cyclical pattern of social complexity increase and decrease if societies once again begin to grow. Societies which can manage those resources will grow, eventually forming larger societies with several levels of internal management (see Chapter 1, Section 1.4). However, the stark simplicity of equation based modelling is also a downside. Too much realism or complexity may make the equation unsolvable and may therefore not be attempted, even if the added complexity is required to fully understand a process. The simplicity of Spencer's (1998) model is supported by comparison with archaeological data insofar as a proliferation of social complexity is usually associated with evidence for territorial expansion and conquest (Spencer, 2014). However, this equation alone does not provide any indication as to why societies may become territorially expansive in some places before others or what the internal structures to maintain social cohesion may be. Mathematical equations such as this may be rendered inflexible by their simplicity and need to be solvable in what is in reality a very complex and flexible world.

An alternative is to formalise a hypothesis as an agent-based model (ABM). ABMs are a type of model which include individuals or 'agents' who can act independently from one another. ABMs can be much more complicated than mathematical equations because they may include multiple sub-processes which can allow for stochasticity and change over time. A lot of information can be contained within the model, which does not need to be 'solved' in the same way that a mathematical equation should be. With individual agents and random elements, each run of the model may be different from the last (how different depends on the complexity of the model). This means that the modeller can see the consequences of different factors as they play out and effectively run experiments on the past (Barton, 2014). This potential for complexity allows us to move beyond single-cause explanations (Carneiro, 2012a; Chapter 1, Section 1.4). The following sections will describe ABMs in more detail and outline how they have been used in this thesis.

2.2 Agent-based models (ABMs)

ABMs are a way to translate our own understanding of the world into a computer simulation that others can see and scrutinise. ABMs are removed from reality, which, counter-intuitively, can make reality clearer to see by excluding extraneous detail to find the simplest (but not simplistic) explanation (c.f. Einstein, 1934). As with any formal model, by simplifying reality we are forced to clarify our assumptions to ourselves and reveal some of our unconscious biases (Aldenderfer, 1991, Smaldino, 2016). The computer has no prior assumptions: any inconsistent statements will cause the model to stop in error which forces the modeller to be precise (Kowarik, 2012). The agents in the model will follow the code exactly, which can lead to some surprising initial results for the unwary modeller.

One advantage of ABMs is that it is possible to run many alternative scenarios with various levels of realism. Mathematical models may show reality in its simplest (solvable) form, but may be constrained by that simplicity when comparing the model with reality. Through the constant negotiation of simplicity and realism, the agent-based modeller must constantly justify the features included in their model. The modeller may thereby have some success in overcoming their own assumptions and biases and explore other possibilities which had not been considered relevant before (Lake, 2015). The flexibility of agent-based models in their scope for simplicity and realism means that the model can be used to explore and test assumptions systematically (Kowarik, 2012). Moreover, that same flexibility means that the agent-based modeller can design experiments from the smallest to the largest scale, and from the most abstract to more realistic levels of detail, as suited for the particular research question (see Section 2.2.2 below). This includes scales of experiment which would be impossible to do in the present (Barton, 2014). In this way, ABMs can be seen as a bridge between plausible verbal thought experiments and the rigidity of mathematical equations to explain observed phenomena.

Bridging the gap between verbal descriptions (which often put the thoughts and actions of individuals at the forefront) and a more data-driven, formal approach to testing ideas is particularly important in archaeology. Archaeological research must, by its very nature, straddle a more quantitative, scientific focus to gather

and analyse data, and interpretation of those data in relation to the humans who left those traces behind. To gather a full picture of what may have happened in the past and why people behaved in the ways that they did, the archaeologist must traverse multiple types of information at different scales of time and resolution to understand the world as those in the past may have done. This means that the archaeologist must always have a degree of self-reflection. What data they choose to collect and how they choose to analyse and interpret that data could be entirely driven by their own assumptions (Dobres and Robb, 2000; Hodder and Hutson, 2003, and see Chapter 1, Section 1.3). It is probably of little surprise that even though ABMs have been used in archaeology for decades, the method is becoming increasingly common only now after the theoretical upheavals between the scientific and interpretivist approaches of the last century (Aldenderfer, 1991; Lake, 2014, 2015; Cegielski and Rogers, 2015, 2016; Premo, 2010). ABMs have the advantage of being able to accommodate individual agency within a quantitative and explicit framework.

In this section I will discuss three main features of ABMs which are particularly useful in archaeological applications: (1) the emergence of complex phenomena; (2) different scales of time and analysis; and (3) the parameter space.

2.2.1 Emergence of complex phenomena

The sum of an ABM is greater than its parts. Complex patterns of change can emerge over time from relatively simple underlying rules (Epstein, 1999). The 'agents' in agent-based models are given a set of rules to behave by, but each agent will decide what to do autonomously (Crooks and Heppenstall, 2012). This means that although agents can be given simple commands (such as 'move right if there is space'), not all agents will behave in exactly the same way (not all agents will have space to move, and the direction 'right' depends on which way the agent is facing). A good example is flocking behaviour. Agents in the model (corresponding to birds in the real world) are told to follow three simple rules: move in the same direction as other agents around; keep some distance between yourself and the next nearest agent; and move towards other nearby agents until they get too close. Flocks of agents will eventually form without a leader organising the flocks at any point (see 'Flocking' model in

NetLogo Models Library: Wilensky, 1998). Agents are not limited to one type in the model. There can be different types of agents given different sets of rules. The behaviour of these different agents can be informed by other agents or not, making the model very flexible. This is particularly pertinent in archaeological research because the archaeological record is, in effect, a pattern of change which has emerged from the accumulation of actions by individual agents over the last 3.3 million years (Harmand, *et al.*, 2015). Archaeologists can therefore work backwards from the emergent patterns seen in the archaeological record using ABMs to test what underlying processes could have resulted in the record that survives (Barton, 2014).

2.2.2 Scale

To be able to distinguish emergent phenomena from underlying processes, the model must have a clear sense of purpose and scale (Chliaoutakis and Chalkiadakis, 2012). There are two axes of scale to be considered when building an ABM: the level of abstraction and the level of resolution (what constitutes an agent, what environment those agents are placed in, and what length of time is being considered).

The level of abstraction will determine how realistic the model should be. If the model is intended to be a generic representation of reality to test an idea without reference to specific scenarios, then little real world data is needed. Criticisms of models being too abstract or too detailed will often stem from a misunderstanding of the purpose of the model. These models, by definition, cannot be tied to too many specific details or they are at risk of losing their relevance as abstract models. More abstract models have the advantage of being potentially more widely applicable to a multitude of scenarios, and by virtue of that, potentially be quite informative as to general, underlying processes which have happened and are happening in human societies (Lake, 2015). A good example of this is the model built by Chliaoutakis and Chalkiadakis (2016). In this model, agents (households) act to maximise their resource gain through either the extensive or intensive cultivation of resources and by deciding whether or not to engage with other households to share their resources, and how those resources should be allocated among households (including egalitarian, basic sharing, hierarchical, self-organised, and

independent). The aim of this generic model is to show how social complexity can arise from the level of individual agents, without prompting from the modellers, in a model format that could be applied to specific case studies. Chliaoutakis and Chalkiadakis (2016) stress how important it is to build archaeological models from the agent-up, and not just to replicate the known archaeological data. Not only does selecting the 'best fit' results fail to use the most useful aspect of ABMs (the opportunity to experiment in ways which are not possible with the past), but also assumes that the archaeological information is accurate. The archaeological record will always be incomplete and it is unwise to assume perfect knowledge of events.

However, detail can be necessary to reduce the infinite possibilities of an abstract model and make the model relevant for archaeological investigation of a particular scenario (Lake, 2015). Chliaoutakis and Chalkiadakis (2016) do just this and go on to focus their model in a particular environment to investigate the emergence of social complexity in Early Bronze Age Crete. The parameters and model environment are set based on the available archaeological evidence, but with the full knowledge that the archaeological evidence is incomplete and should not be taken as absolute. Model experiments reflect this by testing a variety of model conditions and re-running experiments to investigate the effect of land use patterns (with technology) on population dynamics and social complexity in Crete.

Other models are built with the realism of a particular place in mind from the outset. This can be done well, if the model is not beholden to the archaeological data. An easy trap to slip into is building the model so that the desired patterns emerge and discarding results which do not fit as well. The best use of the archaeological data is to inform parameter settings (but not set them in stone) to enable extensive experimentation with the factors of interest.

One example of a very specific ABM is one of the more recent permutations of the Village Ecodynamics Project ABM made for the Pueblo Southwest in North America (Crabtree, *et al.*, 2017). The aim of this model is to see whether the level of social complexity suggested by the great kiva constructions (large, round ritual constructions) could be supported based on what is known about the resources of the landscape and possible connections between groups of

people in the American Southwest over the period 890-1285 CE. The model includes agents (villages in this model), who use resources (primarily maize) and grow in population size, enter into conflict with other groups over resources, and may sometimes share resources in public goods games. Agents can compete over resources and subsume other groups of agents if they are conquered, who must then pay tribute. Many parameters are included in the model to determine variables including the environment and fission rate, and 36 parameter combinations are run with only 15 repeats. The multitude of parameters tested with relatively few repeat runs unfortunately makes the results difficult to interpret as the different patterns observed between parameter combinations could be due to strong parameter or stochastic effects. The authors conclude that the model does support the suggestion that there could have been societies spanning many villages across the region. The results of this model would be firmer if the same results could be generated with further repetitions of the experiments shown, but far more convincing if the model could also be shown to work in an abstract environment without the specific details from the available archaeological data that this model is built around.

The second axis is the resolution that the model is built at (Romanowska, 2015). The use of resolution here refers to the size of the model environment and the length of time covered, while considering the type of agent in the model. Is the model intended to look at a region the size of a petri dish or a continent? And should it cover the course of a day or a millennium? ABMs are flexible enough to accommodate any type of agent, whether individual atoms, microorganisms, whole animals, or cities. The important defining feature of an agent is that it should be able to act as a separate entity to another agent. Often all of these scales are operating at the same time, but not all of them will be useful to include in the model. For example, in investigating the interactions between societies it may not be useful to use individual people as the primary agents of the model. While the archaeological record is created by individual people, often people will act together as family groups or communities. Including extra detail about the age, sex, lifespan, and activities of individuals within those groups may shift the model to focus on unnecessary detail which will be complicated to implement and analyse, and may obscure the processes

which are of interest between groups as a whole. It is in the process of simplification that the modeller can decide which features are too fine-scale or too coarse-scale to include in the model.

A good example of a simplified model has been constructed by Holdaway, Davies and Fanning (2017). They use an ABM to test whether natural deposition and erosion processes could account for the distribution of fireplaces, or hearths, spatially and temporally in New South Wales, Australia. The model includes only the most basic features to test this hypothesis: hearth formation, erosion, deposition, and time. They found that the archaeological record could be explained by natural taphonomic (erosion and preservation) processes without the need to include change in human volition to determine hearth location. Although this model is intended to simulate two millennia, the scale of the model is relatively small with the focus on individual hearths in a small region of Australia.

Other models may be built with the intention of covering a much wider geographic area, longer time span, or allow for greater complexity of interaction between agents. These models will require a correspondingly different set of parameters and agent characteristics. One example is the ABM built by Djurdjevac, *et al.* (2018). In this model individual agents are groups of people, labelled tribes. Tribes can occupy certain areas of land within a landscape modelled on western Eurasia. The aim of this model is to simulate the spread of technology (in this case, wool-bearing sheep) across the landmass, given the social and geographical constraints present from 6200 – 4200 BCE. Archaeological evidence from this period is limited. The model is therefore intended to show how the technology could have spread, given the conditions at the time. The model is a good example of simplifying reality in order to address a particular research question. The authors have assumed simple agent processes: no population growth (because accurate population sizes are not available from the archaeological data of this time period); agents have limited knowledge of their surrounding area; agents will tend to move towards the most suitable land; and agents can transfer knowledge (such as how to use wool from sheep) only to other agents that they are aware of, with a constant rate of spread. The main limitation of this model is the extent to which the authors assume that the model can accurately reconstruct what happened in the past.

Further experiments varying the rate of transfer, population size, and connections between different agents should be shown with enough repetitions to be confident that the model results are reliable.

All models are stupid (a simplification of reality), but not all models are useless (Smaldino, 2016). With all types of model, the modeller must understand their question or the purpose of the model in order to create a model which is useful, and not just stupid.

2.2.3 Parameter space

The past is one run of an experiment that cannot be re-run. Archaeologists must usually rely on existing evidence to construct hypotheses for what happened in the past and gather further data to either support or refute the claim. However, by making a simulated world, we can in effect, re-run the past as many times as we want to (Aldenderfer, 1991). By varying the parameter settings when re-running the model, we can explore potential scenarios which may not have happened in our reality and compare the scenarios which did. By running the model enough times with enough different parameter settings, it is possible to construct a parameter space which can indicate which parameters have the strongest effect in the model. Even though the model does not exactly correspond with reality, the effects of the parameters in the model may indicate which factors were most important in creating the real past that we can see in the archaeological record. Sensitivity analysis is an important step in understanding the relative importance of different parameters and how sensitive the results are to particular parameter combinations (Burg, Peeters and Lovis, 2016).

A good example of an abstract ABM with rigorous parameter space documentation has been written by Enrico Crema (2014). The aim of this model was to test whether changes in settlement patterns could be due to random processes, with a model which is as simple (and therefore universally applicable) as possible. The model shows how difficult it can be to plot the parameter space of an ABM, even a relatively simple one. Where the parameters are bounded (e.g. 0-1) then the parameter space can be systematically explored. Where the parameters are unbounded, then the modeller should try to limit exploration to a range of possible values, where

useful information exists. If there is no useful information, then the behaviour of these parameters within the model needs to be understood in relation to other parameters (Crema, 2014, p393-4). The model shows that polities are more likely to have a shallow settlement hierarchy (where settlements are roughly equivalent in size) when agents are more spatially constrained, if resources are distributed evenly. The results also show that polities are more likely to change back and forth between a shallow settlement hierarchy (convex rank-size) and a deeper settlement hierarchy (primate rank-size) when agents can move freely and have perfect knowledge of their environment. But importantly, the model has the capacity to show what happens at the extremes of the parameter space without being beholden to particular cases or limiting parameters. This type of model is invaluable for understanding more about general patterns of behaviour, but also as an ideal first step in building models that can be used to explain patterns of change in specific places. Launching in to models which include too many parameters which need to be limited using specific data may obscure any underlying processes that could actually be important in explaining the trends observed in the real-world data.

To narrow down the parameter space of interest for larger models, the modeller can use two main methods. The first is to work out if there are any logical or mathematically extreme values which can be excluded. The second is to draw on real-world data to inform the parameter settings. This is particularly important for models which are compared directly with the archaeological record (Chliaoutakis and Chalkiadakis, 2012), and involves the calibration of parameters against data (Romanowska, 2015). The interpretation of the model results will become more informative if the relevant parameter space can be reduced by controlling for as many parameters as possible. For example, in trying to model the life cycle of worms or bees, the modeller can turn to data on relevant species to find data for: length of life, amount eaten, energy used, speed of movement, or any other parameters (van der Vaart, *et al.* (2015); van der Vaart, Johnston, and Silby (2016)). This is especially important but particularly difficult where there are lots of unknowns in the data, such as with the archaeological record. Where exact parameter values are not known, the modeller should use their best judgement based on the available information to estimate what the parameter settings are likely to be, then perhaps double the

maximum and halve the minimum values to ensure that the full range of possibilities is included (Romanowska, 2015). Where model parameters cannot be refined using data or mathematical extrapolation, then the modeller can test a range of parameter values. If these parameters happen to not be the main parameters of interest for the purpose of the model, then the modeller should test them alongside the relevant parameters and ensure that they keep records of all the tests that they have done. This is intended to avoid reporting only the most interesting subset of results without full justification of why those particular parameter combinations are shown.

2.3 How to build a model

ABMs can be a powerful tool to build a deeper understanding of the past. However limitless human creativity is in generating models of reality, it cannot escape the bounds of human error. This section will go over how to build a model while avoiding as many pitfalls as possible, with methods of best practice in the field.

2.3.1 Software

Agent-based models can be built in any computer language, depending on the preference of the modeller. A user-friendly software to use is NetLogo (Wilensky, 1999; Berryman and Angus, 2010; Tissue and Wilenski, 2004; Railsback, *et al.*, 2017). NetLogo is designed to build and run agent-based models, but with the useful additions of a script that uses full words, minimal notation (see NetLogo dictionary) and a graphical user interface (GUI), which can show what the model is doing in real time. This is excellent for error checking the code and for displaying results for other people, especially non-modellers. NetLogo as an agent-based modelling platform is also being increasingly used in science and archaeology. This makes it much easier to share code to build, test, and replicate models. For these reasons, the models in this thesis have been built in NetLogo (version 6.0.1).

2.3.2 Simple to complex

To build a model is to come face-to-face with one's assumptions at every stage. Far from being a difficulty to be overcome, this is one of the greatest strengths

of building ABMs to test verbal hypotheses (as discussed above in Section 2.2). A complex model cannot be built in one go, if for no other reason than human error will sneak into the code and finding any errors becomes much more difficult with more code to sift through. In order to build an ABM with minimal error, the modeller must first decide how to simplify the whole model into a conceptual design with defined parts which can be built and tested separately before being integrated. It is important to check that the model matches the conceptual design throughout the model building process, as it can be easy for the model to become separate from the original concept (Romanowska, 2015). Further details (such as specific archaeological information) or submodels can always be added later, if necessary for the purposes of the model. The model built by Chliaoutakis and Chalkiadakis (2016) followed this pattern by starting with a more abstract model before adding spatially-explicit information (see above, Section 2.2.2).

2.3.3 Verification, validation, replication

There are several stages to building and testing a model. The first is model building (or implementation), as discussed above. Writing the model code can sometimes be the most rapid stage of creating an ABM, with checking the model for errors in the code (model verification) and consistency of the code with the purpose of the model (model validation) often taking at least as long (Romanowska, 2015). The more time taken to check the model for errors the more certain the modeller can be that the results of the model are not just from overlooked mistakes or misconceptions. Even with best practice in model verification and validation, there may still be errors which have been missed. The best way to check that the results of the model are from emergent properties of interest and not from errors is to replicate the model (Romanowska, 2015), by different researchers or using a different computing language (e.g. Olsevi, Cimler, Machalek, 2013). In addition, it should be borne in mind that even a successful model which has been thoroughly error-checked and seems to explain a pattern observed in the archaeological record may not be the only model which can explain the same data (Lake, 2015). Different processes can converge on very similar effects. This means that a model built to test one hypothesis should not be taken as evidence against the role of others.

In order to successfully replicate a model, the aims and assumptions of the model need to be communicated as clearly as possible. Many models reported in the literature are incompletely documented, with details about the model either assumed to be obvious or left out. Grimm, *et al.* (2006, 2010) suggested a solution to this problem was to provide a framework for reporting all ABMs. The intention of this framework was to allow for all types of ABM of different purposes and set at different scales to be reported in a consistent way and therefore comparable. This framework is called the Overview, Design concepts, and Details (ODD) protocol (Grimm, *et al.*, 2006, 2010; Polhill, *et al.*, 2008) and is followed in the results chapters to report the models. This is to ensure that the models are described in sufficient detail for the reader to understand the purpose of each model and replicate the design. Further detail is given in process flow charts for each of the models (see Figures 3.3 and 4.3). Model code for each of the models is provided in Supplementary Materials 1 (Section 3.7), 2 (Section 4.7), and 3 (Section 5.7).

2.4 Agent-based models as a method for this thesis

2.4.1 The use of agent-based models to test the circumscription hypothesis

The purpose of this thesis is to understand more about how and why human societies became more complex in the past. More specifically, I will test the hypothesis that higher levels of circumscription (through environmental barriers, resource concentration, or population clustering) resulted in more intense warfare where more complex societies outcompeted others, leading to an increase in social complexity over time. The circumscription hypothesis has been investigated by verbal comparison with data (see Chapter 1, Section 1.5), but little work has been done to formalise the hypothesis and test it thoroughly.

The circumscription hypothesis is ideal to test with agent-based models because it describes a relatively straightforward sequence of events which can be made sense of mathematically, but also needs to be tested in a more realistic setting to really be fully assessed. Agent-based modelling is a particularly valuable way to test the circumscription hypothesis for three main reasons: (1) it will force the modeller to unpick any hidden assumptions of the

hypothesis which are not apparent in verbal descriptions alone; (2) it is a flexible method that allows for sections of the hypothesis to be tested separately as well as together; and (3) it can be run with as much or little realism as is useful, both in terms of model format (how realistic are the agents and the environment) and in terms of parameter space (how extreme do the parameters need to be for the conditions of the hypothesis to no longer be met). In addition, because the hypothesis is specifically looking at change over time and the relative likelihood that social complexity will form, using mathematical equation modelling alone will not allow for the flexibility of ABMs to simulate different scenarios and test the model against the archaeological record.

The following sections will discuss work which has already been done on testing the circumscription hypothesis, or parts of the hypothesis, using formal models.

2.4.2 Circumscription models

Carneiro's circumscription hypothesis has been tested by comparison with archaeological data in many examples around the world (see Chapter 1, Section 1.5). However, there has been much less work done to formally test the hypothesis using mathematical models or ABMs. From Carneiro's (1988) first reformulation of the circumscription hypothesis, Graber (1988) has attempted to convert the hypothesis into mathematical equations by focusing on population density as the consequence of circumscription (of any type) rather than on measuring circumscription directly. Graber (1988) did find that population density could be linked with circumscription (from environmental, resources, and social factors) among the colonists of western North America (1625-1900 CE) based on historical census data. The focus of Graber's work is, however, in showing how circumscription can translate into population density, and not how population density can lead to the emergence of increasingly complex societies.

More recently, an ABM based on the circumscription hypothesis has been built (Scott, 2011). In this model, agents are 'tribes' with a population size which can grow at a logistic growth rate until carrying capacity is reached. Tribes will then divide into two, with one moving to unoccupied land if it is available. Conflict occurs if a tribe tries to move into an area that has already been occupied. The larger tribe will always win the conflict. Both tribes will suffer a loss in population size through the conflict, but the defeated tribe will become assimilated into the

victorious tribe. To test the effect of circumscription, Scott varied both the area of habitable land and the severity of environmental catastrophes (as the elimination of whole tribes), and measured the formation of social complexity and decrease in ethnic diversity (as tribes are subsumed into other tribes). In constructing this model, Scott has simplified Carneiro's (1970) circumscription hypothesis into a very few factors: population growth, conflict over space, area of habitable land, and the stability of habitable land. The last factor is not directly discussed by Carneiro in the original formulation of the hypothesis (1970), but is suggested as a response to comments in the reformulation of the hypothesis (Carneiro, 2012b).

The results of the model suggest that decreasing the area of habitable land (thereby increasing circumscription) has no effect on the formation of social complexity, but that increasing the severity of catastrophic events will increase the speed at which complexity forms. However, Scott does not explain whether the increased speed of social complexity formation in the more volatile environments could simply be the result of a smaller population size as tribes are eliminated in catastrophic events. A smaller population size means fewer tribes to conquer after the catastrophic event. Moreover, it is not clear how social complexity can increase or decrease in this model as the measure of social complexity is not explicitly defined. In addition, only the 'key model parameters' are discussed, without an explicit consideration of any other potential parameters or inherent biases of the model. The results of the first experiment consistently show no effect of reducing habitable land, but only one combination of parameters is tested (habitable land is varied but population growth rate and initial population size kept at single values), and the experiment does not show if similar results are obtained even if there are no catastrophic events. Lastly, there is no discussion of the different types of circumscription that can occur (environmental, resources, and social) suggested by Carneiro (1970, 2012a), nor any control over the rate of conflict between tribes beyond the implication that increasing population size will result in more competition over units of land.

2.4.3 Warfare models

Elements of the circumscription hypothesis have been tested as part of other models, including the role of warfare in the formation of social complexity.

Warfare is central to the circumscription hypothesis as the main mechanism of change. The role of warfare, or conflict, has been looked at already by different modellers. Some have looked at the role of conflict within societies for the emergence of leaders (Gavrilets and Fortunato, 2014; Gavrilets, *et al.*, 2010), although this is less relevant for the circumscription hypothesis which focuses on the spread of society traits at large. The emergence of leadership and stable institutions within societies is implicit within the circumscription hypothesis.

Other work has been done to model the relationship between warfare and the evolution of larger societies with traits to sustain social complexity. Turchin and Gavrilets (2009) and Gavrilets, Anderson and Turchin (2010) built an ABM in an abstract environment to test whether warfare between polities could amplify the size and complexity of those polities. The assumption here is that the polities which were better able to mobilise more resources and military forces (through organisation and population size) would be more likely to win a conflict. Polities which had the traits to increase the chance of victory would therefore be more likely to spread or be imitated by other polities in competition. In this model agents (communities) can initiate conflict with their weakest neighbour to attempt to subsume the neighbouring polity into their own. The most powerful polities (those with the most resources transferred from subordinates to the chief community) are more likely to win a conflict. Communities within the polity can also choose to rebel from the chief community of the polity. This results in a cycling of complexity over time, similar to observed patterns in the archaeological record (Turchin and Gavrilets, 2009). Increasing the incidence of warfare increases the size that polities can reach, with a single polity potentially attaining more levels of internal hierarchy and covering a greater extent of the available space in the model environment. Building on these results for the evolution of complex societies through warfare, Turchin, *et al.* (2013) built an ABM to test whether a higher intensity of warfare, as evidenced by the presence of technological innovations, could predict where complex societies were more likely to form across the Afro-Eurasian landmass over a period of 3,000 years

(1,500 BCE – 1,500 CE). This agent-based model builds on the work of the previous, abstract model (Turchin and Gavrillets, 2009), but with added detail of environmental conditions, the presence or absence of ‘ultrasocial’ traits to sustain large complex societies, and the presence or absence of military technology. They found that complex societies were more likely to form in areas of the most intense conflict. These areas tended to be along the border of the Eurasian steppe where nomads could come into conflict with agrarian populations and spread technology for cavalry warfare (which intensified the conflict). The model results broadly matched archaeological and historical evidence for the presence of complex societies over this time period. Both the more abstract (Turchin and Gavrillets, 2009 and Gavrillets, Anderson and Turchin, 2010) and spatially explicit (Turchin, *et al.*, 2013) models suggest that warfare is important in explaining the emergence of social complexity. This supports Carneiro’s (1970, 2012a) assertion that warfare is the primary mechanism for social complexity formation. However, neither of these models explicitly test for the impact of any type of circumscription on intensifying conflict. Geographical features (ranging from mountains to agrarian zones) are included in the model to test the realism of the results, but are not systematically manipulated to explicitly understand the effects of geography on social complexity formation.

2.4.4 Human-environment interaction

Warfare is the main mechanism driving social complexity formation in Carneiro’s (1970, 2012a) circumscription hypothesis, but environmental conditions may intensify the effect of warfare. Most archaeological models are already grounded in a representation of a real-world environment. However, in these models the environment is often kept as a constant and used as additional detail to make the model as a whole more realistic and comparable to the archaeological record (Kohler and van der Leeuw, 2007). Some models, such as Turchin, *et al.* (2013), do include the effect of environmental conditions on the proliferation of complex societies. In a model to investigate how large-scale societies can form over time, Salali, *et al.* (2015) include the effect of availability and distribution of resources on population growth and expansion. They found that the number of resources and distribution of habitable land had an effect on the formation of multicellular (complex) societies. When the area of

habitable land was smaller, fewer complex societies formed in the model, but that there was considerable variation between model runs of the same conditions. This model suggests that population growth, as related to resources, could be an important factor in social complexity formation. There is much overlap with the processes proposed in the circumscription hypothesis (including population growth and warfare within different environmental conditions), but the main aim of this model is to develop a life-cycle theory of human groups, based on population dynamics and not to test the circumscription hypothesis. The models of this thesis will draw on the model presented by Salali, *et al.* (2015), but with further in-depth analysis of the importance of parameters specifically included to assess the effect of environmental, resources and social circumscription on the formation of complex societies.

2.4.5 Social complexity models

How and why societies could have become more complex are complicated questions to ask, and many attempts have been made to answer them from different theoretical backgrounds (see Chapter 1, Section 1.4 for more discussion on the theoretical background). There is a huge and growing literature on using ABMs and other formal models to investigate the emergence of social complexity. A wide variety of models have been built and analysed from different theoretical backgrounds. These include models that look at the emergence of leadership within societies (Hooper, Kaplan and Boone, 2010), cooperation (Powers and Lehmann, 2013), entropy maximisation (Altaweel, 2015) and evolutionary theory (Cio, Jong and Bassett, 2012; Mengistu, *et al.*, 2016). However, these models tend to be focused at different scales or on factors which are not relevant to the circumscription hypothesis being tested here. Some examples have been discussed in the sections above, and others will be referred to when elements of the models have been used to inform specifics of the models in the later chapters.

2.4.6 Data and models

Theoretical models and data on their own are useful to understand what may have happened in the past, but using data to test the models, and models to

further inform the theory, is a sensible route of research. There are excellent examples of cumulative modelling efforts to test ideas in abstract models, followed by models testing the same ideas on archaeological data. These include: the location- and time- specific agent-based models by Kohler, *et al.*, (2009) to test the claims of warfare proposed by the more abstract mathematical models of Turchin and Korotayev (2006) against archaeological data from Southwest Colorado; the testing of the Hooper, Kaplan and Boone, (2010) model on real data (Kohler, *et al.*, 2012); and testing the ideal free and despotic distributions on data from the Californian Channel Islands and Polynesian islands (Kennett, *et al.*, 2009; Kennett and Conlee, 2002; Kennett, *et al.*, 2006; Kennett and Winterhalder, 2008). These models show how theory and data can be built on one another through iterative efforts of different researchers.

2.5 Models of this thesis

The models of this thesis are divided into three parts. The first model (Chapter 3) is the simplest. The aim of the model is to test the first core part of the circumscription hypothesis: higher levels of environmental and resource circumscription will result in a faster rate of social complexity formation. This is done in an abstract model environment with the smallest number of parameters possible to test only the effect of environmental and resource circumscription on agent (village) behaviour. The second model (Chapter 4) builds on the work done in Chapter 3 to complete the testing of the circumscription hypothesis in full in an abstract environment. This is done by including population growth and therefore the effects of both population pressure on limited resources and the effects of social circumscription. Both Chapters 3 and 4 in combination provide a complete test of the logic of the circumscription hypothesis and test whether the hypothesis could potentially explain social complexity formation in real-world environments. The models are not intended to be realistic, but certain parameters have been informed by likely values given archaeological or ethnographic evidence. Dividing the hypothesis into logical sections to test in the most simple form, and build upon incrementally, is a good way to go about this to try and minimise the risk of over-complicating the models and losing explanatory power. The third model uses the models of chapters 3 and 4 to test

the circumscription hypothesis in a real-world environment against archaeological evidence for the emergence of social complexity in a highly circumscribed area. This model is used to test whether the logic of the circumscription hypothesis extends to a real scenario and will indicate the possible extent to which the emergence of social complexity in that area could be attributed to the circumscribing conditions. This will tell us more about whether circumscribing conditions could have been an underlying factor in the emergence of social complexity around the world, and if so, which types of circumscription could have been the most important.

Chapter 3: Can environmental and resource circumscription drive the formation of social complexity? (Model 1)



Abstract

At the core of the circumscription theory is the role of environmental and resources barriers to population movement. As discussed in Chapter 1, Carneiro suggests that where people are less able (or less willing) to move away to new areas of land, there will be an escalation in conflict which may increase the chance of social complexity formation. In this chapter, I present and analyse an agent-based model (Model 1) built to test the effect of environmental and resource circumscription on the rate of hierarchy formation between villages in an abstract environment. This model is intended to test the assumptions and predictions of the circumscription theory in its simplest form. The results show that both environmental and resource circumscription may amplify the emergence of hierarchy in polities in the model, but that the effects of each are dependent on the distribution of land types across the model world.

3.1 Introduction

Human societies are embedded in their landscapes. The environment which surrounds people will determine which areas they can live in, the resources they have access to, and the ease of communication between locations. The circumscription hypothesis, proposed originally by Robert Carneiro in 1970, suggests that environmental conditions could have an effect on the trajectory of changes in social complexity over time (see Chapter 1, Section 1.5 for further discussion of the circumscription theory). Carneiro suggests that areas that are more highly circumscribed by environmental barriers could create a pressure for conquest warfare and increasingly complex societies (Carneiro, 1970, 1988, 2012a, 2012b). These environmental barriers can be anything which restricts population movement, whether mountainous regions, barren desert, or simply areas of land which are more difficult to cultivate. The main premise of the hypothesis is that where the external conditions are harsh, people are more likely to accept a subordinate ranking within a larger polity if conquered than move elsewhere and remain autonomous. The environmental conditions which can circumscribe population movement can be classified into two main types: environmental and resource circumscription. Environmental circumscription refers to physical barriers to population movement. Resource circumscription can be seen where some locations are richer in resources than others, even if the other locations are not dearth of resources. Environmental and resource circumscription can be combined on a continuum of environmental conditions.

Archaeological evidence for primary state formation around the world suggests that environmental circumscription may have had an effect on social complexity formation (see Chapter 1, Section 1.5.1 for a more detailed discussion of the archaeological evidence). Locations such as the Nile in Egypt and coastal Peru show strong evidence for environmental and resource circumscription (Carneiro, 1970, 2012a, Sandeford, 2018). Other areas, such as Mesopotamia and China, show more diffuse evidence of environmental and resource circumscription which could nonetheless have had an impact on societal change (Carneiro, 2012a, 2012b, Kirkby, 1973; Nicholas, 1989; Yi, 2012). Describing the geography of landscapes where the first complex societies formed is useful to establish a potential causal link between environment and social change, but has limited explanatory power. Chapter 2 (Section 2.1)

discusses how formal models can be used to test the assumptions of verbal hypotheses. A formal model of the circumscription hypothesis is needed to test the internal consistency of the hypothesis to see whether, when and how environmental conditions could have resulted in increasing the likelihood of the formation of social complexity, and provide more precise predictions that can be subsequently tested in further archaeological work. This chapter presents an abstract agent-based model to test the effects of environmental and resource circumscription on polity formation. The effects of social circumscription, the third type of circumscription suggested by Carneiro (1970, 2012a), will be addressed in Chapter 4.

Using the following model, I aim to answer the question of whether increasing environmental circumscription increases the rate of hierarchy formation, as suggested by the verbal circumscription hypothesis. In order to test this, I have included other features which are implied either explicitly or implicitly in the verbal hypothesis. These include assumptions about the behaviour of groups of people, the structure of society, and the limitations to social complexity formation. This, again, is a major advantage of modelling, as it forces one to make implicit or ignored assumptions within verbal theories explicit, and amenable to scrutiny or further testing. The model processes and parameters are discussed in detail in Section 3.4.

3.2 Verbal outline of the model

In this model, there are a fixed number of villages. Villages can form hierarchical polities by conquering other villages. An autonomous village forms a polity of one village, but a single polity can potentially include every village if all other villages are defeated by and join the same polity. Every village will own a patch of land, from which it gains resources. Polities will enter into conflict with one another to attempt to dominate their neighbours, and larger polities are more likely to win. Polities that are defeated in conflict will become subordinate to the attacking polity if they decide not to escape to a new location. The highest-ranking village of the defeated polity will become directly subordinate to the highest-ranking village of the attacking polity, while maintaining the same internal hierarchical structure (see Figure 3.1). The decision of whether to

escape or join is influenced by the conditions of the surrounding environment and the potential costs incurred in subordination. Polities containing multiple villages will act as a whole group, even if the decision taken means that individual villages within the polity are worse off as a consequence.

It is important to note that this is primarily an abstract model constructed with the aim of testing the logical consistency of the circumscription hypothesis, and not a replication of reality (see Chapter 2 for further discussion on the use of simplified models).

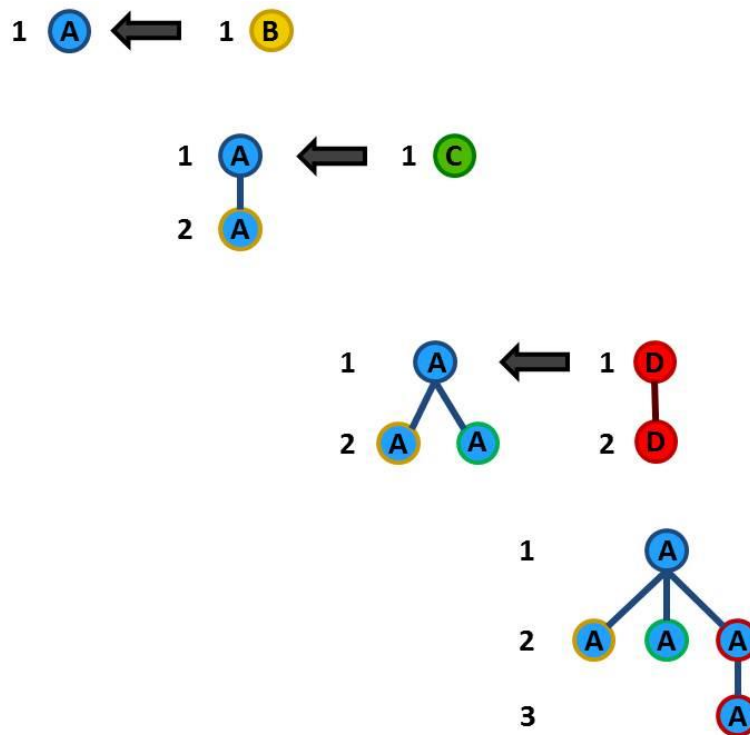


Figure 3.1 Diagram showing increase in polity size as rival polities are defeated and the corresponding hierarchical structure. Circles, here representing villages, with the same letter belong to the same polity. The hierarchy levels of villages within the same polity are labelled, with 1 being the highest level of hierarchy. The black arrow represents conflict between polities, with the defeated polity becoming subsumed by the victorious polity in the direction of the arrow. In the first conflict, the village labelled polity B (yellow) is defeated by polity A (blue), so polity B becomes subordinate to A and is relabelled as polity A. Polity A now consists of two villages with two levels of hierarchy. In the second conflict, another polity (C, in green) is also defeated by polity A. Polity C does not have any additional subordinate villages, so C becomes directly subordinate to the highest-ranking village in polity A. Although polity A now consists of three villages, the number of levels of hierarchy has not increased because only one village was defeated. In the third conflict, polity D (red) consists of two villages, one subordinate to the other. When polity D is defeated by polity A, both villages become subsumed into polity A below the highest ranking village of polity A, but they maintain their internal structure. Polity A therefore grows into a polity consisting of five villages with three levels of hierarchy after these three conflicts. This is a simple example of what can happen in the model as a result of conflict.

3.3 Predictions

3.3.1 Rate of hierarchy formation compared to the overall level reached

The reader should note here that I am focusing on the initial incidence of social complexity formation as the main measure of the impact of circumscription. As Carneiro suggests, '*A region best suited for a state to arise may not be best suited for its further development.*' (2012b, p175). It is possible that regions showing the earliest evidence of social complexity formation are not the regions where the largest societies eventually form, such as along the Yellow River in China where the Shang society flourished after moving further downstream into a more open landscape (Carneiro, 2012b). In building this model, I am primarily testing the extent to which the circumscription hypothesis can predict the first appearances of more complex societies, and therefore the rate of hierarchy formation is the most relevant measure, rather than the eventual or maximum level of social complexity reached.

However, the maximum level of social complexity reached will not be discounted. The level at which social complexity stabilises over time will indicate the suitability of environmental conditions for the maintenance of complex societies. I predict that the environments with the fastest rate of hierarchy formation will also be the environments with the highest overall level of social complexity over time. This relationship may be affected when population size is allowed to vary over time, but this is tested in Chapter 4.

The parameters of the model used to test each of the following predictions are discussed further in Sections 3.4.1.5 and 3.4.2.

3.3.2 Environmental and resource circumscription

The circumscription hypothesis suggests that social complexity is more likely to occur where there is restricted population movement either due to geographical barriers or due to limited areas of concentrated resources. Geographical barriers to population movement (environmental circumscription) are modelled here as zones of land with fewer resources. The concentration of resources

(resource circumscription) is modelled by varying the difference in resource richness between zones of land.

As both types of circumscription can result in competition over limited resources, I predict that increasing both environmental and resource circumscription will result in a faster rate of hierarchy formation. In describing environmental and resource circumscription, Carneiro (1970, 2012a) suggests that environmental circumscription will have a greater effect than resource circumscription alone because of the stark boundary between areas, but that resource circumscription may sometimes have as strong an effect as environmental circumscription when resources are concentrated enough to cause population clustering (Carneiro, 2012a, p24). I therefore predict here that increasing the level of environmental circumscription will cause the rate of hierarchy formation to increase more rapidly and result in a higher level of social complexity than increasing the level of resource circumscription, but that increasing resource circumscription will still have a significant effect.

3.3.3 Random compared to concentrated distribution of land areas

Most landscapes include a mix of different environments in various patterns. A river valley, for example, may have progressively less fertile areas of land as the distance from the river and alluvial plain increases. An extreme version of this is the Nile River valley, where the fertile alluvial plain very abruptly ends and desert begins. The Nile River is a classic example used by Carneiro to discuss the potential impact of environmental circumscription on the formation of social complexity (Carneiro, 1970, 2012a). This layout of more fertile land may be considered to be concentrated along the course of the river, so is modelled here as a continuous band of more fertile land. However, landscapes rarely form simple continuous lines of different types of land. In reality, there may be variations in soil fertility for many reasons, or small pockets of fertile land separated by other boundaries, such as valleys within a mountain range. The inconsistency of land types is modelled here as a patchwork of random locations in the model world (see Section 3.4.2.2).

The two forms of land distribution are not mutually exclusive, but modelling the extremes of both will inform the likely effect of varying land distribution (if any). Given that Carneiro made no explicit predictions regarding land distribution, I

predict that there will be no difference in the rate or overall level of social complexity formation if the total number of resources in the model world is kept consistent between them. The level of environmental and resource circumscription should result in a similar pattern of social complexity formation between the two environmental types.

3.3.4 Incidence of warfare

Warfare is the main mechanism leading to an increase in social complexity, as argued by Carneiro when describing the circumscription hypothesis (Carneiro, 1970, 2012a, 2012b). Carneiro suggests that warfare alone could result in the spread of social complexity, as may have happened in the otherwise relatively un-circumscribed environment of the Eurasian steppe and the formation of the state societies there from around 500 BCE onwards (Honeychurch, 2013). The frequency of warfare is therefore vitally important to control for and to understand in any model testing the impact of environmental and resource circumscription. In line with Carneiro's assumptions, I predict that increasing the frequency of warfare (by increasing the likelihood of attack, increasing the distance that villages are willing to travel for conflict, and increasing the population size), will result in a faster rate of social complexity formation and higher overall level of social complexity. Warfare may increase social complexity even without circumscribing conditions.

3.3.5 Severity of subordination

An implicit assumption of Carneiro's circumscription hypothesis is that there must be a cost to becoming subordinate to other people, which is why the costs of moving to a new location may be preferred. This is an important assumption to unpick because of the relationship with the potential costs of moving. When faced with the option of leaving behind a home or staying put and becoming subordinate to an authority, people may decide that losing their autonomy is a cost worth paying. The costs (perceived or actual) can be modelled as relative resource loss or gain. This assumes rational decision-making and perfect knowledge to the extent that the decision to move or stay should be based on the relative resource gain. But the costs could equally be non-economic, such as the loss of moving away from an ancestral homeland or being trapped in the

obligations of a wider society of strangers. For simplicity, the gain or loss of resources is the focus here. I predict that increasing the costs of becoming subordinate will result in a slower rate of hierarchy formation, unless the loss of resources from moving to another location is greater.

3.3.6 Political stability

The structure and maintenance of social complexity are not discussed by Carneiro as part of the circumscription hypothesis, but are nonetheless important features of any society. Building a society to levels of complexity previously unknown will incur challenges of organisation and communication, as well as instability as problems are being worked out (see Chapter 1, Section 1.4, for discussion on selection of social traits and cyclical nature of societies). In real societies the reasons for instability could be anything from personal disputes between individuals to the drifting apart of groups as they lose contact over time. It is important to include this in the model to understand the effect of instability given the conditions of the rest of the model presented here. Social instability occurs in the model when a subordinate village within a polity decides to rebel from the original polity to create a new autonomous polity (see Figure 3.3. for details of the fragmentation submodel). Political instability can be seen as a force that acts in the opposite direction to circumscription (which potentially brings villages together). I therefore predict that increasing the internal instability of societies will decrease any effect that the environmental or resource circumscription, or frequency of warfare, have on the formation of social complexity.

3.4 Methods

The agent-based model in this chapter was built using the software platform NetLogo (see Chapter 2, Section 2.3.1). The model is used to perform a series of experiments to assess the effect of environmental and resource circumscription on the rate of hierarchy formation in an abstract model environment. This model was designed to test the logic of the circumscription hypothesis, focusing on environmental circumscription independent of any effects of social circumscription, which is considered in Chapter 4.

3.4.1 Model description

The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm *et al.*, 2006, 2010), and is continued in the Supplementary Materials 1 (Section 3.7.1). See Supplementary Materials 1 (Section 3.7) for a link to the model script.

3.4.1.1 Purpose of the model

This model has been developed to test the logic of Carneiro's circumscription hypothesis on the emergence of complex society, with the focus on the effects of environmental and resource circumscription.

3.4.1.2 Entities, state variables and scales

There are two types of entities in this model: villages and patches. Villages can move, interact with other villages, and form collectives called polities. Villages cannot occupy more than one patch, and patches cannot be occupied by more than one village. Villages cannot create any new villages (see Chapter 4 for population growth). The location, polity identification, and hierarchy level of villages can change over time but each village will keep a single unique *who* number. The *hierarchy* attribute is used as the measure of social complexity here.

Patches form the environment that the villages act in and are immobile. Each patch will yield a fixed number of resources set at the start of the model which does not change throughout the model run. Figure 3.2 shows the layout of patches in the model as a grid. Patches form two different types of land depending on the number of resources they own (either fertile or less fertile). The model environment is wrapped on all sides to form a continuous world such that villages can fall off the edge and re-appear on the opposite side. This is to avoid introducing a hard boundary that could affect the results of the environmental conditions being tested.

Arch-polities are agents used in the model to facilitate the identification of different polities during each time step (see Table 3.1 for the state variables of arch-polities). Arch-polities do not have any direct interaction with either villages or patches. Instead, they record the current state of a polity when relevant for a

submodel process (whether there are any villages in that polity, whether the polity is attacking or being attacked by another polity, and how many resources the polity as a whole has access to).

Villages and patches are characterised by different state variables (or attributes which distinguish entities of the same type, Grimm *et al.* 2010), which are listed in Table 3.1.

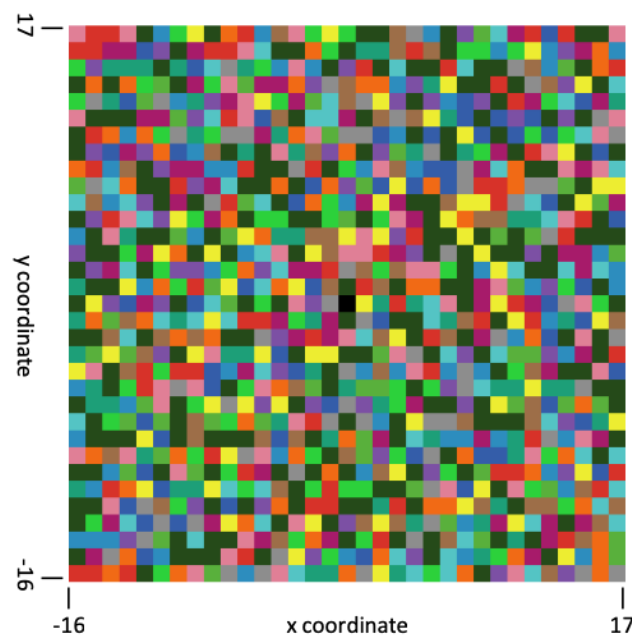


Figure 3.2 A model world consisting of 1089 (33x33) patches in a grid layout. This image shows the model world before patches have been assigned land-resources and before being populated with villages. The colouration shows only the layout of the patches and does not refer to any properties of the patches. The grid pattern remains consistent between all model environments, but the attributes assigned to patches is varied between model experiments. The model environment is wrapped on all sides to avoid introducing a hard boundary to village movement.

Table 3.1 List of the state variables (or attributes) of villages and patches. Only villages have active agency in the model. Patches can be varied in the initial setup of the model, but not within an experiment. The arch-polities are used to inform villages at the polity level but do not directly interact with villages or patches.

State variables	Value range	Purpose
villages		
who	1 to total number of villages	Unique village identification ('who' as a label is specific to the NetLogo program)
polity	1 to total number of villages	Affiliation number shared by villages belonging to the same group to identify each polity and all the villages within it
hierarchy	1 to <i>initial.villages</i>	A positive integer indicating the level of hierarchy of the current village (1 = highest level, >1 means the village is subordinate to a village with the next highest rank within the polity). It is theoretically possible for all villages in the world to form one polity of a continuous chain of hierarchy, so the highest value of <i>hierarchy</i> can be the same as the population size (<i>initial.villages</i>), but in practice this is very unlikely. See Table 3.2 for description of the <i>initial.villages</i> parameter.
level-above	<i>who</i> number range	The <i>who</i> number of the village ranked directly above the current village
level-below	<i>who</i> number range	The <i>who</i> number of the village ranked directly below the current village (see Figure 3.1)
resources	0 – 5	The number of resources owned by the village, equal to the <i>land-resources</i> of the patch it is occupying
defending	true, false	Used to identify villages which are in the polity being attacked by another polity
benefit-move	0 – 5	Used by each village to calculate the potential gain in resources of moving away if defeated
benefit-remain	0 – 5	Used by each village to calculate the potential gain in resources of remaining in the same location and becoming subordinate. (<i>benefit-remain</i> = current <i>resources</i> – <i>tribute cost</i>)
hier-resid	<i>hierarchy</i> range	Used to calculate the <i>hierarchy</i> of subordinates to a rebelling village if it decides to leave the polity

<i>fragmenting</i>	true, false	To identify the rebelling village and its subordinates
patches		
<i>land-resources</i>	0 – 5	Number of resources yielded by each patch, used to denote the fertility of the area
<i>village-claim</i>	<i>who</i> number range	<i>who</i> number of the village which is assessing the patch as a potential location to move to. This number assignment is necessary to avoid multiple villages selecting the same patch
<i>potential-escape</i>	true, false	To identify patches within a given radius of a village's current location which it can assess as a potential area to move to when defeated
<i>territory</i>	true, false	To identify patches within the <i>conquering.area</i> radius for a village to find rival neighbouring villages
<i>pxcor and pycor</i>	-16 to 17	Coordinates of each patch in the grid
arch-polities		
<i>whole-polity</i>	1 to total number of villages	Used to ensure that only one polity is attacking another at any given time and to identify all villages who share the same polity number (<i>whole-polity = polity</i>)
<i>target-polity</i>	true, false	To identify the polity being attacked
<i>attacking</i>	true, false	To identify the polity which is attacking another polity
<i>polity-villages</i>	true, false	To eliminate polities without any villages (the number of polities remains the same, but only those polities with villages can participate in the model)
<i>polity-resources</i>	Range depends on total number of villages and the total resources in the model world	Sum of <i>resources</i> of all the villages in the polity

Table 3.2 The parameters in Model 1, and parameter values used in experiments (see Section 3.4.2 for more detail, and Section 3.5 for results).

Purpose	Parameter	Values	Description
Fertile patch distribution	Distribution	Concentrated or random	The more fertile patches in a concentrated distribution are all adjacent to other fertile patches to form a continuous band. The width of this band is determined by the <i>land.width</i> parameter. The more fertile patches in a random distribution are allocated random locations anywhere in the model world. The number of more fertile patches is determined by the <i>number.fertile</i> parameter.
Environmental circumscription	<i>land.width</i> ; <i>number.fertile</i>	<i>land.width</i> : 2 (high) or 31 (low); <i>number.fertile</i> : 66 (high) or 1023 (low)	The area of fertile land, implemented differently depending on whether distribution is concentrated or random. Concentrated High environmental circumscription: <i>land.width</i> = 2 (66 more-fertile patches in total); low environmental circumscription: <i>land.width</i> = 31 (1023 more-fertile patches in total). Random High environmental circumscription: <i>number.fertile</i> = 66; low environmental circumscription: <i>number.fertile</i> = 1023.
Resource circumscription	<i>resource.difference</i>	0.1 (steep), 0.9 (shallow)	The difference in resources between the more and less fertile patch types. This parameter is the proportion of resources yielded by the less fertile patches compared to the more fertile patches. Steep resource gradient: the less fertile patches contain 10% of the resources of the more fertile patches. Shallow resource gradient: the less fertile patches contain 90% of the resources of the more fertile patches.

Polity conditions	<i>tribute</i>	0.1, 0.5	Proportion of resources owned by the defeated polity demanded by conquering polity
	<i>probability.fragment</i>	0.01, 0.3	Probability of internal polity instability (1% and 30% chance of fragmentation)
	<i>probability.attack</i>	0.1, 1	Chance that one polity will decide to attack another polity (10% and 100%)
	<i>conquering.area</i>	1, 5	Radius of patches that a village can 'see' to interact with (see Figure 3.5)
General setup	<i>initial.villages</i>	5, 50	Number of villages, which in this model is fixed during the entire run
	<i>step</i>	200 time steps	Time measured in steps (1 step = 1 complete run through the code by every agent)

3.4.1.3 Process overview and scheduling

Each time step allows every polity one opportunity to attack a neighbouring polity (see *battle-polities* submodel) and allow one subordinate village within each polity to decide whether to fragment (see *fragment* submodel) from the main polity or not (see flow diagram in Figure 3.3). The order in which polities run each submodel and the choice of village to run the *fragment* submodel within a polity is random. Every polity must complete the *battle-polities* submodel before any polity can initiate the *fragment* submodel. The time step is complete when these commands have been run by every polity.

3.4.1.4 Submodels

There are three submodels in this model. The first is to set up the model environment (see 'Initialisation'). The next two submodels are used to allow villages in the model to attempt to attack their closest neighbour of a different polity and decide whether to rebel from their current polity respectively. The flow diagram in Figure 3.3 shows a simplified sequence of events.

3.4.1.4.1 Submodel 1: *battle-polities*

In the *battle-polities* submodel, each polity is chosen in a random order to run the submodel. The next submodel (*fragmentation*) cannot be run until every polity has run the *battle-polities* submodel.

When a polity is selected, it will choose a village at random belonging to that polity. That village will then attempt to find a rival village belonging to a different polity with the radius *conquering.area*. If a village is found, the polities of these two villages enter into conflict. The larger of the two polities is more likely (but not guaranteed) to win the conflict, as calculated by Equation 1.

Equation 1:

$$\text{Probability of winning} = \frac{\text{total resources owned by all villages within the attacking polity}}{\text{total resources owned by all villages within the attacking polity} + \text{total resources owned by all villages of the defending polity}}$$

If the attacking polity loses, nothing further happens between the two polities. If the attacking polity wins, villages in the defeated polity must decide whether to

stay in the same location and become subordinate or move to one of their neighbouring, unoccupied patches and remain in their original polity. The probability of moving is scaled by the relative costs and benefits of each option (Equation 2).

Equation 2:

$$\text{Probability of moving} = \frac{\text{total resources of only the most fertile neighbouring patches of defeated villages}}{(\text{resources of best neighbouring patches of defeated villages} + (\text{current resources of defeated villages} - \text{tribute}))}$$

Each village in the defending polity will choose one of the four adjacent patches to assess, with a preference for patches with more resources (see Equation 3). If all four neighbouring patches are occupied, the village cannot move and will become subordinate to the conquering polity. Each village will also calculate the potential cost of becoming subordinate by subtracting the proportion of resources that would be demanded in tribute from the resources of their current patch. The sum of all potential resources from moving from all villages in the polity is compared to the sum of all potential resources from staying put and paying tribute to calculate the probability of moving, as shown in Equation 2. The more resources there are in the neighbouring patches chosen by all villages in the polity, the more likely it is that the polity as a whole will choose to move over staying and becoming subordinate, even if that choice is worse for individual villages within the polity.

Equation 3:

$$\text{Probability of choosing a more fertile patch} = \frac{\text{total resources of only the most fertile patches visible to the village}}{\text{total resources of all patches visible to the village}}$$

If the defeated polity decides to stay in their current location it will become part of the attacking polity and ranked subordinate to the highest-ranking (*hierarchy* = 1) village of attacking polity (see Figure 3.1 for a diagram of polity structure formation). If the defeated polity decides to move, all the villages of that polity will change location to the neighbouring patch they chose but will otherwise

maintain the same polity identification and internal structure between villages of that polity.

3.4.1.4.2 Submodel 2: *fragment*

After every polity has run the *battle-polities* submodel, each polity will again be chosen at random to select one subordinate village within each polity at random to potentially rebel from the rest of the polity. Polities consisting of only one village cannot run this submodel. The probability that the chosen subordinate village will rebel is determined by the *probability.fragment* parameter (see Table 3.2 for details of parameter settings). If the village does not rebel, no further action is taken by any villages in the polity. If the village does rebel, it will become the highest-ranking village of a new polity, taking all of its subordinate villages with it into the new polity. After one village from each polity with subordinate villages has made this decision to rebel or not, the time step is complete (see the flow diagram in Figure 3.3).

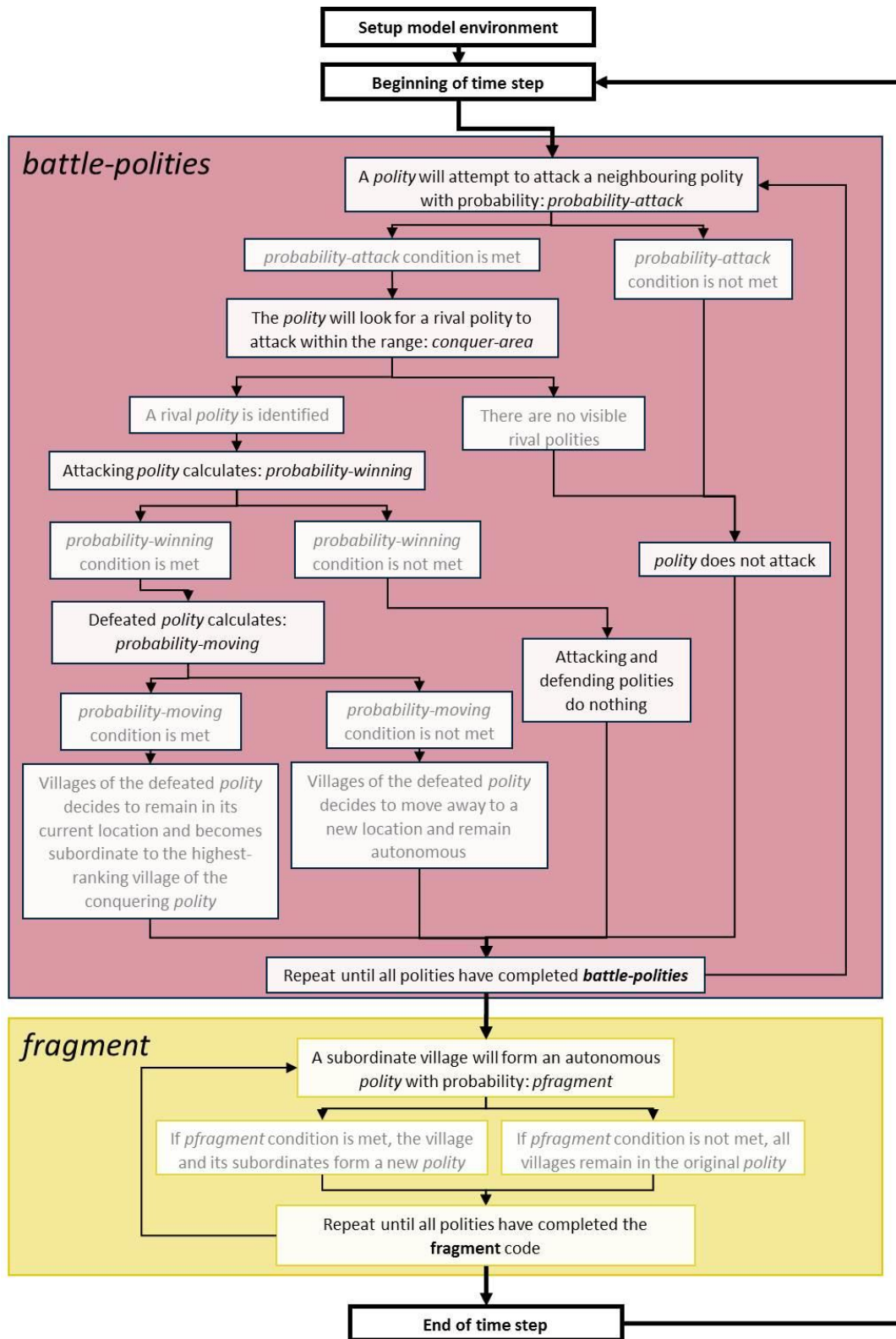


Figure 3.3 Flow diagram showing a simplified sequence of events in Model 1. The initialisation and beginning and end of the time step are in bold boxes. The battle-polities submodel is indicated by the rose coloured background box and the fragment submodel is indicated by the yellow background box. Decision-making criteria are in black text. Potential decision outcomes for villages and polities are in light grey text (see Equation 1 and Equation 2 for details on calculating the probabilities).

3.4.1.5 Model parameters

Eight parameters are tested in this model (see Table 3.2 for more detailed information on parameter values and Table 3.3 for the parameter settings tested here): (1) the area of fertile land (*land.width/number.fertile*), as a proxy for environmental circumscription; (2) the resource gradient between land types (*resource.difference*), as a proxy for resource circumscription; (3) the distribution of fertile patches (concentrated or random); (4) the frequency of conflict/warfare between polities (*probability.attack*); (5) the area around a village in which other villages are visible (*conquering.area*); (6) the population size in number of villages (*initial.villages*); (7) the cost of becoming subordinate (*tribute*); (8) the stability of the hierarchical structure connecting villages in the same polity (*probability.fragment*). Each of these parameters will be discussed below in relation to the relevant verbal predictions initially laid out in Section 3.3.

3.4.2 Model predictions

3.4.2.1 Environmental and resource circumscription (*land.width, number.fertile, resource.difference*)

The model presented here was built primarily to test the impact of environmental and resource circumscription on the formation of complex societies. Two sets of parameters are used to vary the level of environmental and resource circumscription in this model: the area of fertile land and the difference in resources between land types.

Environmental circumscription, as barriers to movement, can take many forms in real life, but one feature they will have in common is that there are few benefits to being in the area considered a 'border' because the land has fewer easily accessible or cultivatable resources, making it less habitable.

Environmental barriers have therefore been modelled here as patches with fewer resources. The extent of the barriers, and therefore the remaining area of more fertile, easily habitable land, is used as a proxy for environmental circumscription. The level of environmental circumscription was varied by changing the area of more fertile patches in the model world, using the *land.width* and *number.fertile* parameters in the concentrated and random patch distribution environments respectively. In the concentrated patch environment,

the more fertile patches are all positioned adjacent to each other to form a straight band across the model environment, much like a simplified river valley (see Figure 3.4 for an image of the layout of this world). In the random patch environment, the more fertile patches are distributed randomly across the model world (see Figure 3.4). The parameters *land.width* and *number.fertile* were set to a high and low level, to model high and low levels of environmental circumscription (see Table 3.2 for parameter settings).

In the verbal predictions discussed in Section 3.3, it was predicted that increasing the level of environmental circumscription would increase the rate of social complexity formation and the overall level of social complexity reached. In terms of parameters, I predict that a high level of environmental circumscription (*land.width* = 2; *number.fertile* = 31), will result in a substantially higher rate of average hierarchy increase than when these parameters are set to correspond to a low level of environmental circumscription (*land.width* = 31; *number.fertile* = 1023). The difference in rate of hierarchy formation between these two conditions should be affected by the *resource.difference* between the two land types.

In addition to the geographical barriers to movement is the severity of those barriers. Resource circumscription, as a concentration of resources making an area more desirable to stay in, can also take many forms in real life. Resources could be concentrated in the fertile alluvial plain of a river where minimal effort is needed to cultivate crops. Resources could also be non-edible materials, such as obsidian, which can be mined only in a few specific areas around the world and traded extensively from there (Glascok, *et al.*, 1994). In whatever form, the concentration of resources should result in a clustering of people hoping to live in or near the desirable area to result in resource circumscription.

The *resource.difference* parameter determines the severity of difference in resources between land types. Two types of land are included in the model: more and less fertile patches. Where the resource gradient is steepest, the less fertile patches contain 10 percent of the *land-resources* of the more fertile patches (see Table 3.1 for patch state variables). In a shallow resource gradient, this proportion is raised to 90 percent of the *land-resources* of the more fertile patches (see Figure 3.4 for an illustration of this).

As both environmental and resource circumscription are predicted to have an effect on the rate of hierarchy formation, by extension I predict that the most highly circumscribed conditions (a small area of fertile land and a large difference in resources between land types) will result in the fastest rate of hierarchy formation and highest overall level of hierarchy. Where the level of environmental and resource circumscription differ, I predict environmental circumscription to have the stronger effect (see Section 3.3.2 above).

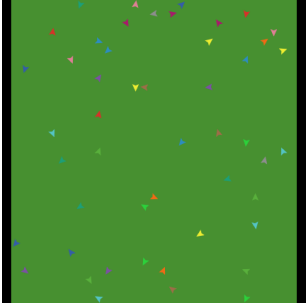

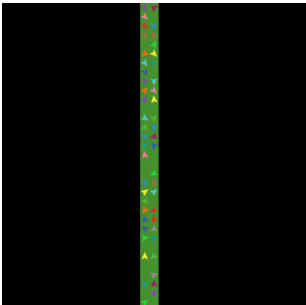
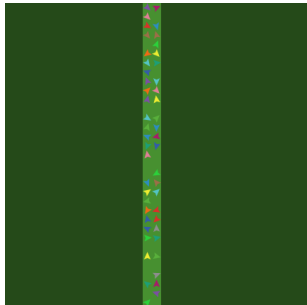
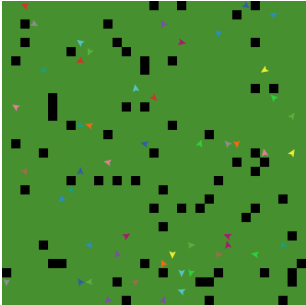

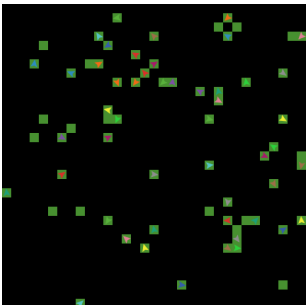
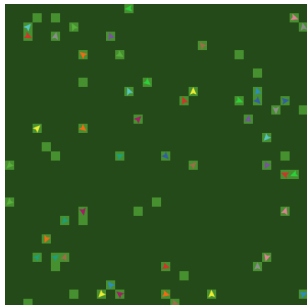
Area of fertile land	Steep resource gradient <div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> 10% fertile 100% fertile </div> <div style="text-align: center;"> 90% fertile 100% fertile </div> </div>	Shallow resource gradient
Concentrated patch distribution		
<i>land.width = 31</i> (number of more fertile patches = 1023)		
<i>land.width = 2</i> (number of more fertile patches = 66)		
Random patch distribution		
<i>number.fertile = 1023</i>		
<i>number.fertile = 66</i>		

Figure 3.4 Example model environments illustrating the layout of patches and villages in different conditions. The area of fertile land is varied by widening the strip of the more fertile patches in the concentrated patch environment (*land.width*), and by increasing the number of more fertile patches in the random environment (*number.fertile*). The land-resources of fertile patches is

kept constant, but the relative resources of the less fertile patches can be varied from low (10 percent of the more fertile patches) to nearly as high as the fertile patches (90 percent of the more fertile patches), as determined by the resource.difference parameter. Villages (coloured triangles) are always initially located on the fertile patches, but may move to the less fertile patches.

Concentrated patch distribution: all patches are clustered into continuous bands such that each land type will have the same land type on at least three sides. The area of more fertile land is varied using the land.width parameter. High and low levels of environmental circumscription will have the equivalent number of fertile patches as set by the number.fertile parameter in the random patch distribution.

Random patch distribution: patches of either land type can be located anywhere on the grid. The number of more fertile patches is determined by the number.fertile parameter.

Steep resource gradient

Less fertile patches (black) contain 10 percent of the land-resources of more fertile patches (resource.difference = 0.1).

Shallow resource gradient

Less fertile patches (dark green) contain 90 percent of the land-resources of more fertile patches (resource.difference = 0.9).

3.4.2.2 Random compared to concentrated layout of land areas

Most landscapes in the world will have an array of different types of land arranged in various patterns. River valleys tend to follow a concentric linear pattern of land change moving further away from the river. Other landscapes may have a more unpredictable pattern of landscape change. I have therefore summarised these landscapes in the model as two extremes in land type distribution: a linear, concentrated alignment; and in a random spread across the whole model world (see Figure 3.4 for an illustration of the difference in patch distribution). The model is setup in either a concentrated or random distribution, which is then fixed and does not change during a run. Variation in the characteristics of the different land types is determined by the area of fertile land (*land.width* or *number.fertile*, see above) and the difference in resources between land types (*resource.difference*). As the total number of resources in each world will be kept consistent between comparable model runs (see Figure 3.4), I predict that there will be no meaningful difference in the rate of hierarchy formation between the concentrated and random distribution of patches.

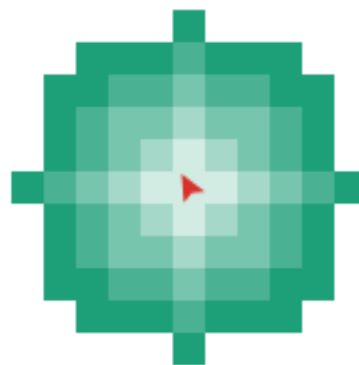
3.4.2.3 Incidence of warfare (probability.attack, conquering.area, initial.villages)

Warfare is the key mechanism by which social complexity emerges according to the circumscription hypothesis. The frequency of warfare is primarily determined

by the *probability.attack* parameter in this model. This parameter is meant to capture the incidence of warfare, for any reason that conflict can arise, and test the effect that higher or lower rates of warfare would have on the rate of hierarchy formation. If *probability.attack* = 1, then every polity will attempt to attack a neighbouring polity each time step. If *probability.attack* = 0, then all polities will remain autonomous as none will be attacked.

The *probability.attack* parameter alone could affect the rate of hierarchy formation while keeping the environmental and social conditions constant. However, villages will only attack one another if they are aware of each other's existence. The range of attack is determined by the *conquering.area* parameter, in combination with the environmental layout of patches.

The *conquering.area* parameter determines how far a village can 'see' into neighbouring patches by allowing all patches within the specified radius to become visible to the village. The larger the radius, the more patches and potential rival villages a village can interact with (see Figure 3.5). Increasing the *conquering.area* should therefore increase the incidence of warfare, and therefore increase the rate of hierarchy formation.



*Figure 3.5 Diagram to show the distance around a village (red triangle) in patches that it can find other villages if *conquer.area* = 1 (lightest teal) to *conquer.area* = 5 (darkest teal).*

The chance that a village will find itself close to another village is also determined by the population size. The more villages there are, the more likely villages are to have neighbours in adjacent patches. The number of *initial.villages* determines the population size in each model run. The population is static to control for the effects of increasing population pressure, but by

comparing a small to large population size (*initial.villages* = 5 or 50, see Table 3.2), it will be possible to get an indication of the effect of population size on the incidence of conflict, and therefore on the rate of hierarchy formation. The population size is also important to note for the highest level of hierarchy that can form. The more villages there are, the greater the number of levels of hierarchy a polity can theoretically form. Increasing the *initial.villages* should therefore result in a higher overall level of hierarchy than a smaller population size. The impact of population size will be explored further in Chapter 4.

3.4.2.4 Severity of subordination (*tribute*)

To understand more about the impact of the costs of becoming subordinate and how these costs compare to the surrounding environmental conditions, I included the parameter *tribute*. The costs of becoming subordinate in real life could include a tax levied on crop yield, gifts of valuable goods to elite members of the society, or the loss of autonomy in making decisions such as embarking on warfare or contributing labour. However, all of these potential costs can be simplified as a single number for the purposes of this model, ranging from 0-1. This represents the proportion of total resources (subsistence or otherwise) that the dominant polity can extract from a conquered polity. Two settings of *tribute* are tested in this model: 0.1 and 0.5, representing 10 percent and 50 percent of a village's total resources. The actual cost depends on the resources available to the village on the patch that it is occupying. The relative cost of becoming subordinate compared to moving to a new patch will depend on the resources of a village's neighbouring patches. The impact of *tribute* should therefore be closely intertwined with the *resource.difference* parameter. If there is little difference in resources between land types, then villages will be less likely to pay even a small cost of tribute. But if there is a stark difference in the resources available, villages may be more likely to pay higher costs of becoming subordinate to avoid the costs of moving to a new location and the loss in resources that will ensue. I therefore predict that increasing the cost of tribute will reduce the rate of hierarchy formation, but that this effect will be less apparent in model environments with a high level of resource circumscription.

3.4.2.5 Political stability (*probability.fragment*)

The formation of hierarchical societies is not necessarily one-way. Societies can break apart or become less cohesive over time as political allegiances change or groups lose contact with each other. The parameter *probability.fragment* has been included in the model to account for the effect of internal instability of complex societies. The parameter is not linked to resources of the environment or any other means for villages to assess their potential gain from separating from the main polity, nor any potential costs of leaving. The reasons for rebellion are not the focus of this model, but the effect on hierarchy formation should be accounted for.

The parameter *probability.fragment* will, by definition, reduce the level of hierarchy within polities. I therefore predict that increasing this parameter should reduce the rate of hierarchy formation and limit the potential highest level of hierarchy that can be reached. Parameter settings are arbitrary in this model, because time steps are not intended to refer to any specific length of real time. In their model, Gavrillets, Anderson and Turchin (2010) estimate that periods of instability will arise in polities roughly every 5-20 years. This translates into a probability of roughly 0.02 to 0.2 of political instability every year. To see the effect of extremes, I have therefore set *probability.fragment* to a low and low setting of 0.01 and 0.3.

3.5 Simulation experiments

To understand the effect of environmental conditions on the rate of hierarchy formation, given the conditions of tribute extraction, frequency of conflict and internal stability, I ran experiments with a range of combinations of values for each of the parameters. The experiments were repeated for both the linear and random distributions of fertile patches. The model parameters and main variations tested are described in Sections 3.4.1.5 and 3.4.2, and listed in Table 3.3. Experiments were run for 200 time steps and repeated 200 times. Most experiments stabilise after around 100 time steps at either a higher level of hierarchy or decrease to a consistent low level, but example experiments run for 2000 time steps can be seen in the Supplementary Materials 1 (Section 3.7.2).

*Table 3.3 The parameter conditions tested for each parameter in Model 1. The parameters *land.width*, *number.fertile*, *resource.difference*, and *tribute* (marked with *) were varied in all experiments. The remaining parameters (*initial.villages*, *conquering.area*, *probability.fragment*, and *probability.attack*) were kept constant between all experiments, unless one of those four parameters was deliberately varied in an experiment. When parameters were not being varied, they were set at the value in bold.*

	Parameter	Values
*	<i>land.width</i>	2, 31
	<i>number.fertile</i>	66, 1023
	<i>resource.difference</i>	0.1, 0.9
	<i>tribute</i>	0.1, 0.5
	<i>initial.villages</i>	50 , 5
	<i>conquering.area</i>	1 , 5
	<i>probability.fragment</i>	0.01 , 0.3
	<i>probability.attack</i>	1 , 0.1

The results shown here are a subset of the full parameter space of the model used to illustrate the effect of the different parameters on the formation of hierarchical polities in the model. A link to the script for Model 1 can be found in the Supplementary Materials 1 (Section 3.7).

The model output is the level of average hierarchy over time. Within each time step, all villages will report their current level of hierarchy within their polity. The mean hierarchy of all the villages is recorded at the end of each time step. Results are plotted as raw data points of the mean hierarchy per time step, and summarised as one standard error above and below the mean among all iterations of the same experiment. Experiments were run for 200 time steps.

Results from different combinations of each of the parameters (see Table 3.3) are shown in turn. The different levels of environmental circumscription (*land.width* and *number.fertile*), resource circumscription (*resource.difference*), and layout of patches (concentrated or random), and cost of becoming subordinate (*tribute*) are shown in all graphs, except for Figure 3.6 where *tribute* is set to 0.1 for clarity. Unless otherwise stated, the remaining parameters are set to the default value (see Table 3.3).

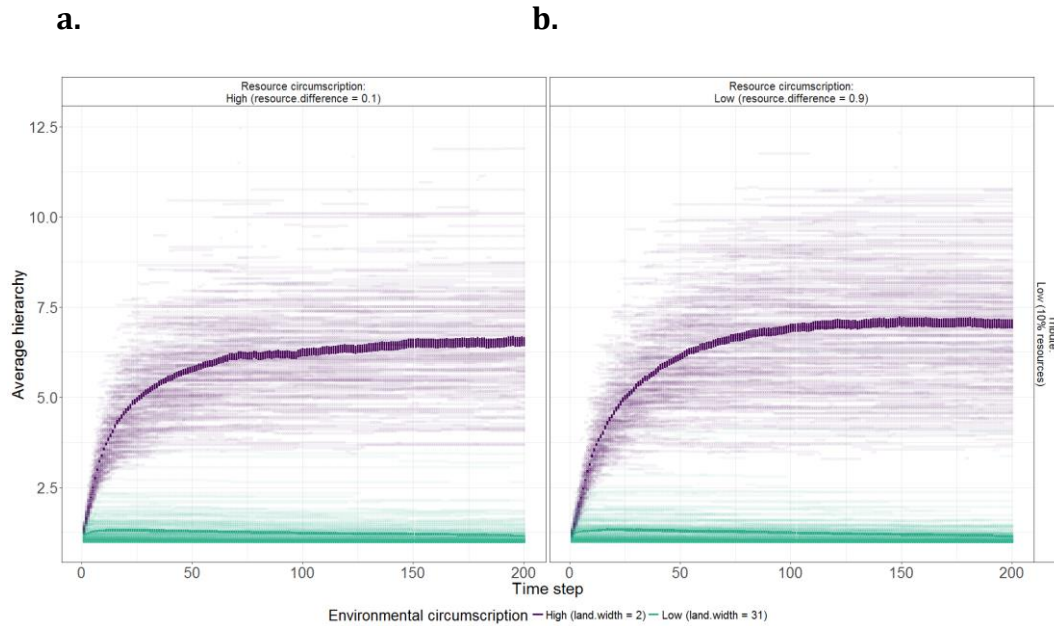
3.5.1 Environmental and resource circumscription (*land.width*, *number.fertile*, *resource.difference*)

In Sections 3.3.2 and 3.4.2.1, it was predicted that increasing environmental circumscription by decreasing the area of fertile land (*land.width* and *number.fertile*) would result in a faster rate of hierarchy formation. This is supported by the results shown in Figure 3.6 (panels a, b, and c) where the higher level of environmental circumscription (purple line) shows a faster increase in average hierarchy over the first 50 time steps. However, when the resource gradient is shallow (*resource.difference* = 0.9) in a randomly distributed patch environment (Figure 3.6, panel d), there is no difference between the purple and green lines, indicating that environmental circumscription has no effect on the rate of hierarchy formation.

It was also predicted in Section 3.3.2 that increasing resource circumscription (*resource.difference*) would increase the rate of hierarchy formation. The effect of resource circumscription is less clear-cut than environmental circumscription. In the concentrated patch environment shown in Figure 3.6, (panels a and b), there is no perceivable difference between the high and low resource gradient. However, the rate of hierarchy formation is much more rapid when the resource gradient is steep in the random patch environment (Figure 3.6, panel c) compared to the shallow resource gradient environment (Figure 3.6, panel d).

The results in Figure 3.6 indicate that environmental circumscription has a greater effect on the rate of hierarchy formation in the concentrated patch environment, but the effect is only visible in the random patch environment when resource circumscription is also high. This partially supports the prediction made in Section 3.3.2 that environmental circumscription would have a greater overall effect than resource circumscription. Resource circumscription does not always have an effect on the rate of hierarchy formation, but can override environmental circumscription to reduce the incidence of hierarchy formation even in severe environmental circumscription conditions. These results do not support the prediction made in Section 3.3.3 and 3.4.2.1 that there would be no difference in average hierarchy formation between the concentrated and random distributions of patches.

Concentrated patch distribution



Random patch distribution

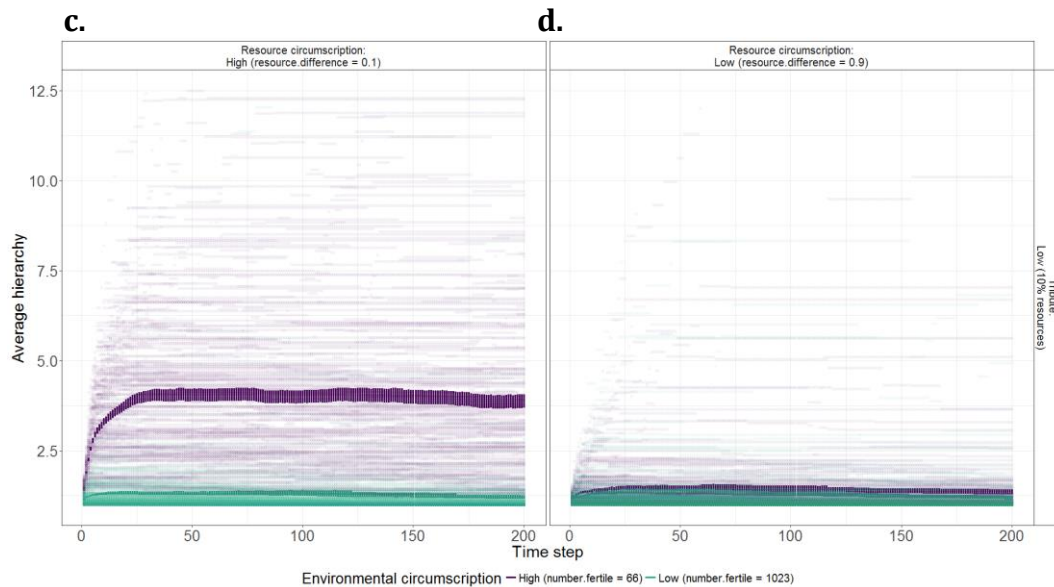


Figure 3.6 Graphs showing the effect of environmental and resource circumscription on the rate of hierarchy formation. The parameters land.width and number.fertile are varied to show environmental circumscription. The parameter resource.difference is varied to show resource circumscription. The remaining parameters are kept constant (see Table 3.3), and tribute is here set to 0.1. The average level of hierarchy for all villages in each model run is recorded for each time step (translucent circles). The average level of hierarchy between 200 model runs is summarised as standard error bars (darker coloured block) for each time step. Results in purple correspond to model conditions with high environmental circumscription where the majority of patches contain fewer resources. Results in green correspond to model conditions with low environmental circumscription, where the more fertile patches are almost universal (see Figure 3.4 for illustrations of these model conditions). The first 50 time steps are included here to show the initial rate of hierarchy formation. Further parameter combinations and time steps can be seen in Figures 3.7 to 3.10.

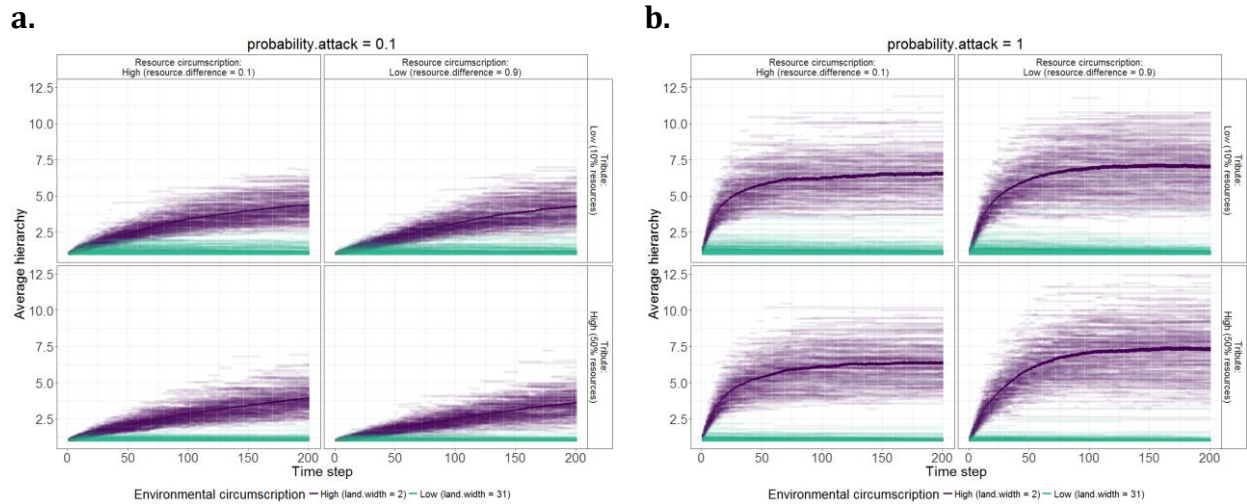
The following sections show the results from varying the parameters: *tribute*, *probability.attack*, *conquering.area*, *initial.villages*, and *probability.fragment*, in combination with environmental circumscription and resource circumscription. The two sets of graphs in the right-hand column show the default parameter settings for all experiments. The left-hand column shows results when varying one parameter (see Table 3.3 for the parameter variations). Graphs are displayed side-by-side to facilitate comparison.

3.5.2 Incidence of conflict

3.5.2.1 *probability.attack*

The *probability.attack* parameter determines the frequency of conflict between villages who are located close enough together to come into contact. In Sections 3.3.4 and 3.4.2.3 it was predicted that increasing the incidence of conflict through increasing *probability.attack* would result in a faster rate of hierarchy formation because of the greater likelihood that villages will be defeated in the more frequent conflicts. The graphs in Figure 3.7 show low *probability.attack* (panels a and c) and high *probability.attack* (panels b and d) in combination with high and low environmental circumscription, resource circumscription and cost of becoming subordinate (*tribute*).

Concentrated patch distribution



Random patch distribution

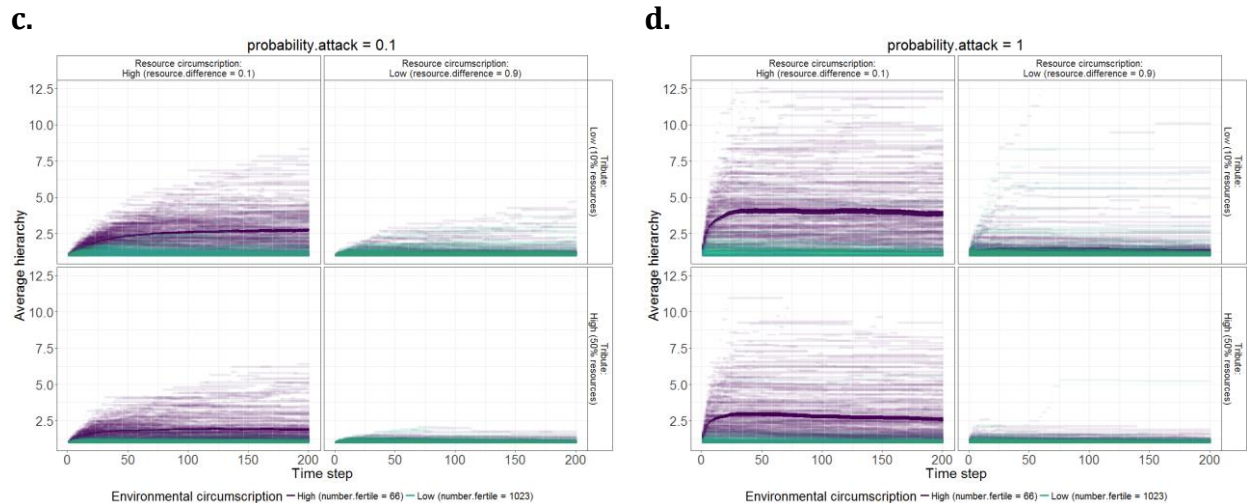


Figure 3.7 Graphs showing the results of varying the frequency of warfare (*probability.attack*) on combinations of high and low parameter values for environmental circumscription, resource circumscription, and tribute costs. Panels a and c show results from the low *probability.attack* (0.1) setting, and panels b and d show results from the high *probability.attack* (1) setting. Panels a and b are the concentrated patch environment, and c and d are the random patch environment.

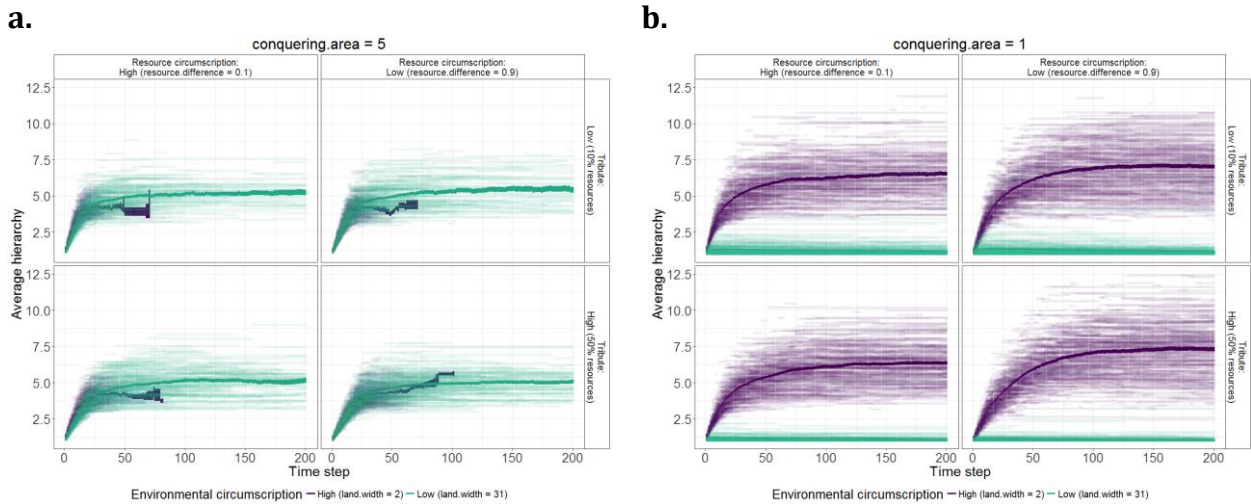
The prediction that a higher *probability.attack* would result in a faster rate of hierarchy formation is supported by the results from the first 200 time steps shown in Figure 3.7. Conditions where the *probability.attack* is high (1) (Figure 3.7, panels b and d) show a faster rate of initial hierarchy increase and earlier plateau in hierarchy level in both the linear and random patch distribution conditions compared to the same environmental conditions when *probability.attack* is low (0.1) (Figure 3.7, panels a and c). The effect is most clearly seen when environmental circumscription is high (purple line). However,

where environmental circumscription is low (green line) the level of hierarchy remains low even when the *probability.attack* parameter is high. This is counter to the prediction in Section 3.3.4 that hierarchy would increase with greater incidence of warfare even in conditions of low environmental and resource circumscription. This may be because villages are too dispersed in the low circumscription environments to be able to find rival polities to attack. This will be discussed further in relation to the *conquering.area* parameter in the section below.

3.5.2.2 *conquering.area*

The *conquering-area* parameter determines the distance that a village can 'see' to find villages belonging to a different polity to potentially attack. This parameter, along with the *probability.attack* and *initial.villages* parameters, can increase the incidence of warfare between polities.

Concentrated patch distribution



Random patch distribution

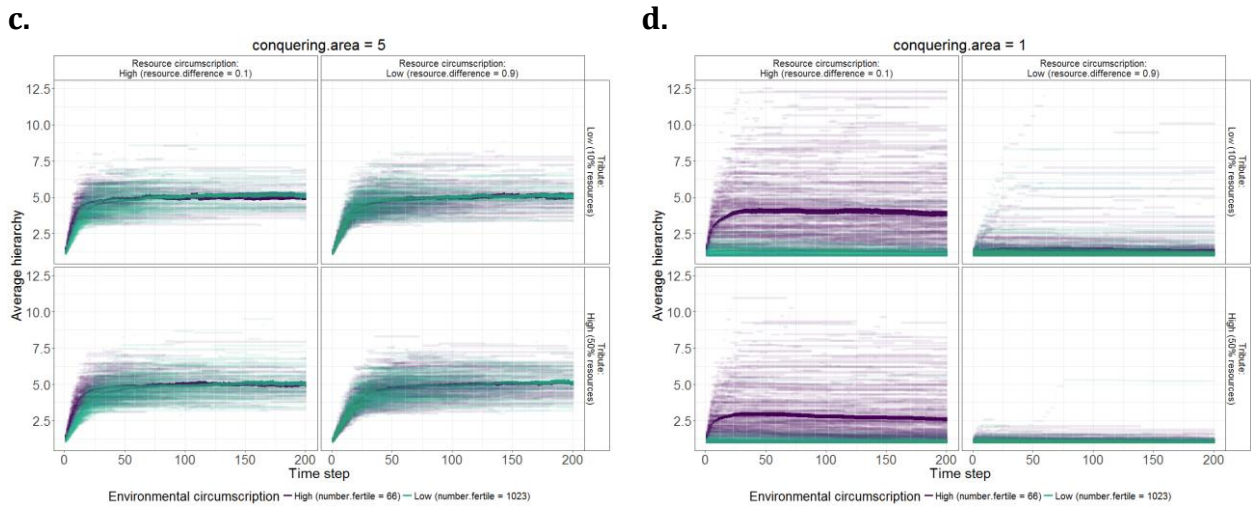


Figure 3.8 Graphs showing the results of varying the internal stability of polities on combinations of high and low parameter values for environmental circumscription, resource circumscription, and tribute costs. Panels a and c show the results from a wide conquering area (5 patches). Panels b and d show the results from a narrow conquering area (1 patch). Panels a and b correspond to the concentrated patch distribution, and c and d to the random patch distribution environments.

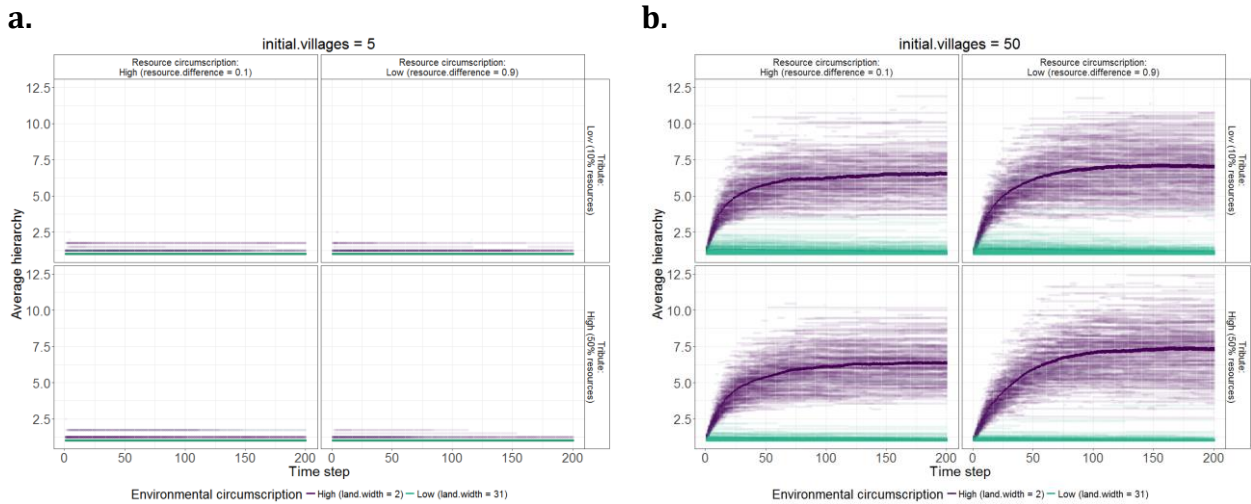
It was predicted in Sections 3.3.4 and 3.4.2.3 that increasing the conquering area distance could increase the rate of conflict between villages as villages are more likely to find rival villages to attack. Increasing the rate of conflict in this way should therefore increase the rate of hierarchy formation, particularly when villages are more dispersed throughout the model. This prediction is supported by the results shown in Figure 3.8. Where villages can ‘see’ five patches away (Figure 3.8, panels a and c), there is no difference in hierarchy formation between conditions of high and low environmental circumscription (purple and

green lines respectively), or between high and low resource circumscription (left- and right- hand side graphs respectively in panels a and c). This suggests that hierarchy can form among villages when there is the possibility of conquering warfare, even when there is very little environmental or resource circumscription.

3.5.2.3 *initial.villages*

The number of *initial.villages* determines the population size of number of villages in the model. The population size remains constant for the duration of the model run. The number of villages in the population will affect the incidence of warfare, along with the *probability.attack* and *conquering.area* parameters, because a greater number of villages present will increase the number of rival villages that can potentially be attacked.

Concentrated patch distribution



Random patch distribution

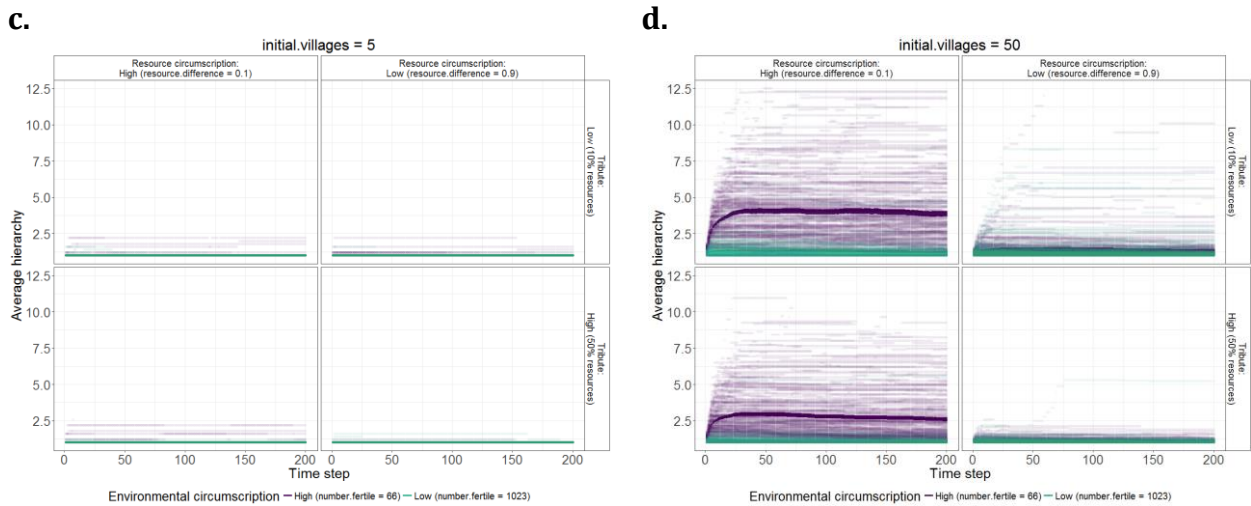


Figure 3.9 Graphs showing the results of varying the population size (initial.villages) on combinations of high and low parameter values for environmental circumscription, resource circumscription, and tribute costs. Panels a and c show results from a small population size (initial.villages = 5). Panels b and d show results from a larger population size (initial.villages = 50). Panels a and b correspond to the concentrated patch distribution, and c and d correspond to the random patch distribution.

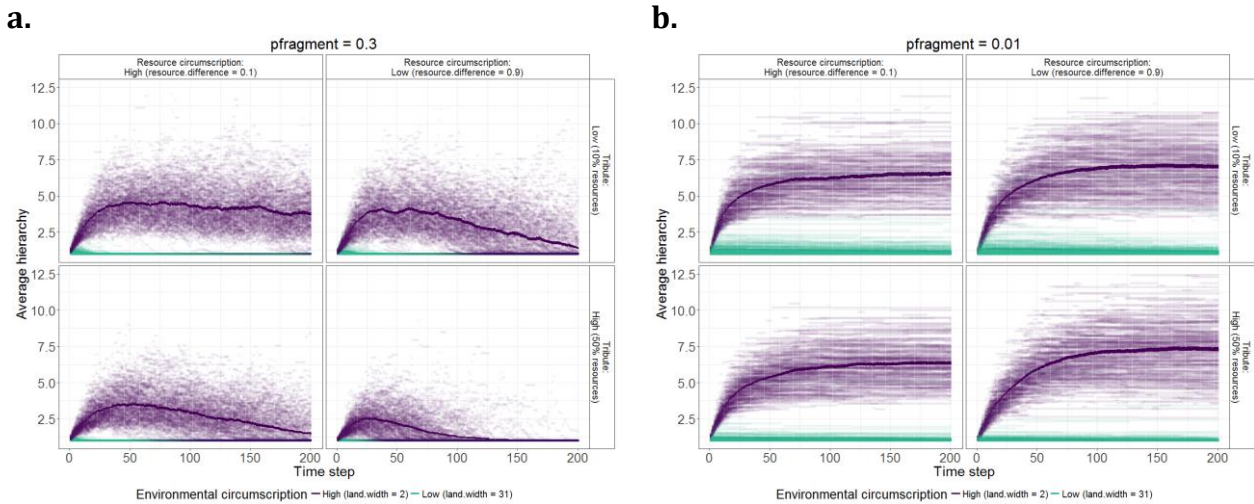
It was predicted in Sections 3.3.4 and 3.4.2.3 that a larger population size would result in a higher level of hierarchy formation. This is supported by the results shown in Figure 3.9. Where the population size is small (Figure 3.9, panels a and c), there is almost no hierarchy formation in any conditions of environmental circumscription, resource circumscription, or tribute costs. There are fewer completed model runs in the low population model because all the villages are more likely to become part of the same polity more quickly and

therefore stop the model running. Only when the population size is larger (Figure 3.9, panels b and d) does hierarchy form. This supports the prediction in Sections 3.3.4 and 3.4.2.3 that increasing the incidence of conflict between villages (in this case by increasing the number of villages which can come into conflict) will increase the rate of hierarchy formation.

3.5.3 Internal polity stability (*probability.fragment*)

The *probability.fragment* parameter determines the internal stability of polities through the probability that a village in the polity will defect and form a separate, autonomous polity.

Concentrated patch distribution



Random patch distribution

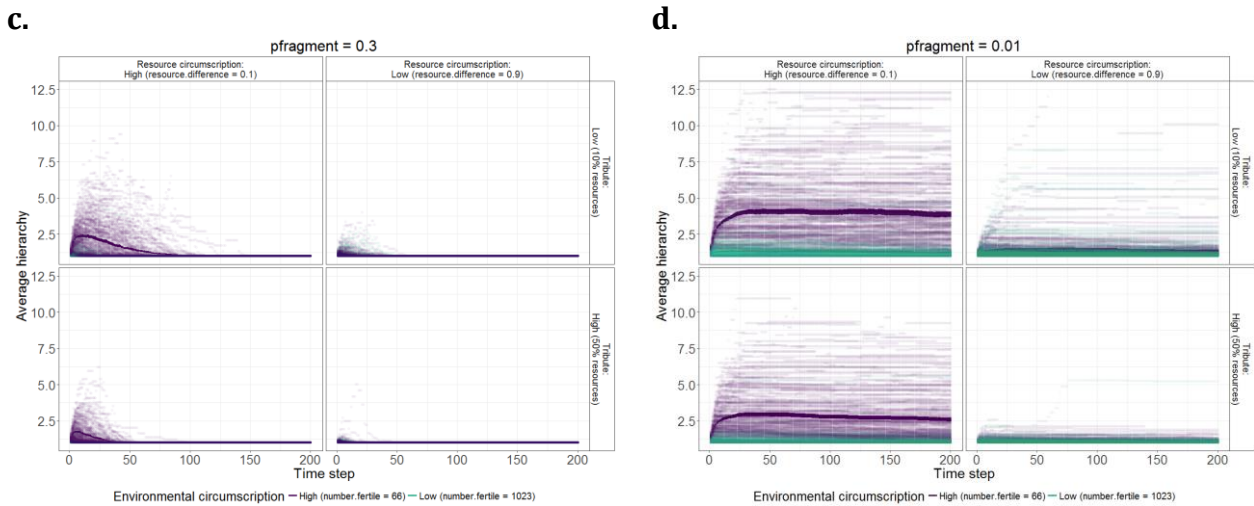


Figure 3.10 Graphs showing the results of varying the internal stability of polities on combinations of high and low parameter values for environmental circumscription, resource circumscription, and tribute costs. Panels a and c show results from high internal instability ($\text{probability.fragment} = 0.3$). Panels b and d show results from low internal instability ($\text{probability.fragment} = 0.01$). Panels a and b correspond to the concentrated patch distribution, and c and d to the random patch distribution.

It was predicted in Sections 3.3.6 and 3.4.2.5 that increasing the *probability.fragment* parameter would decrease both the rate of hierarchy formation and overall level of hierarchy reached because polities would be less stable and therefore less likely to maintain hierarchical structures. These predictions are partially supported by the results shown in Figure 3.10. The first half of this prediction is not supported as there is a similar initial rate of hierarchy increase when *probability.fragment* is high (0.3) (Figure 3.10, panels a

and c) compared to low (0.01) (Figure 3.10, panels b and d). However, the hierarchy level reached is not maintained over time when *probability.fragment* is high (Figure 3.10, panels a and c), which supports the prediction that greater instability would result in a lower. The decrease in average hierarchy over time is particularly pronounced in the high environmental circumscription conditions (purple lines) when patches are distributed in a random environment (Figure 3.10, panel c) and when the tribute costs are high in the concentrated environment (lower two graphs of Figure 3.10, panel a).

3.5.4 Cost of subordination (*tribute*)

The *tribute* parameter determines the cost of becoming subordinate if villages are defeated in a conflict. It was predicted in Sections 3.3.5 and 3.4.2.4 that increasing the cost of becoming subordinate would reduce the rate of hierarchy formation, unless the costs of moving to a neighbouring patch are greater (as determined by the *resource.difference* parameter).

The results of varying *tribute* to high (0.5) and low (0.1) settings can be seen in Figures 3.7 to 3.10, by comparing the upper and lower rows of graphs within panels. The results partially support the prediction. When *tribute* is varied within a concentrated patch environment (panels a and b within Figures 3.7 to 3.10), there is very little difference in the rate or overall level of hierarchy reached between high and low *tribute* settings. However, when the patches are randomly distributed (panels c and d within Figures 3.7 to 3.10), increasing the cost of *tribute* will tend to result in a lower level of hierarchy formation. The exception to this is Figure 3.8 (panel c), where the *conquering.area* is wide (5 patches) and there is no difference in either the rate of hierarchy formation or overall level of hierarchy in the random patch environment with either the high or low *tribute* settings.

3.6 Discussion

The purpose of the model in this chapter was to test whether environmental conditions which limit population movement could have made social complexity more likely to form. The results show that the severity of environmental conditions does have an effect on the emergence of hierarchy, but that the

relative importance of geographical barriers and difference in resources between land types varies depending on the distribution of patches in the model environment. Villages placed in an environment where the more fertile patches are clustered together (similar to a river valley) are more affected by the width of that area than they are by the difference in resources between land types. Villages placed in an environment with a random distribution of land types (similar to the undulations of ecology in a plain), show greater sensitivity to the difference in resources between environmental zones than to the total area of more fertile land.

3.6.1 Environmental and resource circumscription

The level of environmental circumscription in the model was varied by the area of fertile land parameters (*land.width* and *number.fertile* for the concentrated and random patch distribution environments respectively). It was predicted that increasing the level of environmental circumscription would increase the rate and overall highest level of hierarchy formation in polities (see Sections 3.3.2 and 3.4.2.1). This prediction has largely been supported in the different model environments (see Section 3.5.1). The greatest effect was consistently seen in the concentrated patch environment compared to the random patch environment, but the difference was diminished by decreasing the frequency of conflict, increasing internal stability of polities, increasing the range that villages could find rivals within, and decreasing the population size.

The level of resource circumscription was modelled by varying the difference in resources between the two land types (*resource.difference*). It was predicted that increasing the level of resource circumscription would increase both the rate and overall highest level of hierarchy formed, but that the effect of resource circumscription may be less than the effect of environmental circumscription. The latter part of this prediction is supported in the concentrated patch environment, where resource circumscription has very little effect on hierarchy formation. However, resource circumscription has a much greater effect in the random patch environment where reducing the difference in resources will effectively halt hierarchy formation entirely (see Section 3.5.1). Where resource circumscription is high, increasing environmental circumscription will increase the rate of hierarchy formation, as expected.

The sensitivity of the different parameter settings in the random patch distribution environment may be due to the edge effect of the random patches. In the concentrated patch distribution environment, villages which are located in the centre of the strip of more fertile land will behave as if the land is uniform because that is all they can 'see'. But in the random environment, it is more likely that villages will have at least one neighbouring patch of fewer resources. Therefore a higher proportion of villages will be influenced by these neighbouring less fertile patches. This means that the effect of environmental circumscription is more consistent across the range of potential number of fertile patches in the environment because of the spread of border patches (see Supplementary Materials 1, Section 3.7.3.2). In contrast, in the concentrated patch environment narrowing the width of the fertile band will have an increasingly significant effect as more villages are likely to find themselves on the border between the land types (see Supplementary Materials 1, Section 3.7.3.1). The likelihood of a village being located at the border between land types may therefore explain why the resource gradient has a greater effect in the random environment than in the concentrated environment. Environments in the real world are neither fully concentrated nor fully random in land type. The observation of the effect of land type distribution is therefore important in considering how these results may relate to processes in the archaeological record.

From these results we can say that Carneiro's environmental and resource circumscription hypothesis are supported, but with the added caveat that the presence and visibility of borders between land types is important, rather than an absolute measure of circumscription. This had not been explicitly considered in the original verbal formulation of the hypotheses, and illustrates the value of modelling for fine-tuning verbal hypotheses and highlighting otherwise-unconsidered assumptions or factors. In not predicting the importance of a border effect or village isolation, this model has become an example of showing the limitations of a verbal hypothesis alone, and the value of modelling. The assumption that land type should not influence hierarchy formation when the number of resources is the same is plausible in a thought experiment (see predictions in Section 3.3.3 and 3.4.2.1), but untenable given the results presented here. Formalising a thought experiment using agent-based models

can cultivate a much deeper understanding of the implications of verbal statements (see Chapter 2, Section 2.1).

An additional and unexpected difference between the concentrated and random patch environments is that hierarchy levels are more likely to decrease in the random environment. This trend is pointed towards in Figure 3.10, and exemplified in the long-term experiments shown in the Supplementary Materials 1 (Section 3.7.2, Figure 3.11). This difference, like the decrease in social complexity seen when *probability.fragment* is high (see Section 3.5.3 above), is due to the collapse of societies into smaller units over time in the absence of other polities to conquer. Villages in the random environment are more dispersed across the whole model world than in the concentrated environment. Once all the visible villages have been incorporated into the same polity, the only possible change is through internal collapse. Villages cannot move further than one patch to escape, and cannot see further than allowed by the *conquering.area* parameter in this model. Villages are much less likely to become isolated in the concentrated patch environment because they begin clustered together in the same, continuous, band of more fertile land.

3.6.2 Incidence of warfare

It was predicted that increasing the incidence of warfare, primarily through increasing the probability of attack but also through increasing the area of attack and population size, would increase the rate of hierarchy formation. This prediction is supported by all three parameters used here (*probability.attack*, *conquering.area*, *initial.villages*) (See Section 3.5.2). In all three cases, increasing the parameter resulted in increasing hierarchy formation. The highest level of hierarchy formation was reached in conditions of a high probability of attack and high environmental and resource circumscription. From this we can say that the effects of environmental and resource circumscription can be accentuated by the frequency of conflict (and vice versa), particularly so in the concentrated patch environment, which supports Carneiro's 'steam cooker' analogy to describe the conflict arising from a population crowded by surrounding conditions.

In further confirmation of the predictions in 3.3.4 and 3.4.1.5.3, increasing warfare (through village attack range and population size) can cause an

increase in social complexity even when environmental and resource circumscription are low (see *conquering.area* graphs, Figure 3.8, and *initial.villages* graphs, Figure 3.9). However, increasing the probability of attack has a much smaller effect alone. This is because villages cannot attack if they cannot find other villages. This result is particularly important to note for understanding the model of population dynamics in Chapter 4.

3.6.3 Political stability

The internal stability of polities was modelled by varying the parameter *probability.fragment*, which determined the likelihood that a subordinate village would rebel to form an autonomous polity. It was predicted that increasing *probability.fragment* would decrease the rate and overall level of hierarchy formation. This prediction was only half met. The rate of hierarchy formation remained very similar to conditions of low *probability.fragment*, but the level of hierarchy would then decrease over time. As mentioned above, this may be due to the collapse of societies over time as the pressure leading to fragmentation is greater than the pressure to build social complexity with weak internal stability.

3.6.4 Severity of subordination

The cost of becoming subordinate was modelled by varying the proportion of resources that the dominating polity would demand in tribute from a newly conquered polity. It was predicted that increasing the cost of tribute would decrease hierarchy formation, but that the effect would be less pronounced in harsher environmental conditions. This prediction is supported to a certain extent in the random patch environments, where increasing the cost of tribute will decrease hierarchy formation in conditions of high environmental and resource circumscription. The effect in low resource circumscription conditions cannot be seen because very little hierarchy forms at all. Varying tribute in the concentrated patch environment has very little effect, unless *probability.fragment* is high, in which case increasing *tribute* does decrease hierarchy formation. The difference between the random and concentrated landscapes is likely due to the border effect. Villages are only affected by the costs of tribute where they are comparable with the loss of resources in neighbouring patches.

3.6.5 Rate of hierarchy formation compared to the overall level reached

The rate of hierarchy formation, and the maximum level of hierarchy reached (at any point or in equilibrium) are two slightly different measures of hierarchy. In Section 3.3.1 I predicted that the model conditions which resulted in the fastest rate of hierarchy formation would also be the conditions where the highest level of hierarchy was reached and maintained. This prediction was largely supported. Only when the internal stability of polities was relatively precarious did the overall level of hierarchy significantly decrease over time. Once hierarchical societies had formed with a high likelihood of internal collapse, it is inevitable that hierarchy will eventually collapse. The trends of hierarchy formation identified in the model parameter space may therefore be taken as indicative of the conditions in which social complexity is most likely to flourish.

3.6.6 Assumptions and limitations of the model

The aim of this model was to test the logic of the circumscription hypothesis in an abstract simulation environment. As such, my aim was to keep the assumptions of the model consistent with the assumptions of Carneiro's circumscription hypothesis. This has in some cases meant inferring behaviours which are not explicitly included in verbal descriptions of the circumscription hypothesis. In this model it is assumed that villages will enter into conflict with their neighbours in order to maximise their resource gain. It is also assumed that the only alternative option available to villages if they are defeated is to move away to a neighbouring patch. The structure of polities is also assumed to be hierarchical, with some villages able to dominate others after winning a conflict. The reasons why people would decide to enter into conflict, move away or form a hierarchical structure vary greatly in real life. The simplicity of this model means that we can simulate the weighing up of relative costs and benefits, whatever the reasons behind or weight given to those different reasons (even if they are not for pure economic gain), and assess the effect of these decisions.

The model indirectly investigates the selection of larger polities over smaller ones by including the probability of winning based on the relative size of the two

competing polities (Johnson and Earle, 2000). Given the current model conditions, all villages in the model will eventually be included in the same polity (at which point the model stops). Many other factors will determine the victor of a conflict between real human groups (number of able-bodied people, access to technology, military organisation, shared ideology, etc.), which have not been explicitly accounted for here.

It is also assumed in this model that villages will only have a limited awareness of their surrounding environment. Villages are able to identify neighbouring rival villages within the radius of *conquering.area*, but they are not able to make a decision on whether to move location or not based on the land environment beyond their immediate surroundings. This is explored further in Chapter 4.

A further feature of this model to note is that although villages base their decisions on the level of *tribute* to pay, and therefore the relative loss or gain of resources, villages will at no point actually pay this *tribute* to another village. The accumulation of wealth and re-distribution of resources within a polity would be interesting to explore in further work, particularly in investigating which polity-level strategies are most successful at maintaining the polity over time. However, this is beyond the scope of this thesis and against the principle of keeping this model (whose purpose is only to test the impact of environmental and resource circumscription) as simple as possible.

One element of the circumscription hypothesis that has been purposefully excluded from the model in this chapter is population growth and consequent competition as the population reaches carrying capacity. The additional assumptions of rate of population growth and threshold of carrying capacity could obscure the underlying logic of the circumscription hypothesis which has been tested here. The focus of this model is exclusively on the process of conflict resulting in the formation of large, hierarchically complex societies in different environmental conditions without modelling how conflict came to arise. The influence of population growth is discussed in Chapter 4.

3.6.7 Conclusion

The agent-based model presented here was built to test the logical consistency of Carneiro's circumscription hypothesis by focusing on the effects of

environmental barriers and resource concentration on the formation of social complexity. Results show that the severity of environmental conditions do impact the rate of hierarchy formation, but the effect is greatest when villages are located at a border between more and less fertile land types. This model does not test the impact of change in population over time or social circumscription. These will be addressed in Chapter 4.

Chapter 4: Can social circumscription drive the formation of social complexity? (Model 2)



Abstract

The circumscription theory in its entirety suggests that people may experience circumscribing conditions as environmental barriers, concentration of resources, or by encroaching on the territory of other groups of people. The effect of environmental and resource circumscription was investigated in Chapter 3. In this Chapter, social circumscription is introduced to the abstract model (Model 2), to test the effect of population pressure and the clustering of villages. The model results show that when the population is allowed to grow in a uniformly fertile environment, hierarchy can still form if villages are able to find and attack one another. When the population grows within conditions of environmental and resource circumscription, there are three different ways in which villages are more likely to come into contact: (1) through population increase, where there are sufficient resources to do so; (2) through an increase in the distance of village roaming; and (3) through confining all villages to a smaller area of land. The degree and spatial distribution of environmental and resource circumscribing conditions determine the impact of these three situations on the rate of hierarchy formation. This abstract model therefore provides greater insight into the types of landscape most likely to result in the emergence of social complexity in the real world, given the assumptions of the circumscription theory.

4.1 Introduction

The landscape in which any human can live is built up by the geological and ecological elements that we can see, walk on, and eat. But landscapes are also made by people. For a person to survive in a landscape, they must negotiate with the natural world alongside other people doing the same. In Chapter 3, we looked at the effect of environmental and resource barriers on the emergence of complex societies in an abstract model environment. This model was intended to test only part of the circumscription hypothesis, as described by Robert Carneiro (1970, 2012a) (see Chapter 1, Section 1.5). The model in this chapter will investigate the final part of the circumscription hypothesis: the effect of social circumscription, where the barriers to movement are formed by other people. Carneiro suggests that even areas rich in extensive resources could still restrict people's options to move elsewhere if the land is already claimed by other groups of people. Social circumscription may have had a role in the formation of complex societies along the Eurasian steppe, one of the least environmentally circumscribed stretches of land in the world (Carneiro, 2012a, 2012b; see Chapter 1, Section 1.5.4).

Identifying where social circumscription may be having an effect is a more subtle exercise than identifying geographic features because of the many different ways that people can occupy an area. Nomadic people may cover a much larger area and yet not come into contention with others because their population may be smaller or because it is easier to move on to a new area. Agricultural societies may intensify food production to support a much larger population in a smaller area, or use techniques such as slash-and-burn agriculture which requires a much larger area of land to allow regeneration between episodes of cultivation (Palm, Swift and Woomer, 1996). Measuring the degree of social circumscription therefore requires an understanding of how people at the time lived and adjusted to changing circumstances. Changes in farming practices or technology can change the social landscape. People can lay claims to areas in many other ways which may not be related to subsistence (as any monument, burial ground, or graffiti will testify). For simplicity, I focus on the subsistence potential of areas of land.

The abstract model in this chapter has two purposes: firstly, to test whether social circumscription can have an effect on social complexity formation independent of other circumscribing factors (environmental and resource circumscription: see Model 1); and secondly, to test the combined effect of environmental, resource, and social circumscription to see how they interact and which is more influential. Formalising the hypothesis in this abstract model (see Chapter 2, Section 2.2.2) will give a better indication of whether social circumscription may have had an impact on societies in the past, even if direct evidence for it is difficult to find in the archaeological record.

The abstract ABM in this chapter builds on the ABM of Chapter 3. Where the two models are the same in structure or process, the reader will be referred back to the relevant sections of Chapter 3 to avoid undue repetition.

4.2 Verbal outline of the model

As in Model 1 (Chapter 3), villages in this model have the option to attack neighbouring villages if they can find them, and move away if beneficial to do so when defeated. In this model, villages have the added option to create a new village if there is available space to expand into. Villages are more likely to create a new village the more resources the free space has. The population of villages in the model can therefore potentially spread into all corners of the model world, but will do so more quickly if there are plentiful resources available. Figure 4.3 shows a simplified flow diagram of all of these processes, and submodels are discussed in more detail in Section 4.4.1.4 and Chapter 3 Section 3.4.1.4.

4.3 Predictions

4.3.1 Social circumscription independent of environmental variation

In the verbal formulation of the social circumscription hypothesis, Carneiro (1970, 2012a) suggests that if people begin to live in clusters, this will lead to an increase in population pressure where resource demand begins to outstrip supply. As people cluster, warfare may intensify between them as they compete over the limited resources. While increasing the incidence of conflict, population

pressure will also limit the options to move away to a new location if defeated in conflict if the surrounding land is already occupied. Increasing population pressure should result in both more warfare and more restrictions to movement. Carneiro therefore suggests that the more clustered a population is, the more likely it is that social complexity will emerge. There are however a few assumptions in this verbal formulation of the hypothesis that need to be addressed.

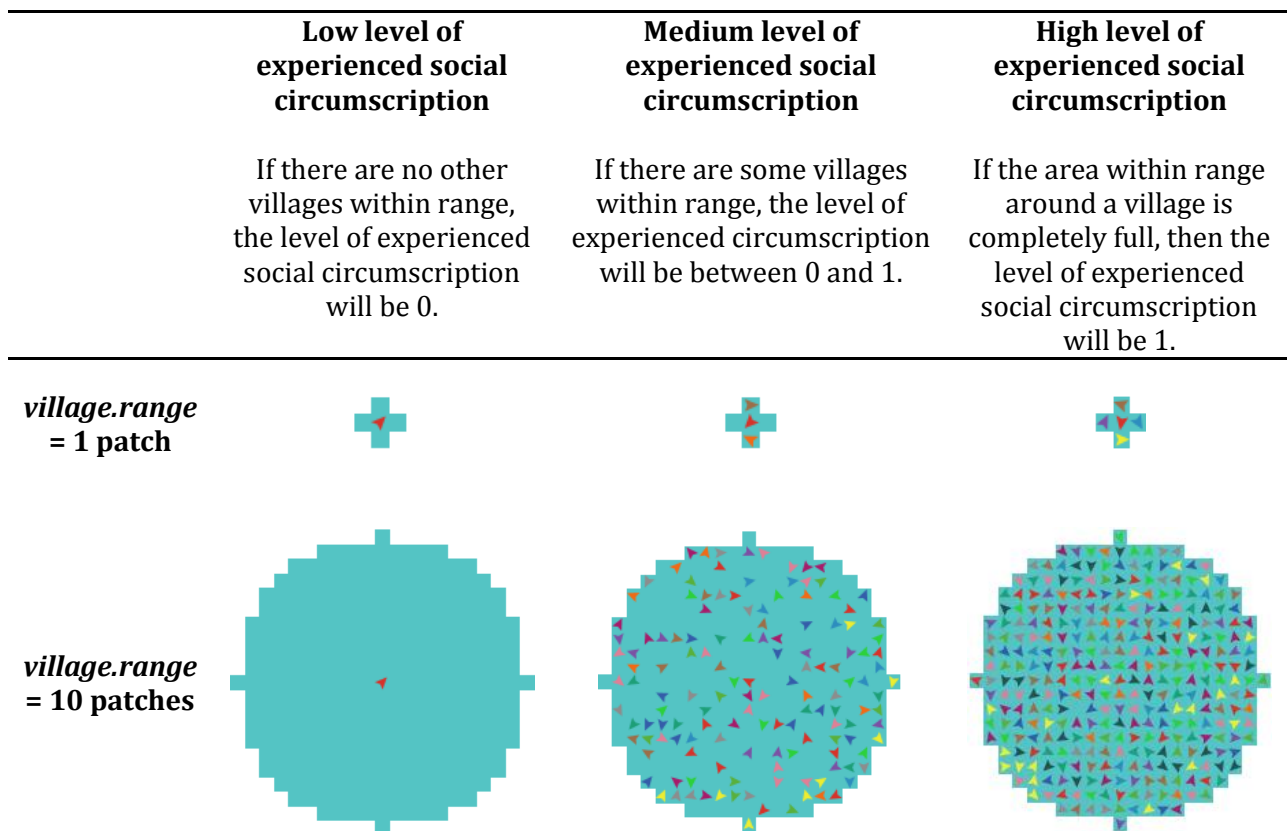
Firstly, population pressure is a nebulous concept which is not clearly defined. Carneiro posits that population pressure will intensify warfare between societies when it is present (2012b), but does not define how exactly population pressure may arise. As we are focusing on subsistence resources, population pressure may therefore apply to the carrying capacity (the total population that can be supported by the resources available). But carrying capacity is notoriously difficult to calculate for human populations, particularly in the past, because people can trade supplies across long distances and intensify cultivation by employing different agricultural tools and technology (Thurston and Fisher, 2007). In this model, I therefore simplify this by assuming that each village will occupy one patch, and there will be increasing population pressure if a greater proportion of the surrounding area is filled by other villages (see Figure 4.1 for details on a measure of population pressure).

Secondly, Carneiro suggests that social circumscription may have a weaker effect than environmental circumscription: *'With social circumscription, the degree of constriction on the impacted population is generally less tight than with physical circumscription, allowing a certain amount of 'leakage' to occur.'* (Carneiro, 2012a, p24, emphasis in original). However, without a clear definition of what population pressure entails, we cannot know the limitations that it presents. I simplify this here by assuming each village occupies one patch of land, vary the distance that villages are willing to move if defeated, and assume that population pressure can be experienced by degree and not as an absolute category of either present or absent.

Thirdly, in the absence of resource concentration acting as an incentive for people to cluster together, Carneiro does not go into detail about why a population may become clustered at all. Based on settlement distribution

information (see Supplementary Materials 3, Section 5.7.3), I make the assumption here that as a population grows, new settlements may be placed relatively close to original settlements. As more settlements are created, each not too far away from the last, this could lead to population clustering in the absence of resource concentration (see Section 4.4.1.5 for details on the distances tested here).

Given the original verbal formulation of the social circumscription hypothesis and the caveats discussed above, I predict that increasing population pressure (where each village is surrounded by more villages) will: (i) increase the pressure exerted by social circumscription by both intensifying conflict between villages and reducing the options that they have to move away if defeated; and consequently (ii) increase the rate of hierarch formation. To show this I measure both the average level of hierarchy reached (as done in Chapter 3) and the level of 'experienced social circumscription', calculated as the proportion of land around villages that is occupied by other villages while accounting for the distance that a village can move (see Figure 4.1 for more information on how this was calculated). If the prediction that social circumscription leads to a greater chance of social complexity formation is supported, I expect the rate of hierarch formation to increase more quickly as the level of experienced social circumscription (as an emergent feature) increases.



*Figure 4.1 Examples of different levels of social circumscription, as experienced by an individual village. Each village will record the proportion of patches occupied by other villages within the distance *village.range*, at each time step. The level of experienced social circumscription is the average proportion of occupied land across every village for each time step. Note: this is not the same as the total number of villages because villages may share neighbours.*

4.3.2 Social circumscription in combination with physical environmental and resource variation

No environment in this world is completely uniform. In the verbal formulations of the circumscription hypothesis, Carneiro suggests that social circumscription will be felt more keenly where environmental conditions also restrict population expansion. That is, a growing population will reach the limits of how many people an area can support if that area is circumscribed by environmental barriers or by pockets of rich resources in an otherwise uniform landscape. In Chapter 3 we saw that areas with greater environmental and resource circumscription create conditions where social complexity is more likely to form, but only when villages could detect these circumscribing conditions. With a growing population, more villages will end up facing boundaries in the environment and are more likely to be hemmed in by other villages. To show

the extent to which villages are enclosed by the environmental conditions of their surroundings, I include a measure of 'experienced environmental circumscription'. This is a measure of the resource availability surrounding a village (as determined by the number of fertile compared to less fertile patches, and the difference in resources between the two land types). A village in a uniform and fertile environment will have an experienced environmental circumscription measure of zero; while a village surrounded by patches with fewer resources than an optimally rich patch will have a value closer to one (see Figure 4.2 for more information on how this measure is calculated). I predict that in model conditions where villages have a higher level of experienced environmental circumscription (where there are fewer fertile patches and greater difference in resources between the fertile and less fertile patches) villages will become clustered more quickly. The effects of environmental conditions and population clustering should increase as the population grows into the most resource-rich areas, and both should therefore result in a higher rate of hierarchy formation than in a less environmentally and socially circumscribed landscape.

However, given the results discussed in Chapter 3 on the difference between the concentrated and random patch environment, this prediction should be elaborated further. In Chapter 3 (see Section 3.5) we learned that whether villages are able to see or move closer to other villages makes a difference in the rate of hierarchy formation and the maintenance of any hierarchy that has formed. In a random patch environment where villages can be separated by large gaps of less fertile land, hierarchy formation is effectively limited to a smaller population size because not all villages in the world are aware of each other's existence. Given that population growth is also limited by the resources surrounding a village (see Section 4.4.1.4: a village is more likely to create another village if it can find an empty location which is richer in resources than if the only available patches are poorer in resources), the effects of environmental, resource, and social circumscription could be altered by the distribution of patches in the model world. A random environment where some of the more fertile patches are isolated from one another may therefore limit population growth, even though villages located on those islands of fertile patches are likely to experience a high level of social circumscription as the

population grows in the confined area. With this insight, I therefore predict that a highly environmentally and resource circumscribed, randomly distributed environment should result in a slower rate of hierarchy increase and lower overall hierarchy level than a highly environmentally and resource circumscribed uniformly distributed environment because of the smaller population size and isolation of clusters of villages in the former.

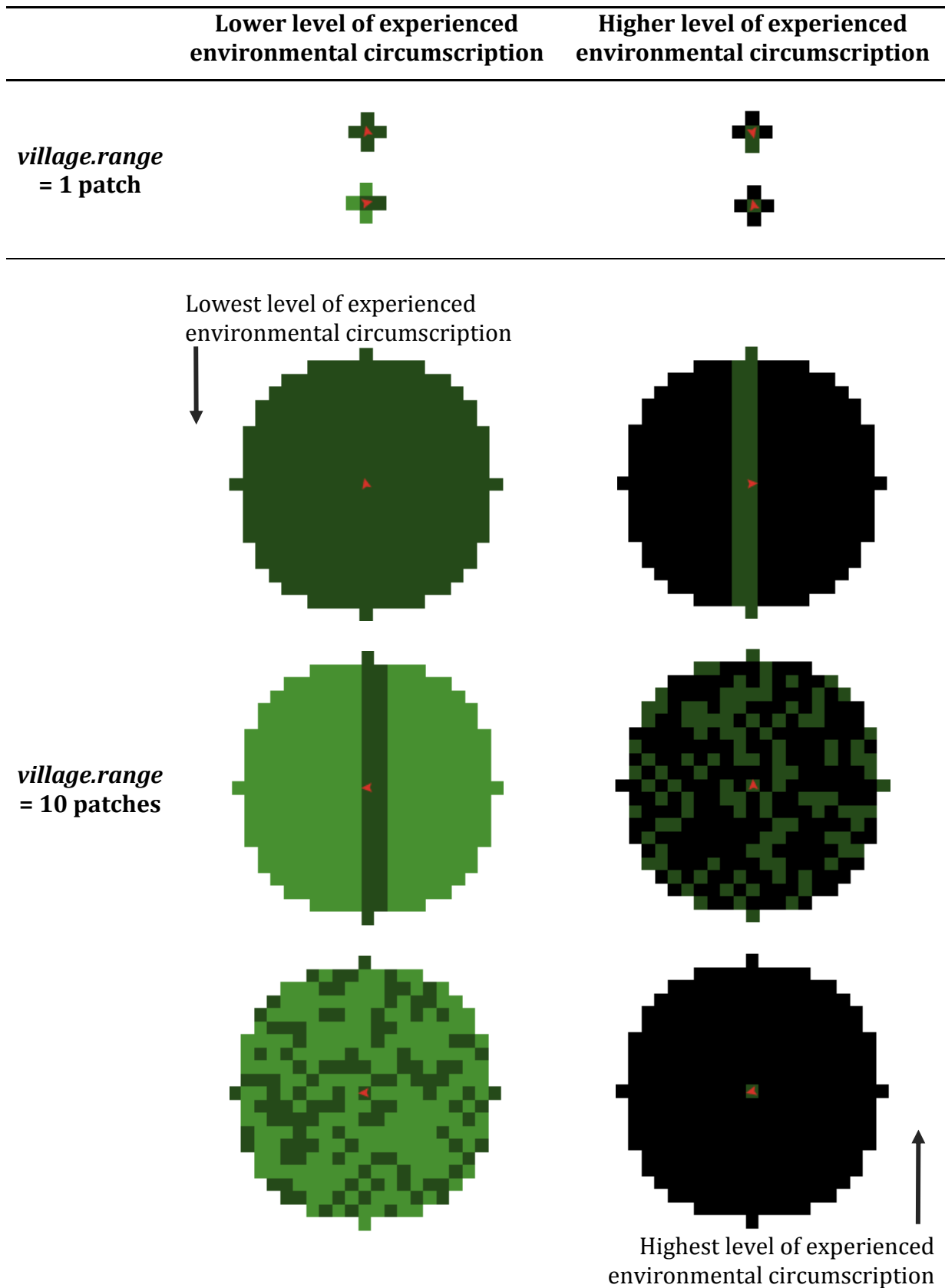


Figure 4.2 Examples of different levels of experienced environmental circumscription, as experienced by an individual village. Each village will calculate the sum of resources across all the patches visible within the distance *village.range*. The sum of visible resources is then compared to the maximum potential resources that would be possible if each of those patches had the maximum number of land-resources to give a measure of experienced

environmental circumscription. This measure combines the effect of both environmental circumscription (the number of more fertile patches) and resource circumscription (the difference in resources between the more and less fertile patches) as both affect the number of potential resources available. Note: this measure is not the same as the total resource of the whole model world because villages can share neighbouring areas. The average experienced environmental circumscription across all villages is taken for each time step. This provides a scale of experienced environmental circumscription from 0 (all surrounding patches are uniformly fertile, therefore there is no experienced environmental circumscription) to 1 (all surrounding patches have no resources, so the village is very highly environmentally circumscribed).

4.4 Methods

The agent-based model in this chapter builds on the work done in Chapter 3, using the software platform NetLogo (see Chapter 2, Section 2.3.1 for further discussion on modelling platforms). The model is used to run experiments to test the effect of social circumscription, both independent of and in conjunction with the effects of environmental and resource circumscription.

4.4.1 Model description

The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm *et al.*, 2006, 2010), and is continued in the Supplementary Materials 2 (Section 4.7.1).

4.4.1.1 Purpose of the model

This model has been developed to continue testing the logic of Carneiro's circumscription hypothesis on the emergence of social complexity from the model discussed in Chapter 3. This model includes the effect of population growth, and therefore population pressure, as well as environmental and resource circumscription. This model is intended to be a test of the full hypothesis proposed by Carneiro (1970, 2012a) in an abstract environment.

4.4.1.2 Entities, state variables and scales

The entities in this model are villages and patches, as described in Chapter 3, Section 3.4.1.2.

Table 4.1 List of the state variables (or attributes) of villages and patches. The attributes listed in this table are the same as those in Chapter 3 (Table**), except those marked with an (*) which are either new or updated from the previous model to allow population growth.

State variables	Value range	Purpose
villages		
<i>who</i>	1 to total number of villages	Unique village identification (' <i>who</i> ' as a label is specific to the NetLogo program)
<i>polity</i>	1 to total number of villages	Affiliation number shared by villages belonging to the same group to identify each polity and all the villages within it
<i>hierarchy</i>	1 to total number of villages	A positive integer indicating the level of hierarchy of the current village (1 = highest level, >1 means the village is subordinate to a village with the next highest rank within the polity). It is theoretically possible for all villages in the world to form one polity of a continuous chain of hierarchy, so the highest value of <i>hierarchy</i> can be the same as the population size, but in practice this is very unlikely.
<i>level-above</i>	<i>who</i> number range	The <i>who</i> number of the village ranked directly above the current village
<i>level-below</i>	<i>who</i> number range	The <i>who</i> number of the village ranked directly below the current village (see Chapter 3, Figure 3.1)
<i>resources</i>	0 - 100	The number of resources owned by the village, equal to the <i>land-resources</i> of the patch it is occupying
<i>defending</i>	true, false	Used to identify villages which are in the polity being attacked by another polity
<i>benefit-move</i>	0 - 100	Used by each village to calculate the potential gain in resources of moving away if defeated
<i>benefit-remain</i>	0 - 100	Used by each village to calculate the potential gain in resources of remaining in the same location and becoming subordinate. (<i>benefit-remain</i> = current <i>resources</i> - <i>tribute</i> cost)
<i>head-village</i>	true, false	To identify the highest-ranking village in a polity
<i>dominant-dying*</i>	true, false	If village dies, this will be labelled true, to facilitate identifying any subordinates of that village to be re-set as autonomous polities
<i>tag*</i>	true, false	To identify any subordinates of a village which is dying or rebelling, to facilitate re-labelling of those villages
<i>remaining-head*</i>	true, false	To identify the highest-ranking village of a polity, to distinguish that village from any potentially rebelling villages
<i>rebellng*</i>	true, false	To identify the rebelling village and its subordinates

<i>rebelling-head*</i>	true, false	To identify the village which is rebelling from a polity
<i>potential-rebels*</i>	true, false	To identify any subordinates below the <i>rebelling-head</i>
<i>hatching-new-village*</i>	true, false	To identify a village which will potentially create a new village, with the spatial range <i>splinter-location</i>
patches		
<i>land-resources</i>	0 – 100	Number of resources yielded by each patch, used to denote the fertility of the area
<i>village-claim</i>	<i>who</i> number range	<i>who</i> number of the village which is assessing the patch as a potential location to move to. This number assignment is necessary to avoid multiple villages selecting the same patch
<i>potential-escape</i>	true, false	To identify patches within a given radius of a village's current location which it can assess as a potential area to move to when defeated
<i>territory</i>	true, false	To identify patches within the <i>conquering.area</i> radius for a village to find rival neighbouring villages
<i>splinter-location*</i>	true, false	To identify patches within the radius <i>placement.distance</i> that a new village can potentially be placed on
<i>pxcor</i> and <i>pycor</i>	-20 to 21	Coordinates of each patch in the grid
arch-polities		
<i>whole-polity</i>	1 to total number of villages	Used to ensure that only one polity is attacking another at any given time and to identify all villages who share the same polity number (<i>whole-polity = polity</i>)
<i>target-polity</i>	true, false	To identify the polity being attacked
<i>attacking</i>	true, false	To identify the polity which is attacking another polity
<i>polity-villages</i>	true, false	To eliminate polities without any villages (the number of polities remains the same, but only those polities with villages can participate in the model)
<i>polity-resources</i>	Range depends on total number of villages and the total resources in the model world	Sum of <i>resources</i> of all the villages in the polity

Table 4.2 The parameters in the model, and parameter values used in experiments (see Section 4.4.1 for more detail, and Section 4.5 for results).

Purpose	Parameter	Values	Description
Fertile patch distribution	Distribution	Concentrated or random	The more fertile patches in a concentrated distribution are all adjacent to other fertile patches to form a continuous band. The width of this band is determined by the <i>land.width</i> parameter. The more fertile patches in a random distribution are allocated random locations anywhere in the model world. The number of more fertile patches is determined by the <i>number.fertile</i> parameter.
Social circumscription	<i>initial.villages</i>	50, 500	The number of villages at time step 0.
	<i>probability.grow</i>	0.1, 0.5	Each time step, every village will attempt to create a new village with the likelihood of <i>probability.grow</i> . A new village can only be created if there is available space within the radius <i>village.range</i> .
	<i>probability.death</i>	0	The probability that a village will become extinct. This parameter is set to 0 in all model runs here, but can be varied between 0-1.
	<i>village.range</i>	1, 10	The radius (in number of patches) that a village can 'see' to find rival villages (<i>conquering.area</i>), create a new village (<i>placement.distance</i>), or move to if defeated (<i>moving.distance</i>). The three parameters are separate in the model, but because they all determine the range of area that a village in the model is aware of, they have been varied together in these model experiments. Figure 3.5 in Chapter 3 shows how the range of patches that a village is aware of can increase by the radius number.

Environmental circumscription	<i>land.width;</i> <i>number.fertile</i>	<i>land.width</i> : 2 (high) or 39 (low); <i>number.fertile</i> : 82 (high) or 1599 (low)	The area of fertile land, implemented differently depending on whether distribution is concentrated or random. Concentrated High environmental circumscription: <i>land.width</i> = 2 (82 more-fertile patches in total); low environmental circumscription: <i>land.width</i> = 39 (1599 more-fertile patches in total). Random High environmental circumscription: <i>number.fertile</i> = 82; low environmental circumscription: <i>number.fertile</i> = 1599.
Resource circumscription	<i>resource.difference</i>	0.1 (steep), 0.9 (shallow)	The difference in resources between the more and less fertile patch types. This parameter is the proportion of resources yielded by the less fertile patches compared to the more fertile patches. Steep resource gradient: the less fertile patches contain 10% of the resources of the more fertile patches. Shallow resource gradient: the less fertile patches contain 90% of the resources of the more fertile patches.
Polity conditions	<i>tribute</i>	0.1	Proportion of resources owned by the defeated polity demanded by conquering polity
	<i>probability.fragment</i>	0.01	Probability of internal polity instability (1% chance of fragmentation)
	<i>probability.attack</i>	1	Chance that one polity will decide to attack another polity (100%), if a village belonging to a different polity is within <i>village.range</i> .
General setup	<i>step</i>	100 time steps	Time measured in steps (1 step = 1 complete run through the code by every agent)

4.4.1.3 Process overview and scheduling

Each time step allows every village to die or create a new village (see *population-growth* submodel), in a random order. When every village has run through the *population-growth* submodel, each polity will then run through the *battle-polities* submodel, before each polity then runs through the *fragment* submodel in a random order, as described in Chapter 3, Section 3.4.1.3. See the flow diagram in Figure 4.3 for a simplified illustration of these processes.

4.4.1.4 Submodels

Submodel 1: *population-growth*

Submodel 2: *battle-polities* (Chapter 3, Section 3.4.1.4.1)

Submodel 3: *fragment* (Chapter 3, Section 3.4.1.4.2)

The *population-growth* submodel determines the population dynamics of the model. Each village will potentially die, create another village, or remain as before, with the *probability.grow* parameter determining the likelihood that any of these decisions will be made (see Figure 4.3 for flow diagram of this submodel). Villages which die are removed from the model entirely and any subordinate villages will fragment into autonomous polities. However, in the experiments presented here, there is no likelihood of a village becoming extinct (*probability.death* = 0). This parameter was kept constant at zero because variations in population size or growth rate could be achieved through the *initial.villages* or *probability.grow* parameters, and this model remains abstract.

For the remainder of the *population-growth* submodel, each village will decide whether to create a new village or not. This decision is influenced by two factors: the availability of surrounding, unoccupied patches; and the potential resources of the new location. A patch can only be occupied by one village at a time. If all the surrounding patches that a village can ‘see’ are occupied by other villages, then it cannot create a new village. If there are available patches, the village will choose one of them, with preference for a patch with more resources (see Equation 3). In this model, there are only two types of patch: those with the maximum level of *land-resources* and those with less than the maximum *land-resources*. The difference between the *land-resources* of the two types of

patches is determined by the *resource.difference* parameter (see Table 4.2). The relative difference in resources between the more and less fertile patches is of importance here because this informs the decisions made by villages. The closer the *land-resources* of a patch is to the maximum potential *land-resources* of a fertile patch, the more likely the village is to interact with that patch (to either move to or create a new village on). The absolute value of *land-resources* of each patch is therefore less relevant to the village than the relative *land-resource* of that patch to any fertile patch.

If a patch is unoccupied, a new village will only be created with a likelihood in proportion to the resources available on that patch (Equation 4). If the chosen patch is rich in resources a new village will very likely be created. If not, then a new village is less likely to appear. The relative richness of resources is scaled compared to fertile patches, which have the maximum *land-resources*. The parameter *probability.grow* therefore only represents the highest possible growth rate and does not guarantee that the population will grow at all.

Equation 3:

$$\text{Probability of choosing a more fertile patch} = \frac{\text{total resources of only the most fertile patches visible to the village}}{\text{total resources of all patches visible to the village}}$$

Equation 4:

$$\text{Probability creating a new village} = \frac{\text{resources of the selected new location}}{\text{highest number of resources that a patch can yield}}$$

When all villages in the model have run through the *population-growth* submodel, and either died, created a new village, or done nothing, then each polity will begin the *battle-polities* submodel. For details on this submodel, and the subsequent *fragment* submodel, see Chapter 3, Section 3.4.1.4, Equations 1 and 2, and Figure 4.3 for a flow diagram of the sequence of processes.

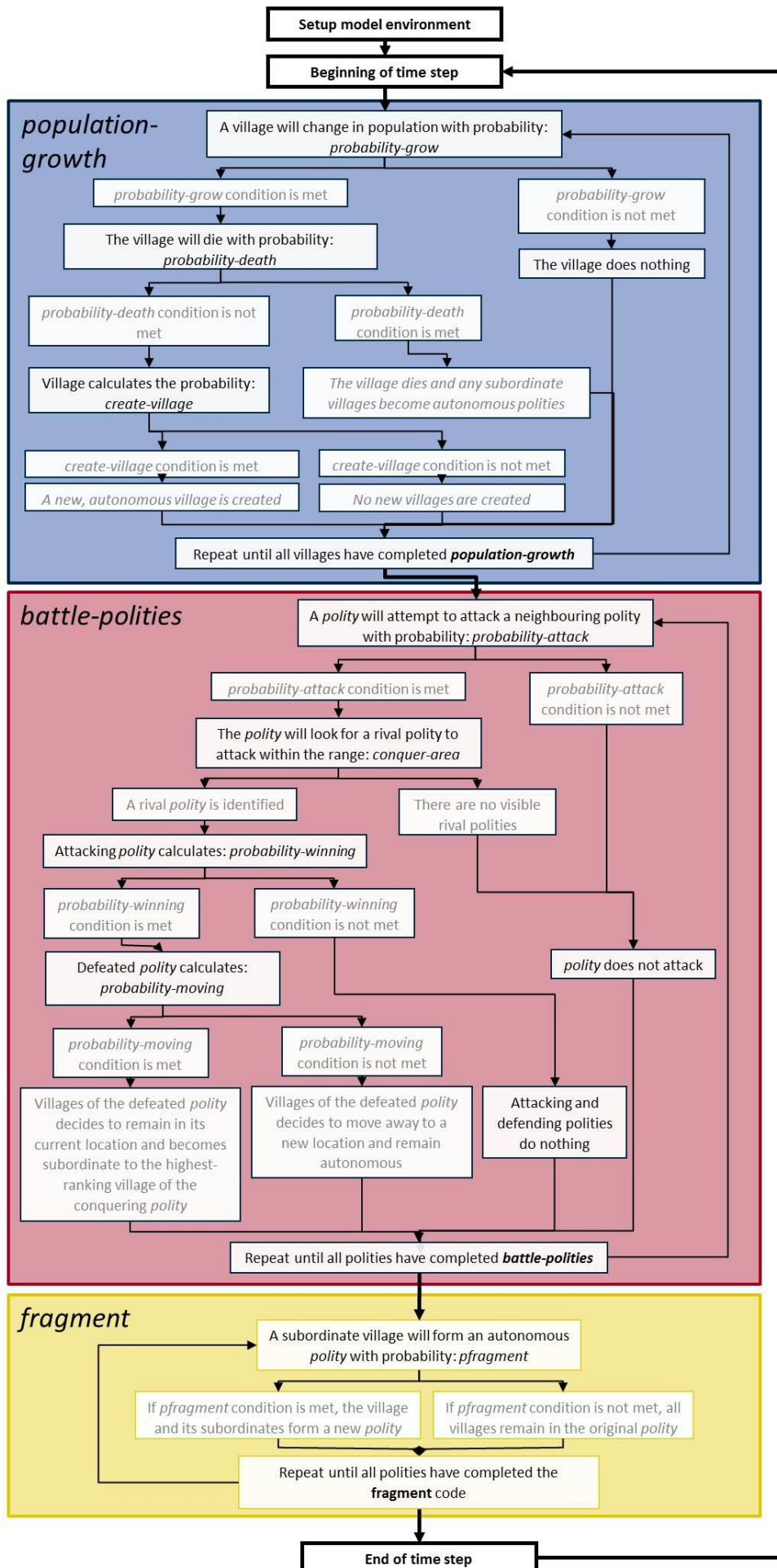


Figure 4.3 Simplified sequence of events in Model 2. The initialisation and beginning and end of the time step are in bold boxes. The population-growth submodel is indicated by the navy coloured background box, the battle-polities submodel is indicated by the rose coloured background box, and the fragment submodel is indicated by the yellow background box. Decision-making criteria are in black text. Potential decision outcomes for villages and polities are in light grey text (see Equation 1, Equation 2 (Section 3.4.1.4.1), Equation 3 (Sections 3.4.1.4.1 and 4.4.1.4), and Equation 4 (Section 4.4.1.4) for details on calculating the probabilities).

4.4.1.5 Model parameters

The parameters in this model can be grouped together by their purpose (see Table 4.2). Parameters which could potentially affect the level of experienced social circumscription by villages in the model (that is, the degree to which any village is surrounded by other villages) include: parameters which can influence the population size at a given time step (*initial.villages*, *probability.grow*, and *probability.death*); and the parameter which influences how far villages can see and move (*village.range*). The parameter *village.range* covers the distance that newly-created villages can move to (*placement.distance*), the distance that a village may consider moving to if defeated (*moving.distance*), and how far away villages are willing to search to find rival villages to attack (*conquering.distance*). A village may be willing to travel further to escape defeat than to initiate conflict, but here I assume that the distance a village is willing to act within is the same for each of these three parameters. I have therefore varied these parameters in conjunction as the *village.range* parameter, to reduce the parameter space investigated in this chapter.

Parameters which determine the environmental and resource conditions are: the distribution of patches (concentrated or random), the area of fertile and (*land.width* and *number.fertile*), and the difference in resources between the more and less fertile patches (*resource.difference*). These and the remaining parameters (*tribute*, *probability.fragment*, *probability.attack*, and time), remain as described in Chapter 3 (Section 3.4.1.5) (see Table 3.2).

4.4.2 Model predictions

4.4.2.1 Social circumscription without environmental or resource circumscription

The purpose of this model is to test the impact of social circumscription on the formation of social complexity. As discussed in Section 4.3, Carneiro suggests that increasing population pressure will lead to more warfare between groups, and that increasing population pressure will also create human barriers to movement if defeated in conflict. These two strands together constitute social circumscription, which can increase the chance of social complexity formation.

I have translated the assumptions of this hypothesis into two sets of parameters in this model which determine: the size the population can be at any given time point (*initial.villages* and *probability.grow*); and how clustered villages may be (*village.range*). The level of experienced social circumscription is calculated as the proportion of the land surrounding a village (within the *village.range*) that is occupied by other villages (see Section 4.3, Figure 4.1). I predict that the level of experienced social circumscription will increase as the population size increases, and therefore increase the rate of hierarchy formation. In addition, I predict that where villages are more clustered (when the *village.range* is small, see Table 4.2), this will lead to a higher rate of social circumscription when the population size is kept constant. This is because when villages are more clustered they are both more likely to find rival villages to attack and less likely to be able to move away to an unoccupied location.

4.4.2.2 Social circumscription in combination with environmental and resource circumscription

A landscape where population movement is limited by environmental conditions as well as neighbours could intensify the effect of population pressure. In these experiments I therefore vary parameters contributing to environmental, resource, and social circumscription. To test social circumscription I vary the parameters: *probability.grow* and *village.range* (as discussed in Section 4.4.1.5 above). The parameter *initial.villages* is not varied in these experiments because the population will grow with the maximum rate of *probability.grow*, and the population size (in number of villages) will be recorded with each time step. To test environmental circumscription I vary *land.width* and *number.fertile* in the

concentrated and random patch distribution layouts respectively (as discussed in Chapter 3, Section 3.4.2.1). The exact parameter settings are different to those used in Chapter 3 because the model world has been expanded to cover 41 x 41 patches (1681 patches in total) to facilitate comparison with archaeological data in Chapter 5, but still show comparable levels of high and low environmental circumscription with the settings in Chapter 3. To test resource circumscription I vary *resource.difference*, as discussed in Chapter 3 Section 3.4.2.1. The village distribution in Figure 4.4 shows the effect on population distribution from varying the range of village movement (*village.range*) within different environmental and resource circumscription conditions.

In Section 4.3.2, I discussed how social circumscription could amplify the effect of environmental and resource circumscription by increasing the number of villages who find themselves at a border of land type and limiting movement within more fertile land through population clustering. I therefore predict that, as in Chapter 3, the highest levels of hierarchy formation will occur where environmental and resource circumscription are also highest.

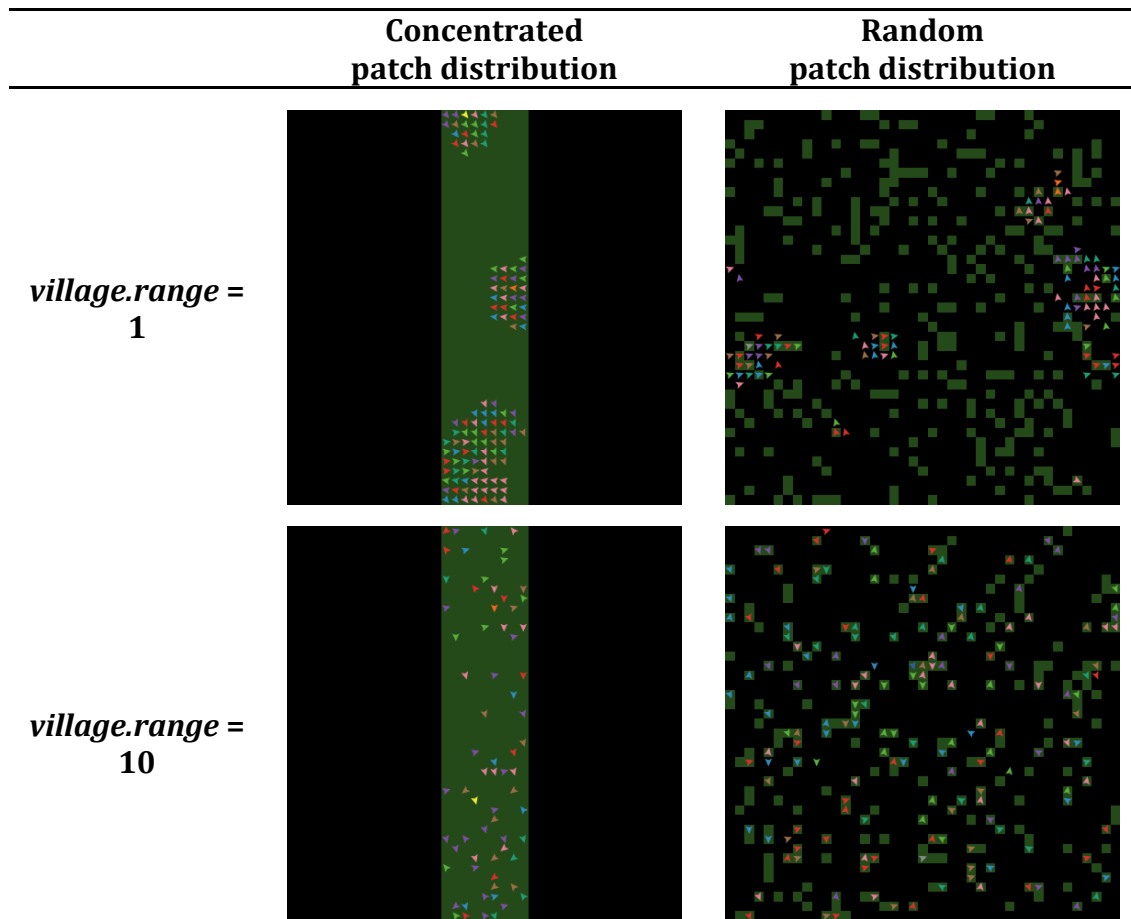


Figure 4.4 Example model landscapes showing how varying the distance that a village is aware of (*village.range*) can result in clustering or dispersal of villages (coloured triangles) in either a concentrated or random patch environment. In all of the model conditions shown here, the green patches are substantially more fertile than the black patches (*resource.difference* = 0.01), which means that villages will both preferentially move to and expand into green patches if available. In both the concentrated and random patch distributions, this means that when a village can only see the neighbouring four patches, the population will grow in clusters focused along areas of more fertile patches. Where villages can see further afield, there is still a preference for the more fertile patches but villages are much more likely to expand further in the random patch environment than in the concentrated environment.

4.5 Simulation experiments

The simulations run in this chapter are intended only to test the most relevant areas of the parameter space for investigating the effect of social circumscription on the formation of social complexity, and not a full parameter sweep. Justifications for the parameter settings used will be discussed for each of the experiments. A model run may stop before the 100 time step limit set here when the population reaches full capacity (every patch is occupied by a village). If this scenario occurs, nothing further will happen in the model, but the

final result (e.g. level of hierarchy) will be carried further through time until 100 time steps is reached.

The effects of the parameters *tribute*, *probability.fragment*, and *probability.attack* were tested in Chapter 3, Sections 3.5.2.1 and 3.5.4, I assume that their effects would be similar in this model and do not test them again here.

4.5.1 Experiment 1: Social circumscription with static population size

In the first set of experiments to test the effect of social circumscription in a uniform environment, all parameters were kept constant except for the number of *initial.villages* and the *village.range* (see Table 4.3). This is to allow an investigation of the effect of population size without adding population change over time, and thereby also control for population clustering as the population increases. In this model experiment, villages are spread out in a random location in each model run. As there are no areas of less fertile land, this means that a village can be placed anywhere in the model world. The *village.range* parameter therefore determines the distance a village is willing to move if defeated and how far a village is willing to search to find rival villages.

The parameters: *tribute*, *probability.fragment*, and *probability.attack* are not varied in these experiments, but see Chapter 3 (Sections 3.5.2 to 3.5.4) for information on their potential effect on the rate of hierarchy formation. Each experiment was run for 100 time steps and repeated for 100 iterations. Data points for each time step are displayed as translucent circles, and summarised among model runs as one standard error above and below the mean (darker coloured blocks).

Table 4.3 The parameter values for the first set of experiments testing the impact of population size independent of population growth on the rate of hierarchy formation. For more detail about each of the parameters, see Table 4.2.

	Parameter	Values
Environmental circumscription	<i>land.width</i> (concentrated distribution)	41
	<i>number.fertile</i> (random distribution)	1681
Resource circumscription	<i>resource.difference</i>	0
Population size	<i>initial.villages</i>	50, 500
	<i>village.range</i>	1, 10
	<i>probability.grow</i>	0
	<i>probability.death</i>	0
Polity conditions	<i>tribute</i>	0.1
	<i>probability.fragment</i>	0.01
	<i>probability.attack</i>	1

4.5.1.1 Experiment 1: results

The results from this experiment confirm the pattern observed in Chapter 3 (Section 3.5.2.3) that the larger the population size, the higher the overall level of hierarchy reached. Here, a population size of 500 (Figure 4.5, panel b) will tend to show a faster rate and higher overall level of hierarchy formation than a smaller population size (panel a). However, the prediction that reducing the *village.range* would result in a higher rate of hierarchy formation than a wider range is not supported. In both panels a and b where the range of village movement is wider (*village.range* = 10, pink) there is a much faster rate of hierarchy formation than when the range of village movement is smaller (*village.range* = 1, dark blue). In these conditions population clustering is not occurring through the *village.range* parameter because there is no population growth.

The second set of panels (Figure 4.5, panels c and d) add weight to the conclusions from panels a and b by showing that the larger the population size, the greater the level of experienced social circumscription. Simply put, the more villages there are in the world, the more likely a village is to be surrounded by other villages (see panels e and f to compare the difference in average number of visible rivals between the population sizes). The level of experienced social

circumscription remains predominantly stable over time because the number of villages does not change in these experiments.

This effect is reflected in both conditions of *village.range* (pink and dark blue lines), where the further a village can see, the greater the level of experienced social circumscription. In the third set of panels (Figure 4.5, panels e and f) we can see that increasing the range of village movement will increase the likelihood that a village will find a rival village to attack. This suggests that the effect of increasing *village.range* is being driven by the *conquering.area* parameter which increases the incidence of conflict and thereby increases the rate of hierarchy formation. These results are therefore not surprising and are reflected in the results discussed in Chapter 3 (Section 3.5.2).

From these graphs we can see that the wider the range of village movement, the more likely any village is to detect other villages when the population size remains constant. There is therefore also a higher chance that a village will detect a rival village from another polity to attack, which will increase the rate of hierarchy formation. The overall level of hierarchy reached is limited by the population size, which in these experiments is fixed.

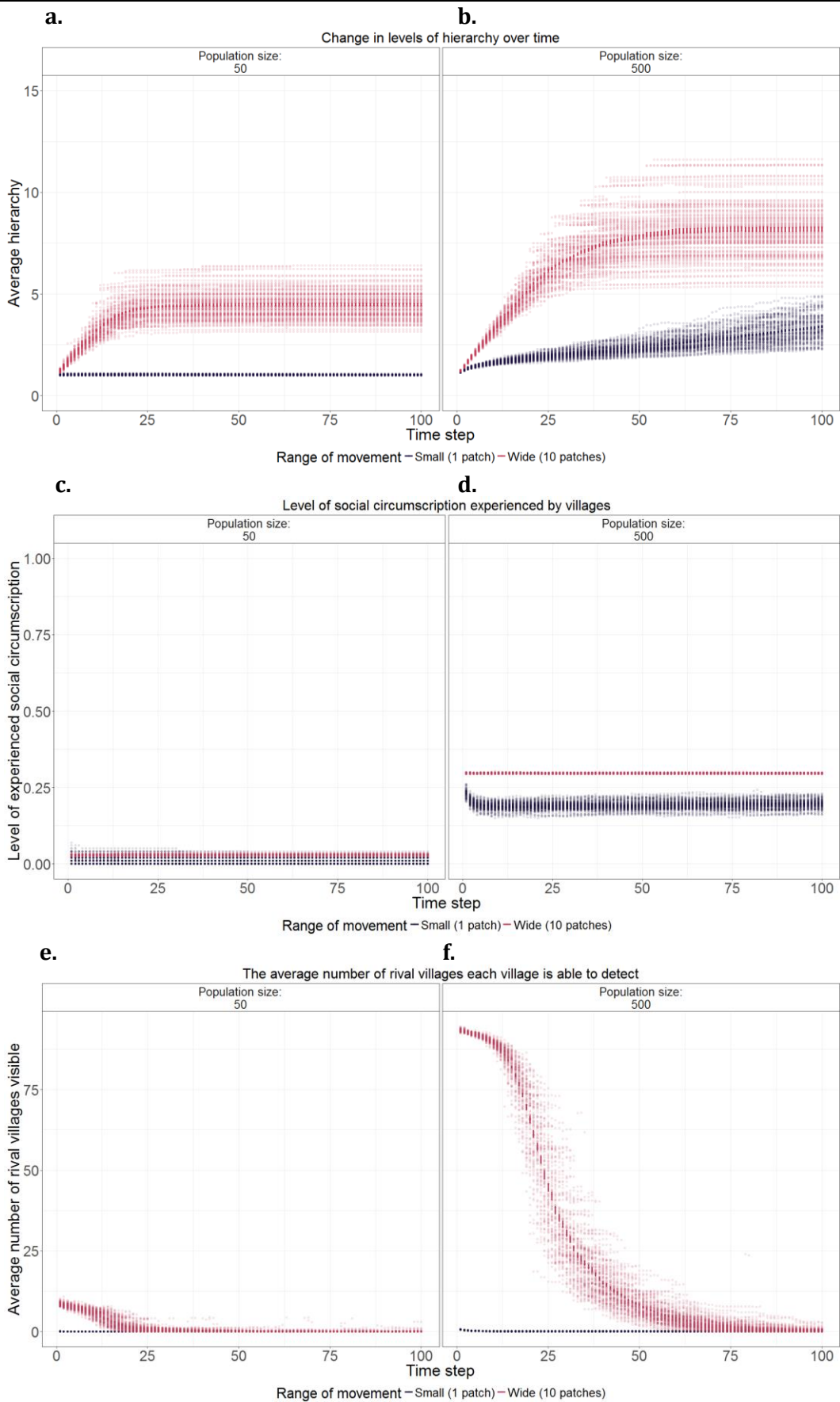


Figure 4.5 Graphs showing the effect of high population size (panels b and d) and low population size (panels a and c) on the rate of hierarchy formation (panels a and b), level of experienced social circumscription (panels c and d), and number of visible rivals (panels e and f) when the range of village

movement is high (*village.range* = 10, pink) and low (*village.range* = 1, dark blue). The level of experienced social circumscription is divided into five categories based on the proportion of patches surrounding a village that are occupied by other villages (see Figure 4.1). The results generally remain at one value over time here because the population size, and therefore the maximum proportion of occupied land, does not vary. The remaining parameters are kept constant (see Table 4.3). The average level of hierarchy and level of experienced circumscription between all villages is recorded for each time step (translucent circles) and summarised as one standard error above and below the mean (darker coloured block) for the 100 iterations of each experiment.

4.5.2 Experiment 2: Social circumscription with population growth

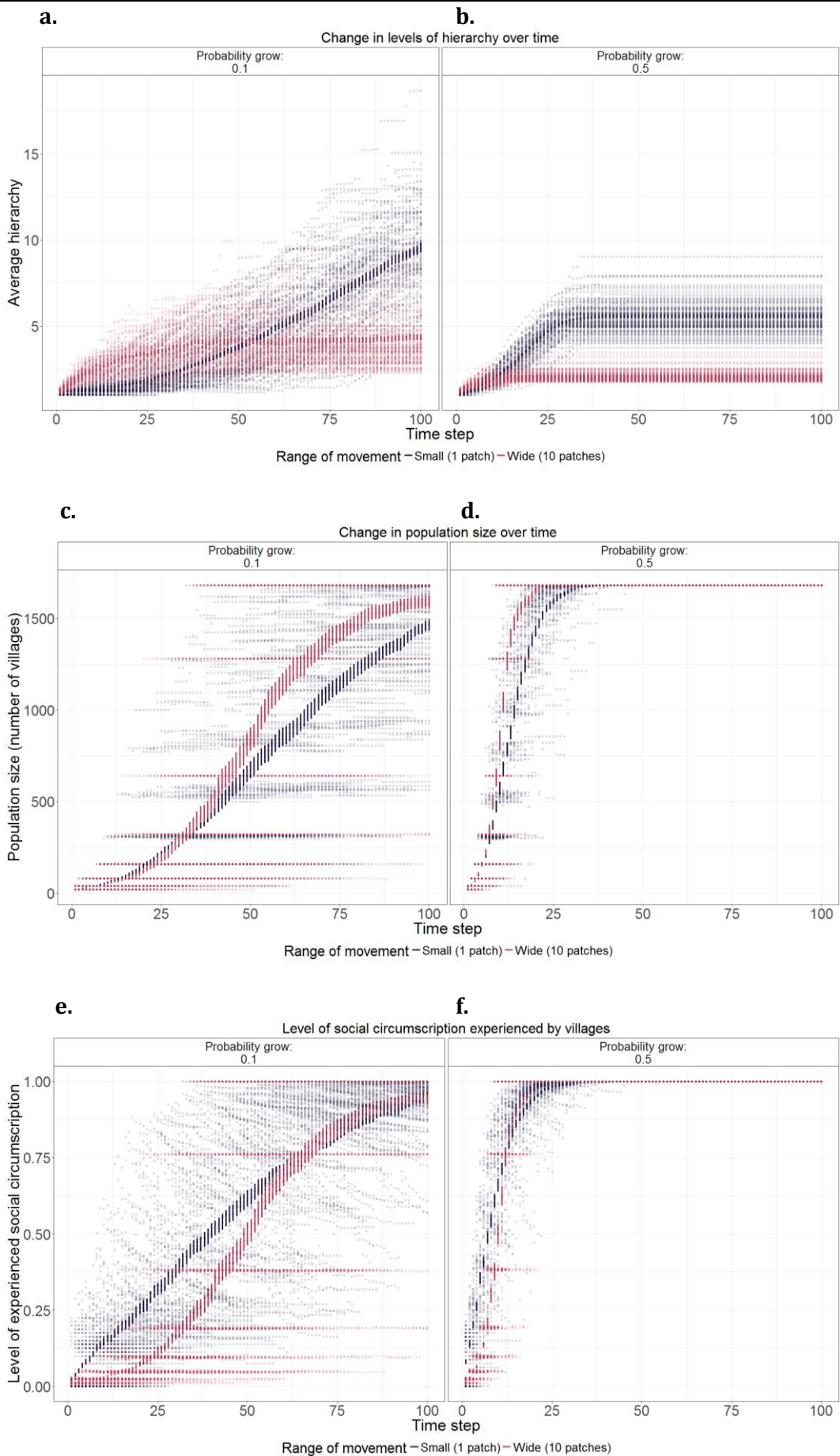
In the second set of experiments to test the effect of social circumscription in a uniform environment, the population is allowed to increase over time at a rate determined by the *probability.grow* parameter, while the starting population size (*initial.villages*) is kept constant. All other parameters remain as in the previous experiment (see Table 4.4). Experiments were run for 100 time steps and repeated 100 times.

Table 4.4 The parameter values for the second set of experiments testing the impact of population size and growth over time on the rate of hierarchy formation. The parameters to determine environmental circumscription (*land.width* and *number.fertile* in the concentrated and random layout of patches respectively) are set to ensure that all patches are the same in this experiment (the model world is 41 columns wide and consists of 1681 patches in total).

	Parameter	Values
Environmental circumscription	<i>land.width</i> (concentrated distribution)	41
	<i>number.fertile</i> (random distribution)	1681
Resource circumscription	<i>resource.difference</i>	0
Population size	<i>initial.villages</i>	10
	<i>village.range</i>	1, 10
	<i>probability.grow</i>	0.1, 0.5
	<i>probability.death</i>	0
Polity conditions	<i>tribute</i>	0.1
	<i>probability.fragment</i>	0.01
	<i>probability.attack</i>	1

4.5.2.1 Experiment 2: results

The four sets of graphs in Figure 4.6 correspond to the average level of hierarchy over time (panels a and b); the change in population size over time (panels c and d); the level of experienced social circumscription (panels e and f); and the average number of visible rival villages (g and h). Within each panel, the pink lines correspond to a wide area that villages can move (*village.range* = 10) and the dark blue lines are where villages can only move over a short distance (*village.range* = 1). The left-hand and right-hand panels correspond to different rates of population growth (in panels a, c, e, and g, *probability.grow* = 0.1, and in panels b, d, f, and h, *probability.grow* = 0.5).



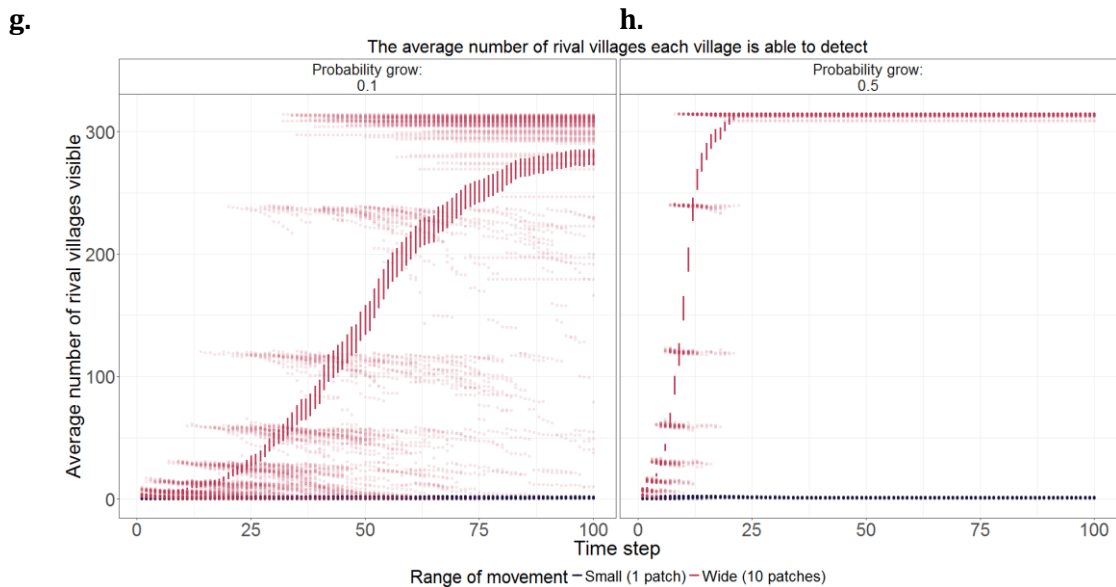


Figure 4.6 Graphs showing the effect of a low maximum population growth rate (probability.grow = 0.1, panels a, c, e, and g) and high maximum population growth rate (probability.grow = 0.5, panels b, d, f, and h) on average hierarchy (panels a and b), population size (panels c and d), level of experienced social circumscription (panels e and f), and the average number of visible rival villages (panels g and h) when the range of village movement is high (village.range = 10, pink) and low (village.range = 1, dark blue). The remaining parameters are kept constant (see Table 4.4). The average level of hierarchy, population size, and level of experienced circumscription between all villages is recorded for each time step (translucent circles) and summarised by one standard error above and below the mean (darker coloured block) among the 100 iterations of each experiment.

There are two main conclusions to draw from these results. Firstly, that increasing the rate of population growth will result in an increase in the rate of hierarchy formation (corresponding with the findings of Experiment 1, when the population size was set directly), but only until the population reaches the carrying capacity of the model world. Secondly, increasing the likelihood that a village will find a rival village to attack will increase the rate of hierarchy formation. These results support the circumscription hypothesis insofar as the size and degree of clustering (how close neighbouring villages are located to one another) of the population will affect the chance of conflict, and therefore the likelihood that social complexity will emerge. The results leading to each of these two main conclusions are discussed further below.

4.5.2.2 Population size

In Experiment 1 we saw that the larger the population size the faster the rate of hierarchy formation and the higher the overall level of hierarchy reached. In this experiment, the rate of population growth will increase the rate of hierarchy formation, but only until the carrying capacity of the model world is reached. In Figure 4.6, panel d, we can see that the population reaches carrying capacity within 25 time steps when the rate of population growth is higher (*probability.grow* = 0.5). In Figure 4.6 panel b, we can see a corresponding plateau in the overall level of hierarchy formation. This is because the model will stop recording further results when the population cannot increase any further. This does not necessarily mean that the level of hierarchy could not continue to increase if there is more than one polity present, but does mean that the population size is stable. When at carrying capacity, extensive computing power is required for every village to run through the model code each time step. For simplicity, I therefore artificially halt the model at carrying capacity. To understand the behaviour of the model, we must therefore look at the pattern of change before carrying capacity is reached.

In comparing the results of the first 25 time steps between the low and high population growth conditions (Figure 4.6 panel a and b), we can see that the rate of hierarchy formation is higher when the rate of population growth is higher, if the range of village movement is small (1 patch distance, dark blue lines). This aligns with the results seen in Experiment 1, which show that increasing the size of the population will increase the rate of hierarchy formation. This pattern is also reflected in the level of experienced social circumscription (Figure 4.6 panel f), which shows that villages become more circumscribed by other villages more quickly when the rate of population growth is faster (compare panels d and f showing high population growth rate with panels c and e showing the low population growth rate). This supports the general prediction (Section 4.3) that increasing population pressure would result in a greater likelihood of social complexity formation.

4.5.2.3 Incidence of conflict

In Experiment 1, we also saw that increasing the distance that villages could see and move would increase the rate of hierarchy formation. The range that

villages can move determines three aspects of village behaviour: the distance from their original location that they can move to if defeated; the distance that villages can search to find an unoccupied patch to place a new village; and the distance that villages can 'see' to detect rival villages. In Chapter 3 (Section 3.5.2.2), we saw that the distance villages could 'see' to find rival villages had an effect on the rate of hierarchy formation. A similar effect on the chance of conflict between villages is likely occurring here.

To assess this pattern, I focus here on the slow population growth rate condition where the population size does not reach carrying capacity (panels a, c, e, and g). In panel a, we can see that the rate of hierarchy formation is indeed higher when villages can see further away (pink line), but only within the first 25 time steps. This initial difference in hierarchy formation between the two *village.range* conditions is not due to a difference in the rate of population growth (see the first 40 time steps of panel c), but may be explained by the difference in the number of visible rivals (see panel g). When villages can the *village.range* = 10, villages can immediately see more rivals than if the *village.range* = 1 (panel g, compare pink and blue lines). This difference rapidly escalates with an increase in population size over time (panel c), but is not immediately reflected in difference in the level of experienced social circumscription. This may be because even though more rival villages are visible if the *village.range* is wider, so are more potential patches to escape to if defeated. So far these results are consistent with those discussed in Experiment 1 (Section 4.5.1).

In both conditions of *village.range*, an increase in population size will increase the level of experienced social circumscription (compare Figure 4.6, panels c and e), if the population is allowed time to grow. Any new villages created will be located within the range that the original village can search for rival villages. As the newly-created villages are autonomous, an increase in population size will therefore also increase the number of rival villages to attack. This may explain why the level of experienced social circumscription is similar between the two conditions of *village.range* after around 60 time steps (see Figure 4.6, panel e, pink and dark blue lines). The lower level of experienced social circumscription for the first 60 time steps when *village.range* = 10 may be explained by the greater number of villages required to proportionally fill the

area that a village can 'see' (see Figure 4.1). However, the overall level of hierarchy reached is much lower when villages can see further (*village.range* = 10, pink line, panel a) than when they cannot. There are two potential explanations for this pattern. Firstly, the carrying capacity of the model is more likely to be reached if villages can see further away (*village.range* = 10, panel c, pink dots), because any unoccupied patches are more likely to be found. When this occurs, the model will stop, even if villages do not all belong to the same polity and the potential for further increase in the levels of hierarchy is still present. Secondly, when villages can see further afield (*village.range* = 10), any conquered villages are more likely to be found before population size has grown. This means that polities are more likely to form with only shallow levels of hierarchy, particularly as the model may stop before all polities have subsumed one other. When villages can only see one patch away (*village.range* = 1), there is more opportunity for deeper levels of hierarchy to form. Villages within isolated clusters may conquer one another before then conquering (or being conquered by) a potentially equally-sized polity from another cluster if they come into contact through population growth.

These results partially support the original social circumscription hypothesis (Section 2.4.1). Increasing population pressure through increasing population size can result in a higher level of experienced social circumscription and a faster rate of hierarchy formation, but only if villages can detect one another. In a uniform environment, such as the ones modelled here, the crucial factor is whether villages can find one another to attack. The chance of a village finding another rival is greatly increased if villages are less clustered, not more, at the start of the model experiment. This is counter to the prediction that a higher level of clustering will increase the level of experienced social circumscription and therefore increase the rate of hierarchy formation (Section 4.3). However, as the population grows, villages are more likely to be completely surrounded by other villages if their range of movement is smaller. The effect of social circumscription through population clustering does therefore increase the chance of conflict as more villages are able to find rival villages, but only with enough time for the population to grow sufficiently. From these experiments, I conclude that hierarchy will be more likely to form the less isolated villages are,

whether by increasing the population size or increasing the distance that villages can move and see.

The original circumscription hypothesis also suggests that where villages are more clustered through the conditions of the surrounding landscape, social complexity is more likely to form. An area limited by geographical barriers such as mountains or desert may not have the same even distribution of villages as has been modelled in this and the previous experiment. In the following experiment, I include the effects of environmental and resource circumscription with population growth over time.

4.5.3 Experiment 3: social circumscription in combination with environmental and resource circumscription

In the third set of experiments, population size is allowed to increase over time (as in Experiment 2), but within varying conditions of environmental and resource circumscription (as in Chapter 3). Each experiment includes a high and low setting for environmental circumscription (the area of fertile land, as determined by the *land.width* and *number.fertile* parameters in the concentrated and random distribution of patches respectively) and resource circumscription (*resource.difference* between the more and less fertile patches) (see Table 4.5). This means that there are eight different model worlds in this experiment, each run with both a high and low population growth setting, and a small and wide range of village movement (*village.range*) (see Figure 3.4 in Chapter 3 for an illustration of the model worlds). Experiments were run for 100 time steps and repeated 50 times.

*Table 4.5 The parameter conditions tested for each parameter in Experiment 3. The parameters *land.width*, *number.fertile*, *resource.difference*, *village.range*, and *probability.grow* were varied in all experiments. The remaining parameters (*initial.villages*, *probability.death*, *tribute*, *probability.fragment*, and *probability.attack*) were kept constant between all experiments.*

	Parameter	Values
Environmental circumscription	<i>land.width</i> (concentrated distribution)	2, 39
	<i>number.fertile</i> (random distribution)	82, 1599
Resource circumscription	<i>resource.difference</i>	0.1, 0.9
Population size	<i>initial.villages</i>	10
	<i>village.range</i>	1, 10
	<i>probability.grow</i>	0.1, 0.5
	<i>probability.death</i>	0
Polity conditions	<i>tribute</i>	0.1
	<i>probability.fragment</i>	0.01
	<i>probability.attack</i>	1

4.5.3.1 Experiment 3: results

There are five sets of results showing the average hierarchy level, population size, experienced social circumscription, experienced environmental circumscription, and the average number of rival villages. These results are divided into groups (see Figure 4.7 for reference): the concentrated patch distribution conditions are shown in Group 1 and Group 2, and the random patch distribution in Group 3 and Group 4. A slower population growth rate (*probability.grow* = 0.1) is shown for both the concentrated and random conditions in Group 1 and Group 3 respectively, while a faster population growth rate (*probability.grow* = 0.5) is shown in Group 2 and Group 4. Within groups there are four panels. Low and high settings for the range of village movement (*village.range* = 1 or 10) are varied between rows. Low and high settings for the severity of resource circumscription (*resource.difference* = 0.1 or 0.9) are varied between columns. Every graph also shows high and low settings for environmental circumscription (*land.width/ number.fertile*), with high environmental circumscription in purple and low in green. Data points are recorded for each time step (translucent points) and summarised between iterations by standard error bars above and below the mean (darker blocks).

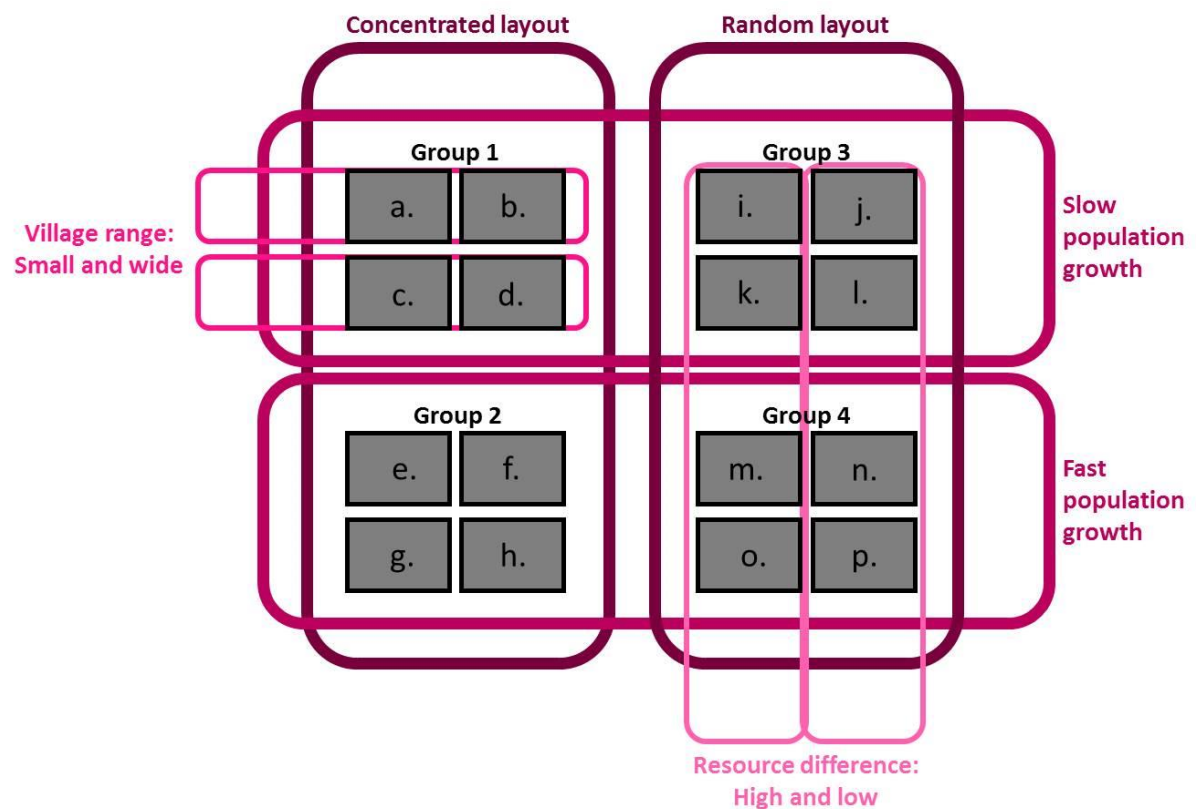


Figure 4.7 A diagram to show the organisation of the results graphs for Experiment 3. Each grey rectangle represents one graph (panels a - h). This layout is repeated for five sets of results: average hierarchy formation, population growth, experienced social circumscription, and experienced environmental circumscription in Figures 4.8 to 4.12.

The results from this experiment show that the rate of hierarchy formation corresponds with the likelihood that villages can detect one another, but that the means by which proximity is increased between villages is variable between different model conditions. The effect of population growth and population crowding by environmental conditions will be described in more detail for each group.

In all groups, the average level of hierarchy will reach a plateau after fewer time steps when the rate of population growth is faster (*probability.grow* = 0.5, Figure 4.8, Groups 2 and 4) than when the rate of population growth is slower (*probability.grow* = 0.1, Figure 4.8 Groups 1 and 3). By comparing the population size over time in Groups 2 and 4 with the population size in Groups 1 and 3 (Figure 4.9), we can see that the early curtailing of hierarchy formation is due to the carrying capacity of the model world being reached more rapidly

when the population grows more quickly (as also shown in the results of Experiment 2, Section 4.5.2). We may therefore assume that in a limitless model world, the increase in hierarchy level seen before any plateau is reached would continue in a similar pattern. For the results of this section I will therefore focus on the patterns observed before the population reaches carrying capacity.

Average hierarchy

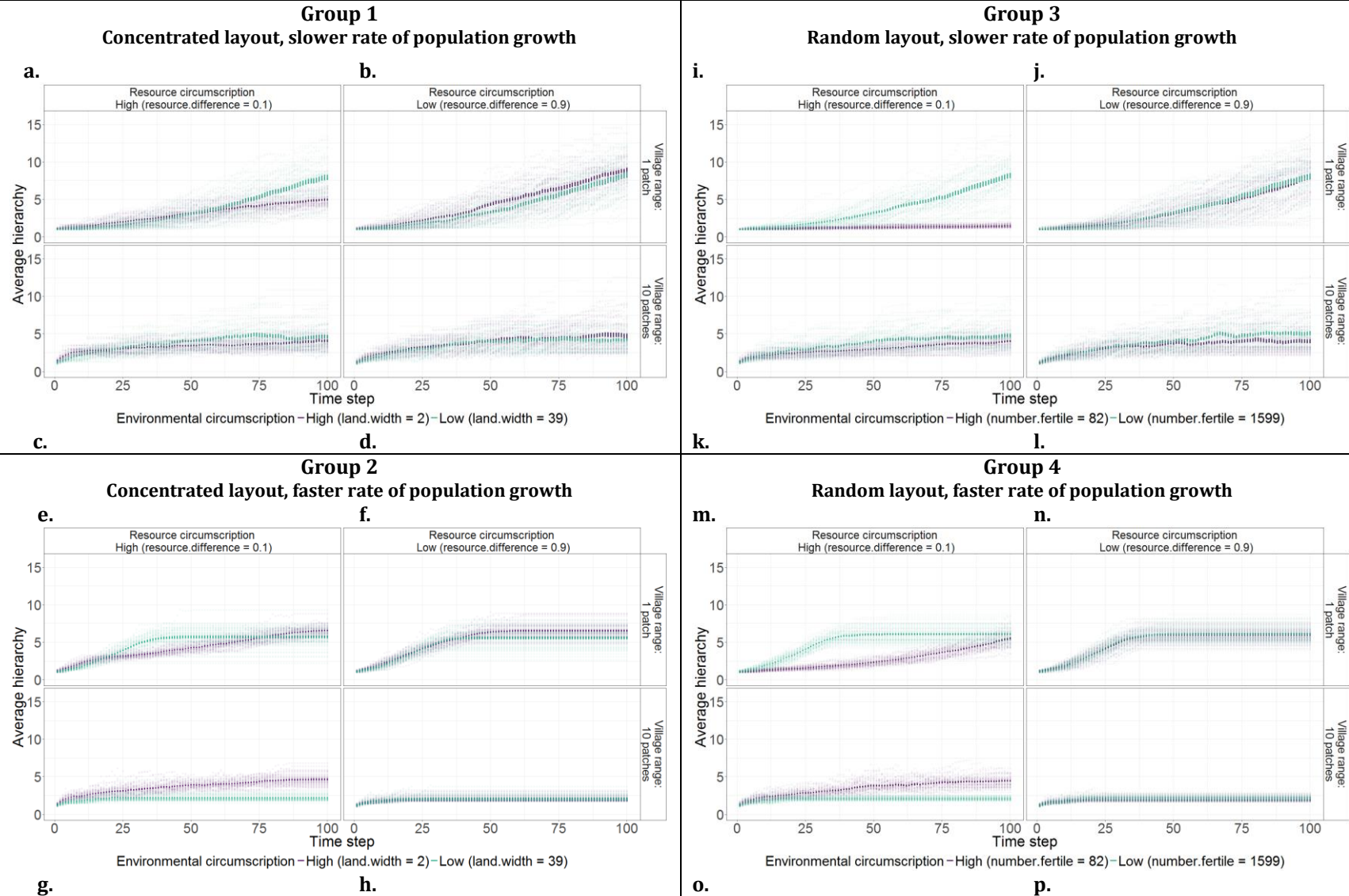


Figure 4.8 The average level of hierarchy reached in the different model conditions of Experiment 3, Groups 1 to 4 (see Figure 4.7 for a reference diagram).

Population size

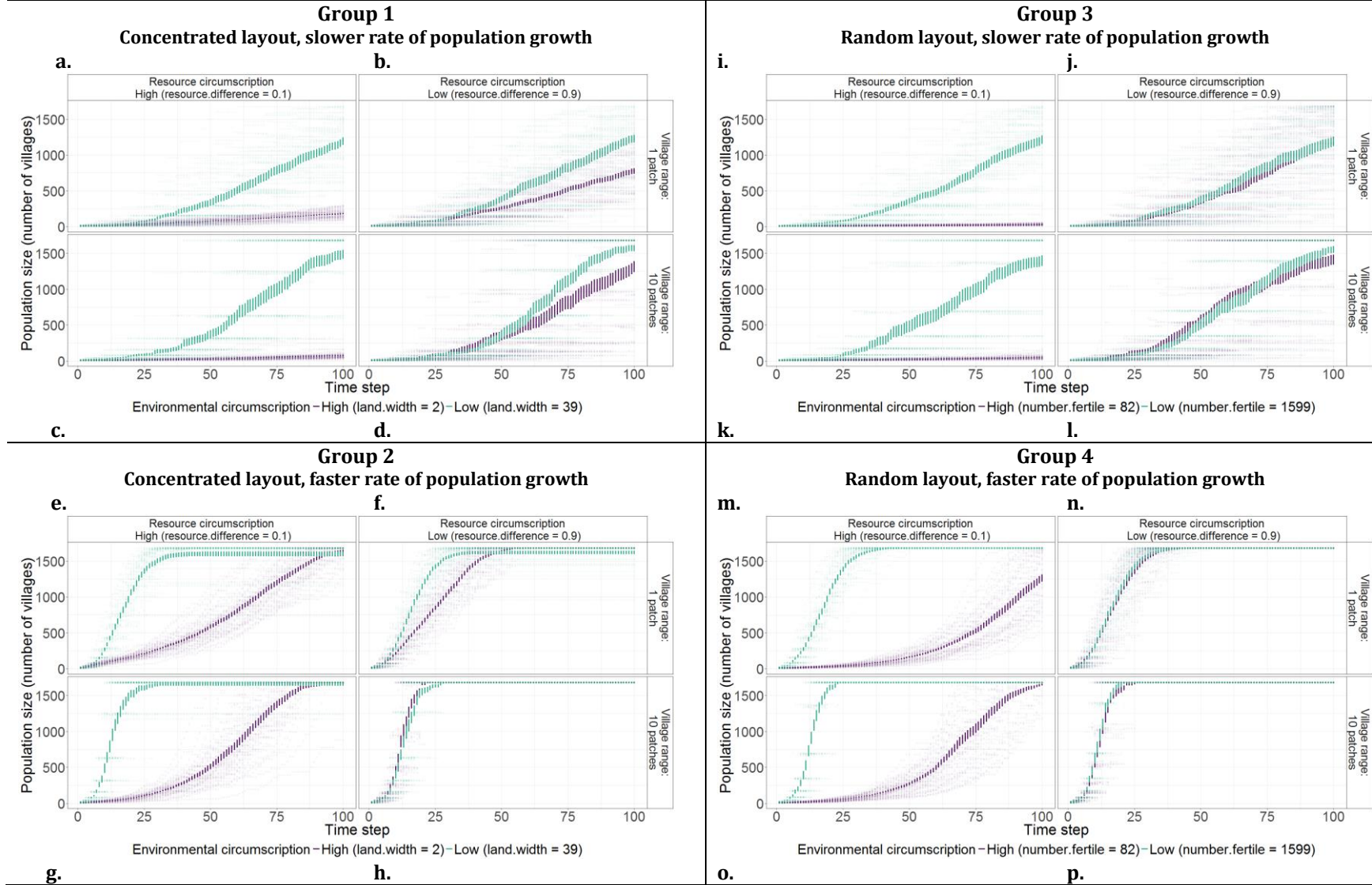


Figure 4.9 The population size reached in the different model conditions of Experiment 3, Groups 1 to 4 (see Figure 4.7 for a reference diagram).

Experienced social circumscription

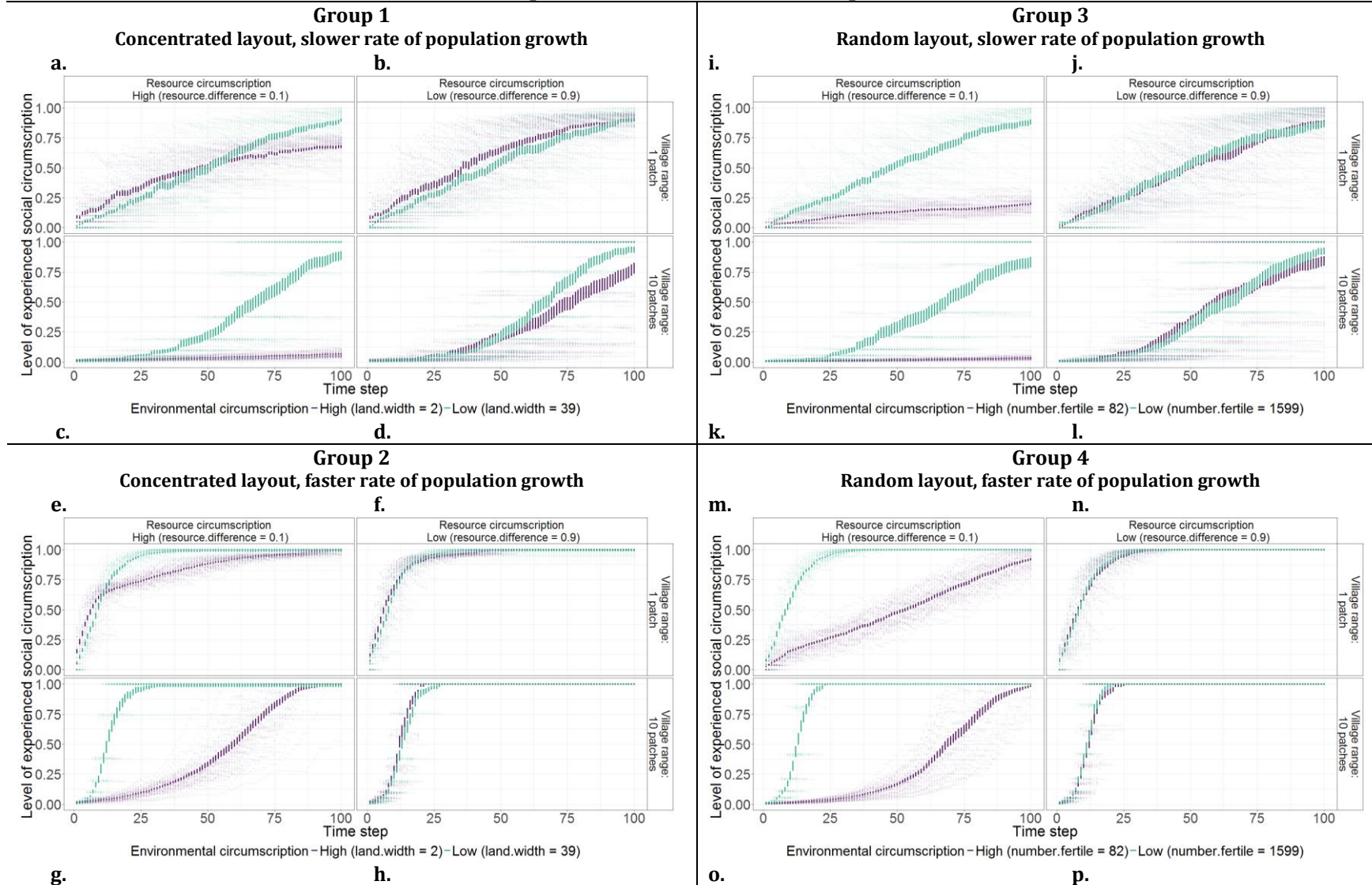


Figure 4.10 The level of experienced social circumscription (see Figure 4.1) in the different model conditions in Experiment 3, Groups 1 to 4 (see Figure 4.7 for a reference diagram).

Experienced environmental circumscription

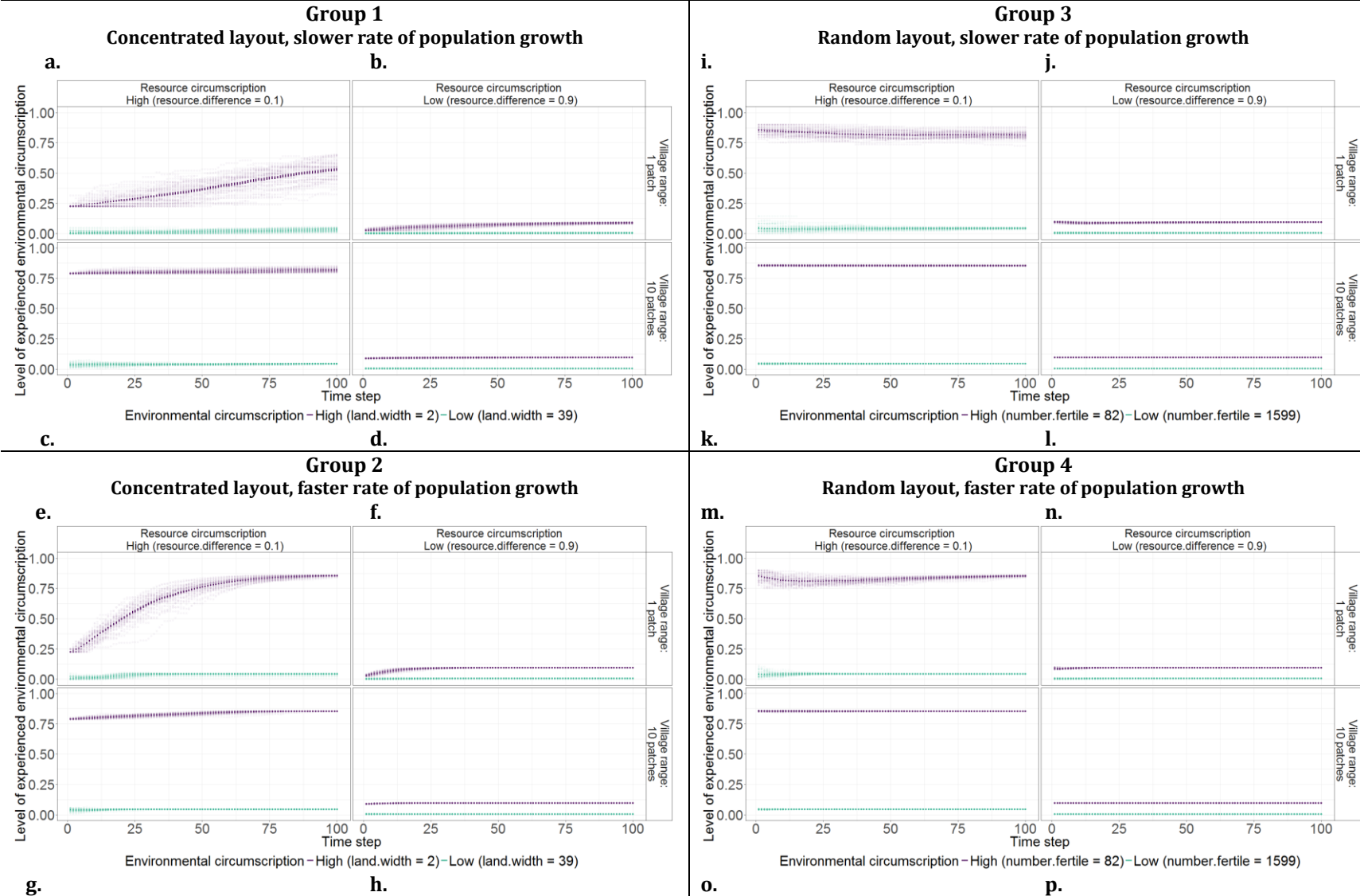


Figure 4.11 The level of experienced environmental circumscription (see Figure 4.2) in the different model conditions in Experiment 3, Groups 1 to 4 (see Figure 4.7 for a reference diagram).

Average number of visible rival villages

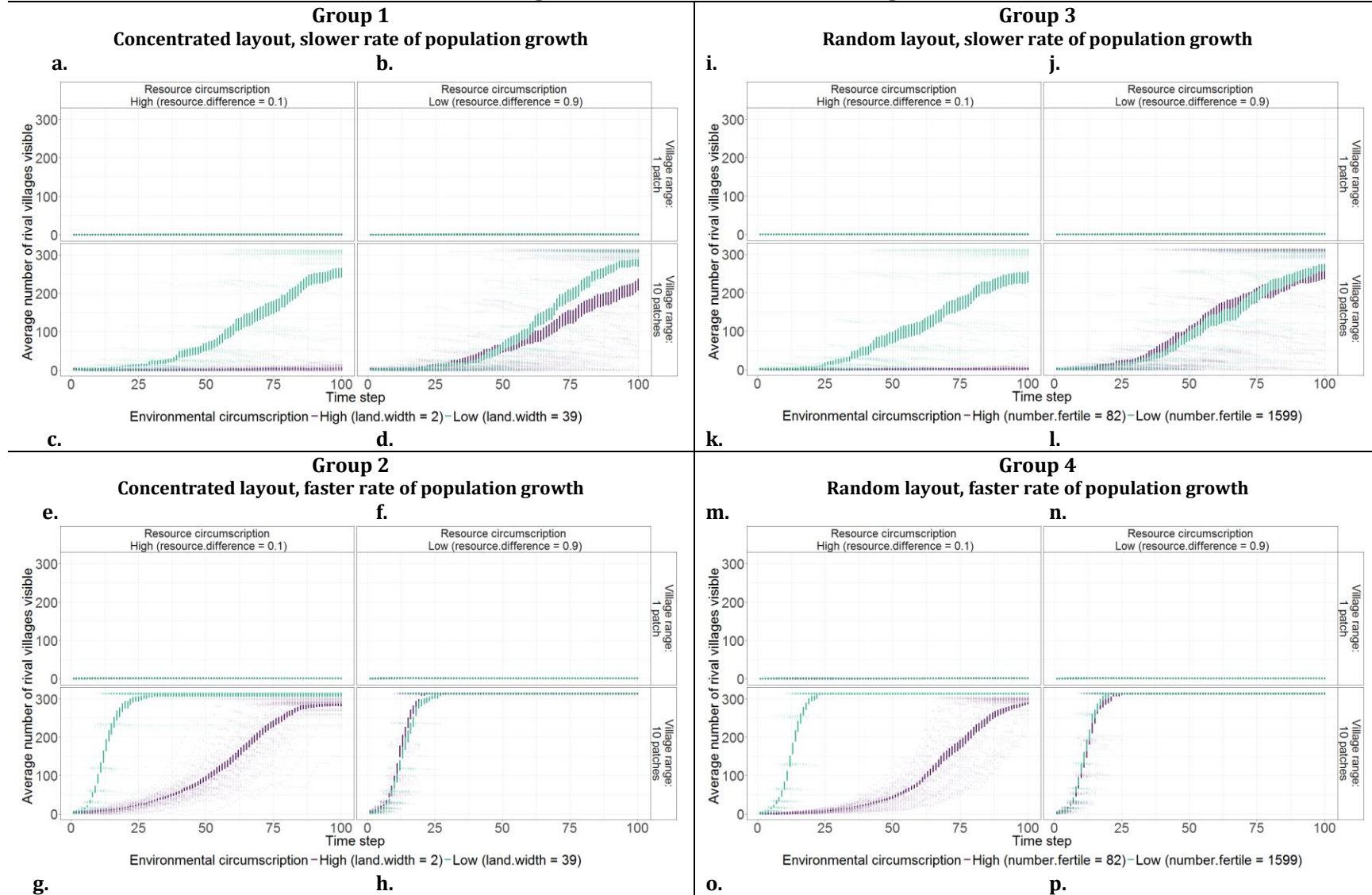


Figure 4.12 The average number of visible rival villages in the different model conditions in Experiment 3, Groups 1 to 4 (see Figure 4.7 for a reference diagram).

4.5.3.2 The effect of population growth on the rate of hierarchy formation overrides the effect of environmental and resource circumscription

The results from both Experiment 1 and Experiment 2 suggest that the faster the rate of population growth, the more likely a village is to find a rival village to attack, and the faster the rate of hierarchy formation. This conclusion is supported by around half of the results from Experiment 3, summarised in Figure 4.13. Model conditions in which this statement is true are highlighted in orange. In all these cases, the population size is determined by the resource availability. Where there is a difference in the rate of hierarchy formation, it is the less environmentally circumscribed (and therefore more resource-rich) conditions which allow for more rapid hierarchy formation (panels i, k, and m). Where the difference in resources between the more and less fertile land is small (Figures 4.8 and 4.9, panels f, h, j, l, n, and p), there is very little difference in either the rate of population growth or rate of hierarchy formation between the different levels of environmental circumscription (purple and green lines). The availability of resources is similar in both conditions of environmental circumscription, leading to a similar rate of population growth. These observations are reflected in the level of experienced social circumscription (corresponding panels in Figure 4.10) and average number of rival villages (corresponding panels in Figure 4.12). The greater the population size, the higher the level of experienced social circumscription and the higher the number of visible potential rival villages at any given time point.

The results showing a faster rate of hierarchy formation in less environmentally circumscribed areas seen in the orange panels (Figure 4.13) may seem counter to the original circumscription hypothesis. The circumscription hypothesis suggests that increasing the level of environmental circumscription should increase the likelihood of social complexity formation (see Chapter 1, Section 1.5; Chapter 3 Section 3.3.2; and this chapter Section 4.3.2). In these orange panels, reducing the level of environmental circumscription instead increases the rate of hierarchy formation. However, by looking at (Figure 4.11), we can see that there is a consistently higher level of experienced environmental circumscription in the high environmental circumscription conditions (purple line). In line with the original circumscription hypothesis, we might expect a higher rate of hierarchy formation in the high environmental circumscription

conditions. This is not the case for the model conditions of the panels highlighted in orange discussed here (Figure 4.13). The effect of environmental circumscription in these panels (orange, Figure 4.12) must therefore be overridden by the effect of population increase. Even though these results do not support the environmental circumscription hypothesis, the suggested process of population pressure leading to an increased incidence of warfare and increased the likelihood of social complexity formation (Carneiro, 1970, 2012a; see Section 4.3) is supported by these results. The importance of population size, and therefore of population growth, when the availability of resources between model environments is fairly uniform, is consistent between Experiments 1, 2, and 3.

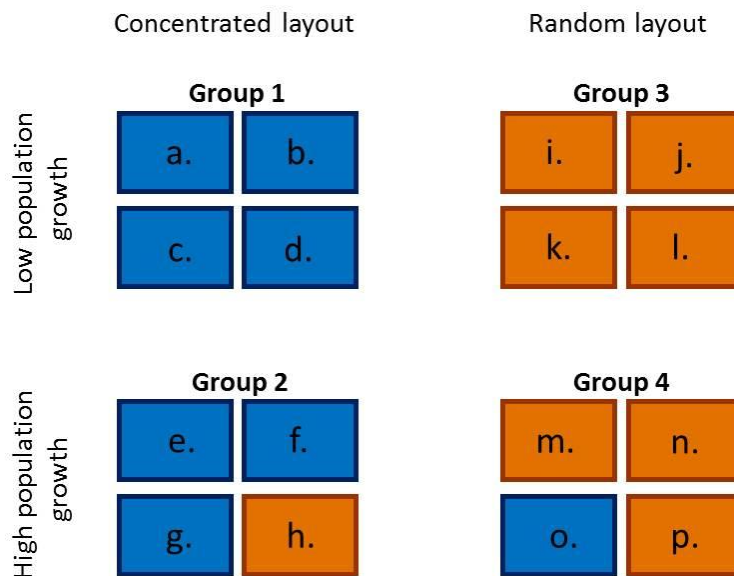


Figure 4.13 Summary diagram of the results from Experiment 3. Each panel refers to the corresponding panel in Figure 4.7 and results in Figures 4.8 to 4.12. The panels coloured in orange show model results in which the rate and overall level of hierarchy reached (shown in Figure 4.8) correlates with the rate of population growth (shown in Figure 4.9). Panels coloured in blue show model results which are better explained by the level of experienced environmental or social circumscription than the rate of population growth.

4.5.3.3 The effect of population crowding in conditions of high environmental and resource circumscription also affects the rate of hierarchy formation

Despite the importance of population size for the formation of hierarchy in the model, population size alone does not predict the rate of hierarchy formation in all model environment conditions (see panels highlighted in blue in Figure 4.13).

In half of the results (blue panels, Figure 4.13), population size does not directly correspond with the rate of hierarchy formation. In Groups 1 and 2 (concentrated patch distribution with low and high population growth rates) the rate of hierarchy formation in the high environmental circumscription condition (Figure 4.8, purple line) is roughly equivalent to the low environmental circumscription condition (Figure 4.8, green line), despite a much higher rate of population growth in the low environmental circumscription condition (Figure 4.9, compare green with purple lines).

To explain the pattern of hierarchy increase over time beyond the effect of population size, we must therefore include the level of experienced social circumscription (corresponding panels in Figure 4.10). In panels a and b (Figure 4.10), there is a higher level of experienced social circumscription than would be expected based on the population size alone. In these results, the population size increases much more quickly in the low environmental circumscription condition (green line) but there is very little difference in the level of experienced social circumscription between the high and low environmental circumscription conditions (Figure 4.10, panels a and b, purple and green lines). This is likely due to a crowding effect of the concentrated environmental layout. Villages in the concentrated patch layout are all placed within the same, continuous band of more fertile patches. When that band is narrower (the high environmental circumscription condition, Groups 1 and 2, purple line), the villages are initially placed much closer together. This will immediately increase the level of experienced social circumscription before any population growth has occurred (Figure 4.10, panels c and d).

The results in panel a are key in interpreting these results. The level of experienced social circumscription in panel a (Figure 4.10) starts higher in the high environmental circumscription condition (purple line), but is overtaken by the low environmental circumscription condition (green line) after around 70 time steps. To explain this cross-over, we can turn to the population growth results (Figure 4.9, panel a), where we can see that the population size in the low environmental circumscription condition (green line) begins to increase much more rapidly than the high environmental circumscription condition (purple line) after around 60 time steps. In these results we can therefore detect both the effect of environmental circumscription and population size on the level

of experienced social circumscription. Both of these effects combined result in very little difference in the increase in hierarchy formation between the high and low environmental circumscription conditions (Figure 4.8, panel a, purple and green lines), but does explain why the population size alone does not predict the level of hierarchy formation.

4.5.3.4 A concentrated layout of more fertile patches is more likely to increase initial village crowding in conditions of high environmental and resource circumscription

The effect of the layout of patches is important to highlight here. In panel a, the more fertile patches are distributed in a continuous band, whereas in panel i, the patches are distributed randomly across the whole environment. The results from panel a suggest that the higher level of experienced environmental circumscription should result in a higher level of experienced social circumscription at the start of the model run before the population size has grown sufficiently in the low environmental circumscription environment. Instead, in panel i (Figure 4.8), we can see that there is a faster rate of hierarchy formation in the low environmental circumscription condition as soon as the population size begins to differ between the high and low environmental circumscription conditions (Figure 4.9, panel I, green line). I conclude from these results that the villages in the random layout (panel i) are too isolated to interact with one another, unlike in the concentrated layout (panel a) where the small number of initial villages are crowded together in the same area of land. This suggests that an environment can be *too* environmentally circumscribed to allow for social complexity formation, if it restricts contact between villages, and supports the findings in Chapter 3 (Section 3.5.1).

4.5.3.5 A faster rate of population growth produces similar effects of environmental, resource, and social circumscription, but in fewer time steps

The model conditions of Group 2 are similar to those discussed for Group 1, except that the rate of population growth is faster (*probability.grow* = 0.5), making the average level of hierarchy plateau more quickly (see Experiment 2, Section 4.5.2, for discussion on this point). The one exception is panel g, where the rate of hierarchy formation is much higher in the high environmental circumscription environment (Figure 4.8, panel g, purple line) than would be expected based on the population size or level of experienced social

circumscription (see panel g in Figures 4.9 and 4.10). This I consider to be a by-product of hierarchy ceasing to accumulate in this model once carrying capacity has been reached, rather than a more meaningful result of the model. The level of hierarchy in the low environmental circumscription condition (green line, panel g, Figure 4.8) is curtailed early as the population size reaches carrying capacity (see panel g, Figure 4.9). If the population size were allowed to continue to increase, I would predict a similar pattern of hierarchy formation to that seen in panel c (Figure 4.8).

In Group 4 (random patch distribution, high population growth rate) the rate of hierarchy formation can mostly be predicted by the population size at any given time step (panels m, n, and p). However, in panel o (Figure 4.8), the rate of hierarchy formation in the high and low environmental circumscription conditions (purple and green lines) does not fit the pattern seen in the remaining panels (m, n, and p). Instead, the rate of hierarchy increase is faster in the high environmental circumscription condition (Figure 4.8, purple line) even though the rate of population growth is much faster in the low environmental circumscription condition (Figure 4.9, green line). Like the pattern of hierarchy formation seen in the comparable concentrated layout model environment (Figure 4.8, Group 2, panel g), this may be explained by the rapid population increase in the low environmental circumscription environment (Figure 4.9, panel o, green line), resulting in an early plateau in hierarchy increase once carrying capacity has been reached. If the population were allowed to increase further in this model, we may expect the level of hierarchy to have been higher in the low environmental circumscription condition than in the high environmental circumscription condition, based on the results of the other panels in Group 4.

4.5.3.6 Population crowding can occur through the movement of villages to areas richer in resources, even if villages are not initially crowded together

One additional feature which has not yet been discussed is the clustering of villages on more fertile land through village movement rather than through population growth. To assess this I have compared the rate of hierarchy formation in only high environmental circumscription and high resource circumscription conditions. In Figure 4.14, data from Group 1 (panel a and c), Group 2 (panel e and g), Group 3 (i and k), and Group 4 (m and o) have been

consolidated to compare the rate of hierarchy formation when village movement is restricted to one patch (*village.range* = 1, dark blue lines) and ten patches (*village.range* = 10, pink lines). I assume that if villages can see further afield, they are more likely to find unoccupied fertile patches to move to or place new villages in by preference. This may therefore cause greater conflict over the available high-resource patches, and increase the rate of hierarchy formation. In Figure 4.13, we can see that the rate of hierarchy formation is higher when the range of village movement is wider (*village.range* = 10, pink lines), particularly in the random patch layout (panels b and d). This effect persists even when the population size is small (compare Figure 4.14 panel b with Figure 4.15 panel b). This offers some support for the resource circumscription hypothesis (Section 4.3.2), that a concentration of resource may lead to increased conflict and therefore an increase in social complexity formation. However, this is only apparent in conditions of high environmental circumscription where the rate of population growth is slower than in low environmental circumscription environments (compare purple and green lines in Figure 4.8). Where there is a greater availability of resources, the population will grow more rapidly and the effect of social circumscription through population crowding may override the effects of environmental and resource circumscription.

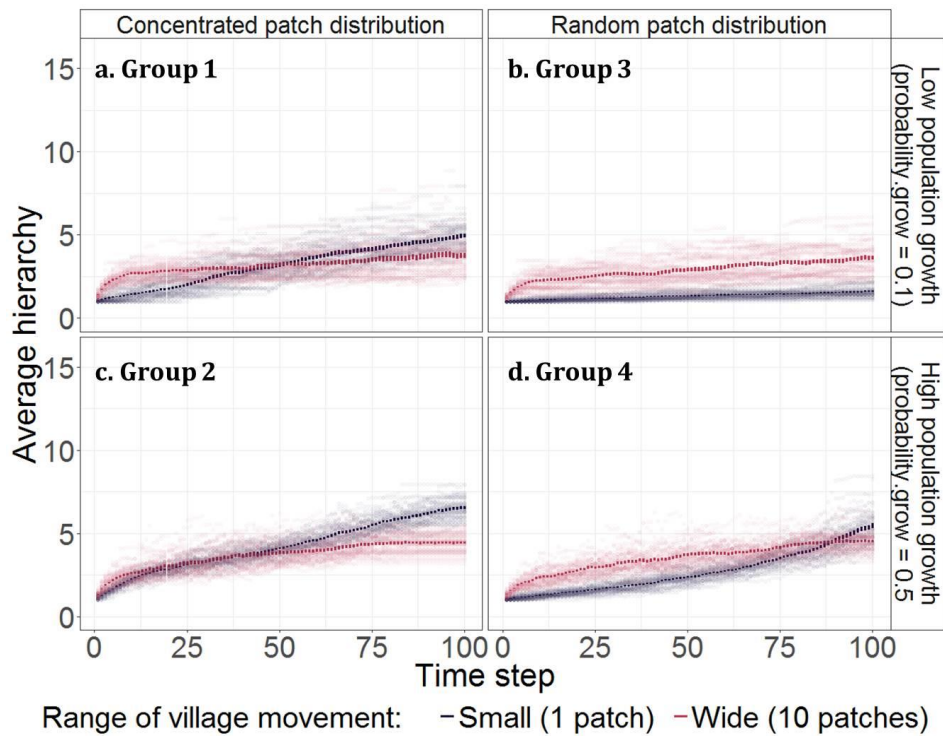


Figure 4.14 Data from Groups 1 to 4, consolidated to compare the effect of the range of village movement on the rate of hierarchy formation in conditions of high environmental circumscription (*land.width* = 2 in Group 1 and 2; *number.fertile* = 82 in Group 3 and 4) and resource circumscription (*resource.difference* = 0.1).

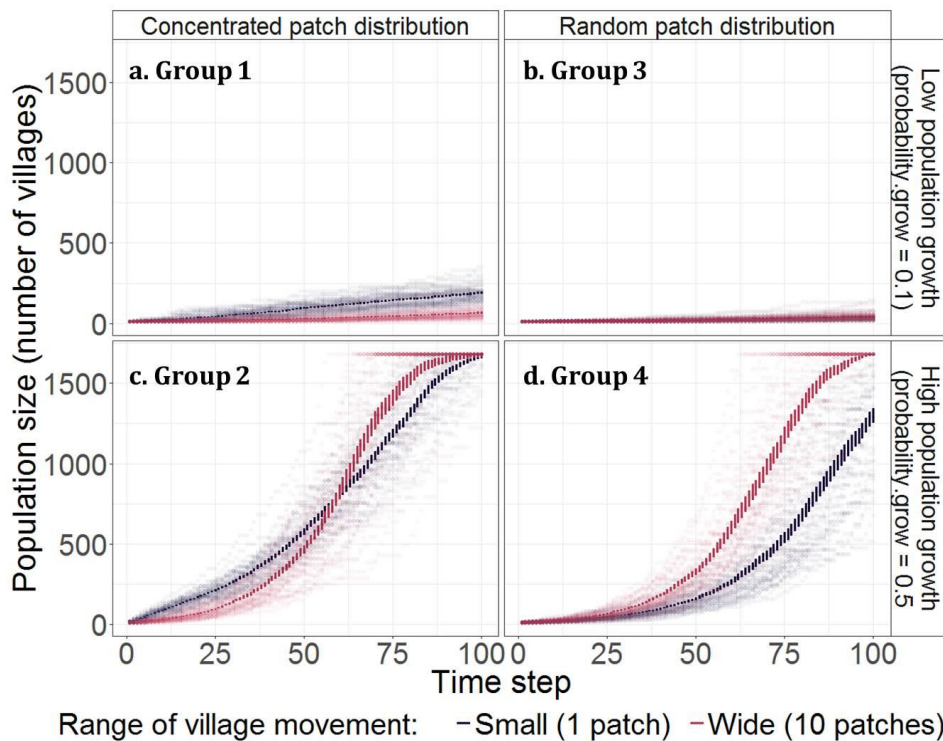


Figure 4.15 Data from Groups 1 to 4, consolidated to compare the effect of the range of village movement on the rate of population growth in conditions of high environmental circumscription (*land.width* = 2 in Group 1 and 2; *number.fertile* = 82 in Group 3 and 4) and resource circumscription (*resource.difference* = 0.1).

4.5.3.4 Summary of results from Experiment 3

The results from Experiment 3 support the importance of proximity between villages as a driver of the rate and overall level of hierarchy formation suggested by the results from Experiment 1 and 2. In model environments where fertile patches are distributed randomly, the rate of population increase in the low environmental circumscription condition has the overriding effect on the rate of hierarchy formation. But in the random layout, villages may be too isolated in the high environmental circumscription layout to find and conquer one another if their range of movement is small. If allowed a wider range of movement, villages are more likely to move to the more fertile patches and encounter other villages to enter into conflict with. In the concentrated layout of patches, the initial crowding together of villages in the high environmental circumscription environment makes it much more likely that villages will be located close to one another, regardless of the distance that villages can move, and thereby increases the chance of conflict. In this case, the proximity of villages as determined by the environmental layout will override the effect of population growth, at least initially until the population size in the low circumscription environment begins to have a comparable circumscribing effect on villages.

These results support the results discussed in Chapter 3, suggesting that environmental circumscription may have an effect on the likelihood of social complexity formation, but that too much environmental circumscription can isolate villages and diminish any chance of contact between them. The results presented here add the dimension of population pressure through population growth and population clustering over more fertile resources.

4.6 Discussion

The purpose of Model 2 was to test whether social circumscription could increase the chance that social complexity would form. The results show that proximity between villages is the most important factor influencing the incidence of conflict and therefore the emergence of hierarchical polities in this model. Villages are more likely to have neighbouring villages (to potentially fight with) if there are more villages present, if villages are crowded together by

environmental conditions or by clustering with population growth, or if villages can see further afield.

In more detail, the results from the three experiments presented here show that proximity between villages can be increased by: (1) increasing the population size (Experiment 1); (2) increasing the rate of population growth and therefore the population size at any given time step (Experiment 2); (3) increasing the availability of resources, which increases the rate of population growth (Experiment 3); (4) increasing the distance that villages can 'see' (Experiments 1, 2 and 3); and (5) increasing how close together villages are initially located by constraining them with environmental barriers (Experiment 3). The results also show that increasing environmental or resource circumscription alone is insufficient to predict the formation of social complexity. A high degree of environmental circumscription, where there are few of the more fertile patches, may isolate villages instead of confining them together in the same area if the land types are distributed randomly across the model world. In this case, hierarchy is only likely to form if villages can see and move across long distances, or if villages are surrounded by sufficient resources to proliferate rapidly in number.

In the original formulation, Carneiro argues that the core of the hypothesis is that: "*A heightened incidence of conquest warfare, due largely to an increase in population pressure, gave rise to the formation of successively larger political units, with autonomous villages being followed by chiefdoms, the process culminating in certain areas with the emergence of the state.*" (Carneiro, 2012a, p27). The results from the model presented in this chapter do, by and large, support this statement if we interpret population pressure to mean proximity between villages. Carneiro elaborates this by suggesting that population pressure may be increased by the presence of environmental barriers, concentrated areas of resources, or clustering of population. Complex societies may be more likely to form in areas of the world where population pressure through circumscribing conditions is highest. The model suggests that all three types of circumscription may contribute to social complexity formation, but not always in the ways suggested by Carneiro. I will discuss each in turn.

Environmental barriers to population movement, such as mountains or desert, may increase the incidence of warfare and therefore increase the chance that complex societies will form (see Chapter 1, Section 1.5). On this basis, I predicted that the rate of hierarchy formation would be faster if environmental conditions were more circumscribing, but that a random distribution of the more fertile patches may limit hierarchy formation by isolating villages (Sections 4.3.2 and 4.4.2.2). The results from this model suggest that increasing the intensity of environmental circumscription by reducing the area of more fertile land will result in a faster rate of hierarchy formation than a less environmentally circumscribed area, but only if villages can access each other without needing to cross the environmental barriers. In effect, this means conditions such as a river valley or expanse of plain between environmental barriers may create conditions most likely to support an increase in social complexity. If the environmental barriers isolate villages too much, such as in small valleys dotted between a mountain range or in islands with limited transport across waters, social complexity is much less likely to form because warfare between villages is more difficult to engage in. The model therefore supports the environmental formulation of the circumscription hypothesis, with the added caveat that areas may also be *too* circumscribed for social complexity to appear and that the effect of population growth may quickly outstrip the effect of environmental barriers.

In addition to environmental barriers, Carneiro suggests that pockets of land concentrated in resources may also restrict population movement as people prefer to live in the richest areas (Carneiro, 1970, 2012a; see Chapter 1, Section 1.5, Chapter 3, Section 3.3). I predicted that the fastest rate of hierarchy formation would occur when resource and environmental circumscription occurred in tandem (Section 4.3.2, and Chapter 3, Section 3.3.2). The results from the model in Chapter 3 support this prediction: we saw that a greater difference in resources would result in a faster rate of hierarchy formation when patches were randomly distributed in with a high level of environmental circumscription (see Section 3.5.1). The opposite result occurs in Model 2 when including population growth when the model environment is rich in resources. Increasing the resources available will increase the likelihood that a village will create a new village and therefore increase the rate of population growth.

However, if few resources are available where there is a high degree of both environmental and resource circumscription, villages may cluster on areas more fertile patches if they are able to find them. In the concentrated patch layout, villages will always be adjacent to a more fertile patch. But in the random patch layout, villages will cluster on the more fertile patches only if they are able to 'see' further afield. This will increase the chance of conflict between villages, even when the population size is small (Section 4.5.3.3). The original premise of the resource circumscription hypothesis is therefore supported in harsher model environments. This is an important distinction to note because these results suggest that a shallow ecological gradient (where a concentration of resources is detectable but not distinct) may not be sufficient to amplify conflict over resources. We should therefore look for locations in the real-world which are bounded by a sharp difference in the availability of resources as areas most likely to increase conflict between groups of people through environmental and resource circumscription.

The effect of social circumscription is the final part of the circumscription hypothesis. Carneiro suggests that social circumscription, as experienced through population pressure, will intensify with environmental and resource circumscription, but social complexity may still form where there are few restraints to population movement as long as the population is able to come into conflict. In Sections 4.3.1 and 4.4.2.1, I predicted that increasing the level of experienced social circumscription would increase hierarchy formation by both increasing the incidence of warfare and restricting options to move away if defeated. In Section 4.3.2, I added that the effect of increasing the degree of environmental circumscription through environmental barriers would be amplified by population pressure as the population fills the available land where more resources are available. The results presented here support Carneiro's suggestion that population pressure, as experienced through social circumscription, is one of the most important factors influencing the likelihood of social complexity formation. The results from Model 2 in this chapter show that: environmental circumscription may increase population pressure by crowding villages together in a confined space; the availability of resources will determine how quickly a population can grow; and reducing the distance that villages are able to move will increase clustering as the population grows. These combined

effects offer different scenarios for the formation of social complexity. Where a population is crowded closely together, social complexity may form more quickly than if a population is more dispersed. But if a population has greater access to resources, such as an area with fewer environmental and resource barriers to movement, the population may grow more quickly and increase the chance that social complexity will form with a time lag to allow for greater population growth. This is an important observation for assessing areas of the world where social complexity is more likely to form. To find conditions likely to amplify the effects of social circumscription, we should first look for areas which are rich in resources and therefore potentially able to support a growing population. Of these areas, those which are bounded by additional barriers may result in a faster emergence of social complexity, but will not necessarily be the same areas that the highest levels of social complexity can be built or sustained (see Chapter 3, Section 3.3.1).

4.6.1 Assumptions and limitations of the model

As discussed in Chapter 3 (Section 3.6.6) and Chapter 2, this model is intended as a simplification of reality. The assumptions that villages will come into conflict with one another and that the largest polity is more likely to be victorious have been carried over from the model presented in Chapter 3. In addition, in this model I continue to assume that villages will behave in a rational manner to maximise resource gain.

One important feature of the model as it is presented here is that villages are unable to act further if the population size reaches the carrying capacity of the model world. This has skewed some of the results in Experiments 2 and 3, but the patterns of change can still be interpreted from the results before carrying capacity occurs.

In this model, I expand on the assumption that villages have only a limited awareness of the world around them. This assumption is not entirely consistent with the world as people would have seen it in the past, or even as we see it now in the present. From the archaeological record, particularly through evidence of trade routes, we can infer that people could have been aware of other people living many miles away even if they had no direct interaction with them. For example, the presence of materials such as silk or cowrie shells in

areas where they did not originate across Eurasia provide evidence for extensive trade networks (Christian, 2000; Yang, 2011). However, awareness of foreign lands does not necessarily mean that people would have been willing to move there or find these other people to attack. By limiting the range of village movement in this model I am therefore making the assumption that people would have preferred to act within a smaller area. Further elaborations of this assumption could include increasing or decreasing that range of movement based on topography and transport technology (for example, to ensure that people are only willing to move to or attack within a day's travel from their home village), or by scaling the preference for action such that people are more likely to interact with areas closer to their home but are still able to move further afield. These are reasonable assumptions to include in a model such as this, but for the sole purpose of understanding the effect of a range of movement I have not included them here.

In this chapter I also make several assumptions about population growth. I assume that population growth is directly tied to resources and available land. This does not include the possibility of intensifying cultivation through agricultural technology or allow for any other limitations on population growth, such as disease. In addition, the effect of population growth is simplified in this model to include only the number of villages and not the number of people occupying those villages, or the area of land required to support different population sizes of settlements. I have simplified population growth in this way because the focus of the model is at the village-level, not at the individual person level. The effect of population pressure can be seen through the proliferation of settlements without a detailed understanding of fluctuations in the number of individuals within them. I also assume that any new village is fully autonomous. This does not allow for personal bonds between people which would likely have been the norm. A clustering of settlements may have arisen as people prefer to live close to their friends and relatives, rather than to only occupy land richest in resources. The range of village movement may proxy this effect, but I have not included any relations between villages other than through conquest warfare.

The results discussed in this chapter highlight the importance of population size for the rate of hierarchy formation in Model 2. However, in this chapter I have

only presented the absolute level of hierarchy. This was intentionally done for two reasons: (1) to ensure the hierarchy levels are as directly comparable to the archaeological record as possible (see Chapter 1, Section 1.3.4 and Chapter 5, Section 5.2.1); and (2) to investigate the effect of population size on the formation of hierarchy directly. An alternative approach would be to scale the absolute level of hierarchy by the population size for any given time step. This would have the advantage of controlling for the effect of population size on the level of hierarchy and would facilitate the comparison of hierarchy formation between populations of different sizes. In applying the model to the archaeological record, a relative scale of hierarchy may enable more accurate predictions as to the effect of environmental and resource circumscription on the formation of social complexity. In Figure 4.5, a comparison of panels a and b shows that although a higher overall level of hierarchy emerges when the population size is larger (500 villages), this level is not substantially higher than the lower population size (50 villages). The difference in relative hierarchy formation suggests that the probability of hierarchy formation is larger for smaller population sizes. This may be due to the space between villages in the uniform environment. A smaller population size means that each village is less likely to encounter a rival village (Figure 4.5, panel e), and is more likely to find an unoccupied surrounding patch (Figure 4.5, panel c). While this decreases the likelihood of successful conquering warfare, it may also increase the opportunities for polities to build up multiple levels of hierarchy before all villages are subsumed into the same polity. With a greater population size, villages are much more likely to be found and conquered more quickly, resulting in an extensive polity with a shallower level of hierarchy. This suggests that even areas of the world with small population sizes may experience rapid rates of hierarchy formation, even if the overall level reached is lower than seen in areas with a larger population size.

However, the purpose of this chapter is to understand the effect of social circumscription on the emergence of the highest levels of social complexity. Larger polities will tend to leave more substantial traces in the archaeological record, making any small-scale hierarchy formation less detectable (see Chapter 1, Section 1.3). Moreover, to scale the level of hierarchy by population size requires accurate information on population size in the past. As discussed

in Chapter 5, it is often difficult to accurately interpret population size of an area through the archaeological record alone. In this chapter, I have therefore focused on the absolute level of hierarchy to understand the effects of environmental, resource, and social circumscription in combination.

Lastly, this model is built in an abstract landscape that bears little direct relation to any area in the real world. The extremes of environmental conditions have been included here to understand the effect they may have while controlling for other factors as much as possible. The landscapes we can find on this world are not limited to two land types, nor are they usually laid out in either continuous bands or completely randomly. In Chapter 5 I will adapt the landscape of this model to correspond with an area in highland Mexico, to test whether the environmental conditions there could have contributed to the formation of social complexity.

4.6.2 Conclusion

The agent-based model presented here was built to test the entirety of Carneiro's circumscription hypothesis in an abstract world, including the combined effect of environmental, resource, and social circumscription. The results confirm the importance of warfare as a primary driver of social complexity formation. Parameters determining the population size, distance that villages are willing to move, availability of resources, and surrounding environmental barriers will increase the chance of social complexity formation only if they increase the chance that rival villages will come into conflict. Where villages are more isolated, a faster rate of population growth allowed by an abundant environment rich in resources will increase the rate of hierarchy formation. However, increasing the distance that those isolated villages are able to travel across a harsh environment will also increase the rate of hierarchy formation as villages are more likely to encounter one another in the few, more fertile areas and enter into conflict. If the area of fertile land is unbroken by less hospitable areas, villages are more likely to find one another even if they cannot travel far or if the rate of population growth is low. That is, if villages are confined to a smaller area in a continuous band of land (similar to a river valley), environmental and resource circumscription will restrict population movement and increase the chance that rival villages will come into conflict. These

situations support the weight given to warfare as the core mechanism of the original circumscription, insofar as conditions of environmental, resource, or social circumscription may increase the likelihood of villages coming into conflict.

Whether these circumscribing conditions were experienced by people in the past, and whether those conditions amplified or diminished the likelihood of the emergence of social complexity, cannot be shown by this abstract model alone. A test of the circumscription hypothesis applied to a scenario in the archaeological past is discussed in Chapter 5.

Chapter 5: Could the level of environmental, resource, and social circumscription in the Valley of Oaxaca have contributed to the emergence of social complexity there? (Model 3)



Abstract

Building on a full test of the internal logic and assumptions of the circumscription theory in Chapters 3 and 4, in this chapter I test the applicability of the theory to the real world. In Model 3, I tie the abstract agent-based models to reality using data from the Valley of Oaxaca in Mexico. The valley was the location of some of the earliest evidence of the emergence of social complexity in Mesoamerica and is surrounded by high mountains, making it an ideal test case of the circumscription theory. The model results show that hierarchy does emerge within a comparable timeframe and spatial location in the model, if the starting location and distance of village movement is taken into account. Moreover, the model highlights that further archaeological investigation to determine the frequency of warfare in the valley would be a useful avenue to investigate whether the circumscribing conditions could indeed have amplified the emergence of social complexity.

5.1 Introduction

The models in Chapters 3 and 4 tested the circumscription hypothesis in abstract worlds. From these models we can see that environmental and resource circumscription can increase the rate of hierarchy formation, but that social circumscription from population size and clustering is highly influential in determining whether and to what extent hierarchy can form at all. We also learned that an area can be *too* circumscribed, resulting in isolated groups of villages who cannot conquer one another. However, these models are a simplification of reality (see Chapter 2). The landscapes that people actually occupy are patchworks of different ecologies, with undulations and unexpected challenges in all corners. Moreover, time does not simply stop when agents reach the carrying capacity of the model world. So while the models of the previous two chapters show us what may be possible in extremes of conditions with different parameter settings, they cannot directly tell us anything more about the emergence of real societies in the past.

In this chapter I tie the model discussed in Chapter 4 to a valley in the real world to test whether those particular environmental, resource, and social conditions could have contributed to the formation of social complexity there within a comparable time frame. This is the final stage in testing the circumscription hypothesis proposed by Robert Carneiro (1970, 2012a, see Chapter 1, Section 1.5) in this thesis, and will show whether the circumscribing conditions could have contributed to the formation of social complexity in the past.

5.2 Valley of Oaxaca, Mexico

The area of the real world I focus on here is the Valley of Oaxaca in southern highland Mexico. This area is an ideal test case for three reasons: firstly, it is the location where the earliest signs of social complexity appear in Mesoamerica (see Section 5.2.1); secondly, there is substantial archaeological evidence documenting the changes in social complexity over the 3,000 years from the first occupation of the valley (see Section 5.2.1); and thirdly, the valley itself is highly environmentally circumscribed, with mountains on all sides (see Figure 5.1, and Section 5.4.4). The environmental circumscription of the area makes the valley a prime example of the effect of circumscription on the

formation of social complexity in the verbal hypothesis described by Carneiro (2012b, p133), and therefore an excellent test area for the model.



Figure 5.1 The Valley of Oaxaca, within the modern day state Oaxaca in southern Mexico, as it is seen today (image from GoogleEarth). The area of surveyed data is delimited by the red line (Kowalewski, et al. 1989a, 1989b). The area around the valley is predominantly mountainous, which is partially visible from the view from the hilltop of the central plaza at Monte Albán in the photograph in Figure 5.3, where the mountains circling the valley can be seen in the background. Figure 5.4 shows a more detailed map of the different environmental zones within the valley.

5.2.1 Evidence for social complexity in the Valley of Oaxaca

To investigate the emergence of social complexity in the Valley of Oaxaca, I focus here on the 1600 years between the start of the Tierras Largas phase (1400 BCE) to the end of the Monte Albán II phase (200 CE) (see Figure 5.2).

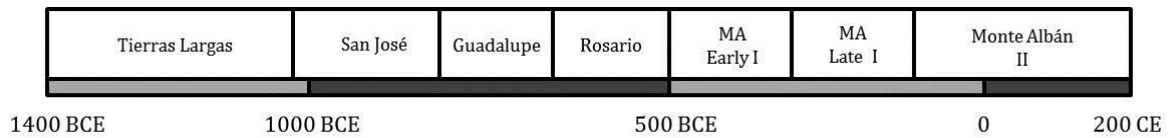


Figure 5.2 Timeline of the different archaeological phases in the Valley of Oaxaca (Kowalewski, et al. 1989a, 1989b. The dating of each phase is based on a ceramic chronology. This is the standard method for dating sites within the Valley of Oaxaca, but does not allow for more fine-scale resolution to date the occupation of sites within those phases.

As discussed in Chapter 1 (Section 1.3), social complexity is a nebulous concept and our interpretations of the archaeological record should assess multiple lines of evidence. It is during the 1600 years discussed here that multiple signs of increasing social complexity begin to appear in the Valley of Oaxaca, culminating in the political unification of the valley during the Monte Albán II phase (Flannery and Marcus, 1996; Spencer and Redmond, 2003). In general, we are looking for three main lines of evidence to determine whether social complexity is increasing in this area. (1) Population increase in a region over time, as indicated by size of settlements or census by burial remains, where the evidence exists (see Chapter 1, Section 1.3.1). (2) Evidence that those people in the same region considered themselves part of the same polity, as indicated by stylistic similarities in material goods, the presence of monumental constructions (implying the mobilisation of labour), and the presence of non-residential buildings with administrative or ideological purposes (to allow for more effective integration of the population) (see Chapter 1, Sections 1.3.1 and 1.3.3). (3) Evidence for increasing scales of warfare between ever larger competing polities, as may be indicated by defence constructions, hilltop locations, burning of buildings, or battlefields (see Chapter 1, Section 1.3.3). In Section 5.2.1, I discuss the evidence for population size (see Figure 5.6) and political integration in the Valley of Oaxaca from 1400 BCE to 200 CE, and how these different lines of evidence for social complexity may be summarised simply as a level of settlement hierarchy for polities in the valley. In Section 5.2.2, I discuss evidence for warfare in the valley.

Table 5.1 The levels of settlement hierarchy in the Valley of Oaxaca from the Tierras Largas to the Monte Albán II phase. The archaeological evidence supporting the levels of settlement hierarchy used here is discussed further in Sections 5.2.1.1 to 5.2.1.6.

Phase	Dates	Maximum number of levels of settlement hierarchy within polities
Tierras Largas	1400 – 1150 BCE	1-2
San José	1150 – 850 BCE	1-2
Guadalupe	850 – 700 BCE	1-2
Rosario	700 – 500 BCE	2-3
Monte Albán Early I	500 – 300 BCE	2-3
Monte Albán Late I	300 – 100 BCE	3-4
Monte Albán II	100 BCE – 200 CE	4

5.2.1.1 Tierras Largas phase (1400 – 1150 BCE)

Most of the settlements during this phase were small in size (0.1-1.5ha) and did not include any non-residential buildings. The one exception is the settlement San José Mogote, which extended over 7.8ha and included subterranean storage facilities, buildings interpreted as ritual houses, as well as a palisade defence along the western edge (Flannery and Marcus, 1983, 2003).

San José Mogote is usually interpreted as a first tier settlement within a polity consisting of two tiers of settlement hierarchy, based on the comparatively larger size of the settlement and presence of specialised non-residential buildings. However, San José Mogote was located in the northern ETLA subregion of the valley (see Figure 5.9) and the relationship that residents of this settlement had with the residents of other settlements in the valley is not clear (Flannery and Marcus, 2005). I have therefore recorded the settlement hierarchy level of this phase as being between one to two levels, to represent the different levels of settlement hierarchy likely present among polities across the valley (see Table 5.1).

5.2.1.2 San José and Guadalupe phases (1150 – 700 BCE)

During both the San José and Guadalupe phases, San José Mogote continued to be the sole larger settlement across the valley, but increased in size (up to an estimated 70-80ha in area) and internal specialisation compared to the earlier

Tierras Largas phase (Flannery and Marcus, 2005). San José Mogote remained the only settlement with evidence for non-residential buildings in the valley (Flannery and Marcus, 1983; Marcus and Flannery, 1996). The remaining settlements in the valley also increased in size and number, with most being between 0.95-3ha in area (Flannery and Marcus, 1983), implying an increase in population size from the Tierras Largas phase. Some estimates do suggest a settlement hierarchy of up to 3 tiers during this period (Flannery and Marcus, 1983), but based solely on relative settlement sizes across the valley with no further evidence for different specialisations or connections between those settlements. There is no evidence for political integration across the valley at this point (Spencer and Redmond, 2003), which means that settlements in the other subvalleys may still belong to polities of only one level of settlement hierarchy. In addition, although San José Mogote is much larger than in the Tierras Largas phase, there is no evidence to suggest further settlement hierarchy divisions based on internal specialisation or political unification of the valley. I have therefore recorded the level of settlement hierarchy for this phase as between one and two (see Table 5.1).

5.2.1.3 Rosario phase (700 – 500 BCE)

During the Rosario phase, there were three primary settlements across the valley, each located in one of the three arms of the valley. These settlements are considered the focal points of three different polities in the valley, separated by a sparsely-occupied 'buffer-zone' (Balkansky, 1998). These primary settlements are all between 35-60ha in size and contain multiple non-residential buildings for ritual and defence purposes (Spencer and Redmond, 2004, using settlement survey data from Kowalewski, *et al.* (1989a, 1989b); Balkansky, 1998; Flannery and Marcus, 1983; Marcus and Flannery, 1996). These features differentiate them from the remaining settlements surrounding them in each valley, with the next largest settlements being closer to 25ha in size (Spencer and Redmond, 2003). These second-tier settlements also contain evidence for non-residential buildings and internal specialisation of roles (including occasional rich burials, such as at Tomaltepec (Marcus and Flannery, 1996)), but on a smaller scale than the primary centres (Flannery and Marcus, 1983; Marcus and Flannery, 1996). Small scale settlements extending 1-3ha with no evidence for non-residential building remain present in the valley and constitute a third

tier of settlement hierarchy. However, in a re-analysis of settlement site area and density of archaeological remains, Drennan and Peterson (2006) show how the largest settlements in the Etna valley are clearly distinct from settlements in the remaining two valleys, and estimate that up to two thirds of the population resided there. I have therefore recorded two to three levels of settlement hierarchy for polities in the valley during the Rosario phase, to reflect the different scale of polities between the subvalleys (see Table 5.1).

5.2.1.4 Monte Albán Early I phase (500 – 300 BCE)

During the Monte Albán Early I phase, there are substantial shifts in population location but little change in settlement hierarchy or polity affiliation across the valley (Marcus and Flannery, 1996). The primary centres in the southern Ocotlán-Zimatlán subvalley and eastern Tlacolula subvalley remain with two further levels of settlement hierarchy present (Spencer and Redmond, 2004; Kowalewski, *et al.*, 1989a, 1989b; Flannery and Marcus, 1983). However, in the northern Etna subvalley the primary centre at San José Mogote is largely abandoned as most of the population moved to the newly-founded settlement Monte Albán. Monte Albán became the largest settlement in the valley (estimated at 324ha (Spencer and Redmond (2004), based on the survey data by Kowalewski, *et al.* (1989a, 1989b)); Marcus and Flannery, 1996). Despite the large size of Monte Albán, there is little evidence for three levels of settlement hierarchy in this region during this phase. I have therefore classified two levels of settlement hierarchy during this phase. The third potential level of settlement hierarchy recorded here is to allow for the uncertainty of the interpretation of the significance of Monte Albán as a primary centre, in relation to the settlement hierarchy levels evident in the preceding and proceeding phases (see Table 5.1).

5.2.1.5 Monte Albán Late I phase (300 – 100 BCE)

Settlements during the Monte Albán Late I phase continued to grow in size from the previous phases. Monte Albán, for example, grew to cover 442ha (Spencer and Redmond, 2004). There is also more prolific evidence for specialised, non-residential architecture across the valley (Flannery and Marcus, 2003; Marcus and Flannery, 1996), indicative of the need for administrative internal specialisation to manage the growing populations of the polities (Spencer and

Redmond, 2004; see Figure 5.6 for an indication of the increase in population size over time). This includes communal plazas suitable for large gatherings of people, and some of the first indications of a specialised multi-room temple and elite palace residences, such as at El Palenque in the Ocotlán-Zimatlán subvalley (Spencer and Redmond, 2001, 2003; Redmond and Spencer, 2008; Blanton, *et al.* 1979; Sherman, *et al.* 2010).

The division of settlements within polities into settlement hierarchy tiers based on relative size would suggest that the polities in the northern ETLA subvalley and southern Ocotlán-Zimatlán valley consisted of four distinct levels of settlement hierarchy. The polity in the eastern Tlacolula valley shows some evidence for four levels of settlement hierarchy, but the distinction is less clear than in the ETLA and Ocotlán-Zimatlán subvalleys (Spencer and Redmond, 2003, 2004).

Using the combined evidence of increasing internal specialisation in the polities of the valley and the division of settlement hierarchy tiers suggested by Spencer and Redmond (2003, 2004), I record four levels of settlement hierarchy during this phase (see Table 5.1). However, I also record a lower estimate of three levels of settlement hierarchy for this phase to take the uncertainty of the scale of the Tlacolula polity into account. This measure does not include settlement data from areas beyond the Valley of Oaxaca which may have been conquered by the Zapotec polity based in the northern ETLA subvalley (such as Cañada de Cuicatlán (Spencer and Redmond, 2003)). The full measure of settlement hierarchy of the Zapotec may therefore have been greater than four, but the comparison is beyond the scope of Model 3.

5.2.1.6 Monte Albán II phase (100 BCE – 100 CE)

This is the first phase during which the residents of the whole valley may be considered part of the same polity (Spencer and Redmond, 2003).

Standardised specialised buildings in the Monte Albán style (including temples, ballcourts, and plazas) appear in primary, secondary, and tertiary settlements across the valley, including sites which had previously been identified as belonging to different polities (Flannery and Marcus, 1983; Marcus and Flannery, 1996). Monte Albán became the clear dominant settlement of the valley, extending out over 10,000ha with a large central plaza and multiple

temple buildings (Kowalewski, *et al.* 1989a, 1989b) (see Figure 5.3 for a photograph of the central plaza as it is seen today). In addition to the extent of non-residential buildings, four levels of settlement hierarchy can be identified based on the relative size of settlements across the valley (Spencer and Redmond, 2003, 2004). I therefore record four levels of settlement hierarchy for this phase (see Table 5.1). As in the Monte Albán Late I phase, this measure of settlement hierarchy does not include settlement information from beyond the Valley of Oaxaca as the full geographical extent of the Zapotec polity is beyond the scope of Model 3.



Figure 5.3 Photograph of the central plaza at Monte Albán in the Valley of Oaxaca. Mountains surrounding the valley are visible in the background. Photograph by Alice Williams (2016).

5.2.2 Evidence for warfare in the Valley of Oaxaca

There are two points to note about the evidence for warfare in the Valley of Oaxaca. Firstly, there is increasing evidence for warfare over the phases focused on here (Flannery and Marcus, 2003), corresponding to the increase in social complexity (see Section 5.2.1). In the Tierras Largas phase, evidence for warfare is limited to small-scale raiding between settlements and a defensive palisade at the principal settlement in the Etla subvalley (San José Mogote) (Flannery and Marcus, 1996; 2005; Kowalewski, *et al.* 1989a, 1989b). Over the next phases, there is increasing evidence for defensive structures (Flannery

and Marcus, 1983; Marcus and Flannery, 1996), as settlements increase in size. Warfare becomes an important factor in settlement location from the Rosario phase, when settlements in the three arms of the valley were separated by a sparsely-occupied 'buffer-zone'. This, combined with evidence for burnt temple, extensive settlement fortifications, and the first recorded evidence of a captive, carved on a stone slab at San José Mogote (Marcus and Flannery, 1996; Flannery and Marcus, 2005; Spencer and Redmond, 2003, 2004; Balkansky, 1998). During the subsequent Monte Albán I and II phases, occupants of Monte Albán continued to commemorate their conquests by carving 310 *danzantes* of captives, and recording conquered settlements on over 50 conquest slabs, which were displayed in the Main Plaza at Monte Albán (Marcus and Flannery, 1996; Spencer and Redmond, 2003; Feinman, *et al.*, 1985; Balkansky 1998; Flannery and Marcus, 1983; Redmond and Spencer, 2012; Spencer, 2010). Some of the recorded conquests were located outside of the Valley of Oaxaca, and there is evidence for Zapotec presence in these locations based on the style of material remains (Spencer and Redmond, 2003).

The second point to note is that warfare is present in all phases discussed here. Warfare is the main proposed mechanism for social complexity formation, suggested by Carneiro (1970, 2012a, see Chapter 1, Section 1.5). The occurrence of warfare from the beginning of the time period considered here along with an increase in scale of warfare with social complexity is therefore consistent with Carneiro's suggestion that warfare may be the main mechanism of social complexity formation. However, the evidence available from the Valley of Oaxaca does not allow us to make more detailed comparisons between the frequency or intensity of warfare and the emergence of social complexity. Fortifications at settlements suggest inhabitants at the time were concerned about warfare, but do not provide fine-scale detail on the number of attempted conquests they endured. Similarly, while the presence of burned daub and burned buildings at settlements, and carved stone records of settlement conquests suggest warfare at various levels of intensity, none of these lines of evidence can provide an accurate representation of the frequency of conflict. Settlements may have been conquered without either arson or documentation. For comparing Model 3 with the archaeological data, I therefore assume that conflict did occur at all phases, but vary the frequency at which conflict may

have occurred to allow for different scenarios (see Table 5.2 for parameter settings).

5.3 Predictions

In the verbal formulation of the circumscription hypothesis, Carneiro (1970, 2012a) suggests that conditions of environmental circumscription which limit population movement could intensify pressure from warfare and accelerate the formation of social complexity (see Chapter 1, Section 1.5). The mountains around the Valley of Oaxaca may form one such example of an environmental barrier, as suggested by Carneiro (2012a, 2012b) (see Figure 5.1). However, in testing the assumptions of the verbal circumscription hypothesis in Model 1 and Model 2 (Chapters 3 and 4 respectively), we have found that the layout of different land types as well as population growth dynamics can both have important effects on accentuating or diminishing the likelihood of social complexity formation within different conditions of environmental, resource, and social circumscription.

The first question posed of Model 3 in this chapter must therefore be whether hierarchy forms when agents are placed in a landscape based on the Valley of Oaxaca. The results from Model 2 suggest that hierarchy is more likely to form if villages are hemmed in to the same area by environmental conditions, particularly if that area has sufficient resources to allow rapid population growth. Given that the Valley of Oaxaca does form one relatively continuous area (see Figure 5.1) and there is cultivatable land across the valley (see Section 5.4.4, Figure 5.4), I predict that hierarchy is likely to form within the specified timeframe.

However, environmental barriers are not the only potential source of circumscription. Carneiro also describes the effect of resource circumscription, where people are more likely to cluster around areas which are richer in resources (1970, 2012a, see Chapter 1, Section 1.5). The valley floor of the Valley of Oaxaca is relatively uniform in resources (Section 5.4.4, Figure 5.4), but there is a higher concentration of more easily cultivatable land in the northern Etna subvalley (Figure 5.9). It is in the Etna valley that the first differentiation in settlement hierarchy also appears, with the presence of San

José Mogote (see Section 5.2.1), and where the centre of the Zapotec polity at Monte Albán was located (Sections 5.2.1.4 to 5.2.1.6 and Supplementary Materials 3, Figure 5.19). Therefore, although Carneiro suggests that resource concentration was unlikely to have had a circumscribing effect within the Valley of Oaxaca (Carneiro, 2012a), I predict that hierarchy will form more quickly in the ETLA subvalley when tested in Model 3.

The final form of circumscription suggested by Carneiro (1970, 2012a) is social circumscription imposed by other groups of people living in the same area. With the high level of environmental circumscription and less discernible resource differentiation, Carneiro makes no specific predictions as to the effect of social circumscription in the Valley of Oaxaca beyond the effect of population pressure in a confined area. In Chapter 4 (Model 2) we learned that population size and population clustering can have an impact on the rate of hierarchy formation if these two factors mean that villages are more likely to come into contact with one another. In this model, I keep the population size tied as closely as possible to that seen in the archaeological record. I therefore predict that hierarchy will increase as the population size increases, if the landscape of the valley allows for rival polities to come into contact.

5.4 Model description

5.4.1 Purpose of the model

The purpose of Model 3 in this chapter is to build on the insights on the circumscription theory developed from Model 1 (Chapter 3) and Model 2 (Chapter 4) by testing the model against archaeological evidence for the emergence of social complexity in the past. This will confirm whether environmental, resource, or social circumscription could have had an effect on the formation of social complexity in the Valley of Oaxaca, given the assumptions of the circumscription theory.

5.4.2 Agents and submodels

The agents and submodels in this model (Model 3) remain as described in for Model 2 (Chapter 4), except for selection of patches to move to by villages which has been adjusted to allow for five rather than two land types (see

Supplementary Materials 3, Section 5.7.1 for details). In addition, this model differs from Model 2 in the parameterisation of different variables (Section 5.4.3).

5.4.3 Parameters

In Model 3, all parameters are tied as closely as possible to the available archaeological information. Where the archaeological data is insufficient to narrow down the parameter range, parameters are varied between extreme values. The model environment does not vary between experiments. Instead, patches are assigned *land-resources* values based on environmental data from the Valley of Oaxaca (see Figure 5.4, Table 5.2, and Section 5.4.4). Time-dependent parameters (*probability.grow*, *probability.death*, *probability.fragment*, and *probability.attack*) are scaled relative to 10 years per time step (see Table 5.2 and Section 5.4.5.3 for details).

Table 5.2 The parameters in Model 3, and parameter values used in experiments (see Sections 5.4.4 and 5.4.5 for more detail, and Section 5.5.1 and 5.5.2 for results).

Purpose	Parameter	Values	Description
Social circumscription	<i>initial.villages</i>	21	The number of villages in the valley during the Tierras Largas phase (1400 – 1150 BCE) (see map, Figure 5.5 for estimated archaeological location of the villages).
	<i>probability.grow</i>	0.1	The probability.grow parameter works as described in Chapter 4 (Section 4.4.1.4, Figure 4.3, Table 4.2). I have used the rate of population growth to determine how long each time step equates to in real-time (see Section 5.4.5.2, Figures 5.6 and 5.7). A population growth rate of 0.1 relates roughly to 10 years per time step.
	<i>probability.death</i>	0.01	The probability that a village will become extinct. This parameter is set to 0.01 to allow for some chance of village abandonment, as it is known to have occasionally occurred from the archaeological record (Kowalewski, <i>et al.</i> 1989a, 1989b; Flannery and Marcus, 2005). As the data are not present to determine an exact rate of extinction, I have kept this parameter low. If each time step equates to 10 years, a village is likely to become extinct once every thousand years with probability.death at 0.01.
	<i>village.range</i>	1, 10, 50	This function of this parameter is as described in Chapter 4 (Table 4.2). Archaeological data of settlement patterns show that most settlements cluster within 0.5-2km distance from one another (Supplementary Materials 3, Figure 5.19), but are also locate across the valley. In this model, one patch equates to roughly 1.2km distance. This means that a village range of 1, 10, and 50 patches is roughly equivalent to 1.2km, 11.4km, and 57.2km distance across the valley respectively. This therefore allows for both close clustering and the possibility of moving further afield to form new clusters, as suggested by the settlement pattern distribution (Supplementary Materials 3, Figures 5.18 and 5.19).
Environmental circumscription	Geographic landscape	<i>land-resources</i> of patches are either 0 (mountainous) or greater than 0 (non-mountainous)	The distribution of land types in the Valley of Oaxaca is shown in Figures 5.4 and 5.5. It is assumed in this model that areas outside the border of the surveyed area are mountainous, as well as land areas classified as mountainous within the valley. Mountainous patches are given <i>land-resources</i> = 0. Non-mountainous patches are given <i>land-resources</i> scaled by the potential productivity of the different land types within the valley.

Resource circumscription	Ecological zones within the geographic landscape	<i>land-resources</i> of patches range from 0 to 100	Based on yield estimates by Kirkby (1973) and land type classifications by Nicholas (1989), I scale the productivity of land types by the lowest estimated yield of tons per hectare possible: - Class I (highest productivity), over 2 metric tons of maize per hectare = 100 <i>land-resources</i> - Class II , between 1.21 – 2 tons per hectare = 60 <i>land-resources</i> - Class IIIa , between 0.41 – 1.2 tons per hectare = 20 <i>land-resources</i> - Class IIIb , between 0.21 – 0.4 tons per hectare = 10 <i>land-resources</i> - Mountain , between 0 – 0.2 tons per hectare = 0 <i>land-resources</i> The distribution of land types across the valley is based on the survey presented by Nicholas (1989) (Figure 5.4), and imported into NetLogo with a resolution of 61x61 patches (see Figure 5.5).
Polity conditions	<i>tribute</i>	0.1	Proportion of resources owned by the defeated polity demanded by conquering polity. The level of tribute demanded by conquering polities had little effect on the rate of hierarchy formation (Chapter 3, Section 3.5.4), and is therefore not varied here.
	<i>probability.fragment</i>	0.01	Probability of internal polity instability. There is little evidence for the fragmentation of polities in the Valley of Oaxaca before the Zapotec polity began to collapse from around 500 CE (Flannery and Marcus, 1983). This is considerably beyond the end of the time period investigated here. I have therefore kept the probability of fragmentation low (1% chance of fragmentation, equating to roughly one fragmentation event per polity every 1000 years when each time step is the equivalent of 10 years).
	<i>probability.attack</i>	0.1, 1	The chance that one polity will decide to attack another polity, if a village belonging to a different polity is within <i>village.range</i> . There is extensive evidence of warfare in the Valley of Oaxaca over the time period focused on here (see Section 5.2.2), but it is difficult to determine the frequency or intensity of warfare from the archaeological evidence alone. Given that each time step is here taken as 10 years, the probability of attack is varied here between low (a polity will attempt to attack another polity once every 100 years) and high (a polity will attempt to attack every 10 years) NOTE: this is per polity, so actual incidence of warfare will increase with the number of polities.
General setup	<i>step</i>	200 time steps	Time measured in steps (1 step = 1 complete run through the code by every agent, which here relates to roughly 10 years of archaeological time). 200 time steps therefore equates to roughly 2000 years, which is slightly longer than the archaeological time period being investigated here (see Section 5.4.5.3, Figures 5.6 and 5.7).

5.4.4 Environmental conditions

Once down from the surrounding mountains, the valley floor of the Valley of Oaxaca is relatively uniform. Differences in the yield of areas of the valley arise mainly from the access to, and reliability of, water supplies. Anne Kirkby (1973) and Linda Nicholas (1989) have classified environmental zones within the valley by the potential maize yield of the different areas at the time of survey (see Figure 5.4 and Table 5.2). Other crops would have been grown to supplement a diet of maize, but estimating maize yields provides a proxy measure of land type productivity (Nicholas, 1989, p452).

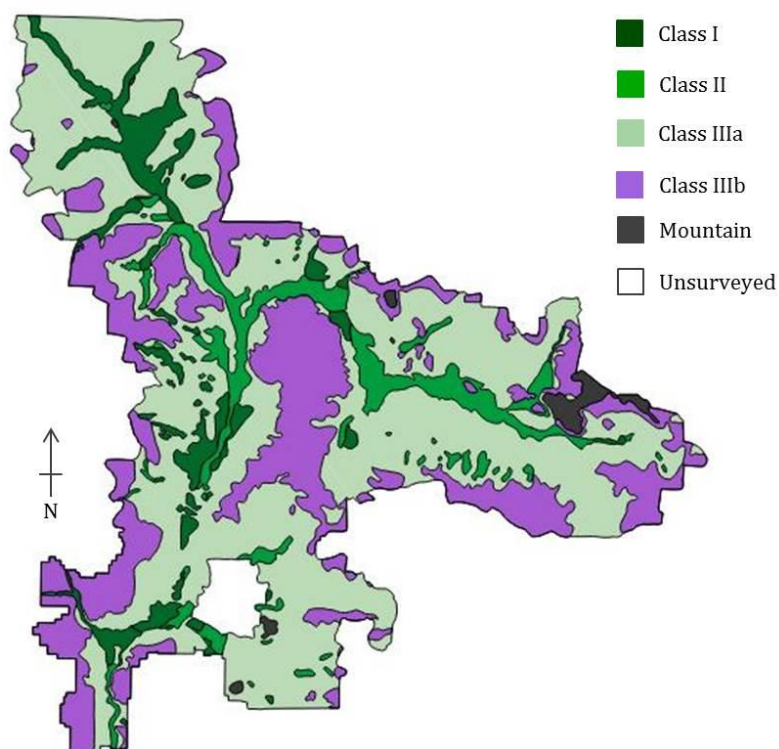


Figure 5.4 Map showing the different land types in the Valley of Oaxaca, based on the map produced by Nicholas (1989, Figure 14.3, p461). The blank area in the southern subvalley is unsurveyed land (Kowalewski, et al. 1989a, 1989b), but by comparing the map with an additional land type map produced by Kirkby (1973, Figure 25, p66, Supplementary Materials 3, Figure 5.10) and with the GoogleEarth image (Figure 5.1), we can see that the blank area is similar in land type to the surrounding regions. When including this map in Model 3, I have therefore re-assigned the gap of unsurveyed land as Class IIIa land. Although assigning only one class type for the whole unsurveyed area will not accurately represent the topography of that area of the valley, it is more accurate than leaving the area blank with the incorrect implication that it is inhospitable.

The water table is highest in Class I land (the low alluvium), which means that intensive cultivation techniques are not needed to grow crops (upwards of 2 metric tons per hectare, Kirkby (1973, pp64-66)). Indeed, during the Tierras Largas phase (1400 – 1150 BCE) of occupation most villages were located near to this type of land (see Figure 5.6 for population size estimates; see Figure 5.5 and Supplementary Materials 3, Figure 5.18 for initial locations of villages), and there is no evidence for any of the irrigation techniques used in the later phases, despite a reliance on domesticated crops for subsistence (Flannery, *et al.*, 1967; Flannery and Marcus, 2005). Areas with a higher elevation may still yield as much produce as areas with easy groundwater access, but may be more prone to fluctuations in rainfall (Kirkby, 1973; Nicholas, 1989). Class II land is similar to Class I, being almost as close to the water table and with good floodwater farming opportunities. Crop yields from this type of land may be as high as in the Class I land, but less reliably so. Crop reliability may be increased using simple water control techniques such as pot irrigation, as used after around 1000 BCE (Kirkby, 1973, pp127-8). Class IIIa land is located higher on the piedmont, but may provide productive land with the additional use of small-scale canal irrigation techniques, as employed by residents of the valley from around 500 BCE onwards (Kirkby, 1973, pp127-8; Neely, Caran and Winsborough, 1990). The mountainous areas are considered very minimally cultivatable, if at all (Nicholas, 1989, p452).

One caveat with the resource yield data used here should be mentioned. The resources available to people in the Valley of Oaxaca was dependent not only on the agricultural technology available, but also on the labour supply to cultivate land (Kirkby, 1973), and on the size of maize cobs available at the time. Most of the crops cultivated in the Valley of Oaxaca between 1400 BCE and 200 CE had already been domesticated (Flannery, *et al.*, 1967; Flannery and Marcus, 1976, 2005), but the maize cob continued to grow in size over this time from around 4cm during the Tierras Largas phase to 8-9cm in the Monte Albán phases (Kirkby, 1973; Manglesdorf, MacNeish and Galinat, 1964; Benz and Long, 2000). The combination of these factors effectively means that the potential productivity of the valley increased from the Tierras Largas phase onwards. However, as pot irrigation was used for most of the time period considered here, villages in the model cannot access resources beyond their

own patch (in effect limiting potential productivity by population size), and there is no further data providing estimates of maize productivity in the valley with different cob lengths, I assume that productivity in the valley does not change over time in Model 3.

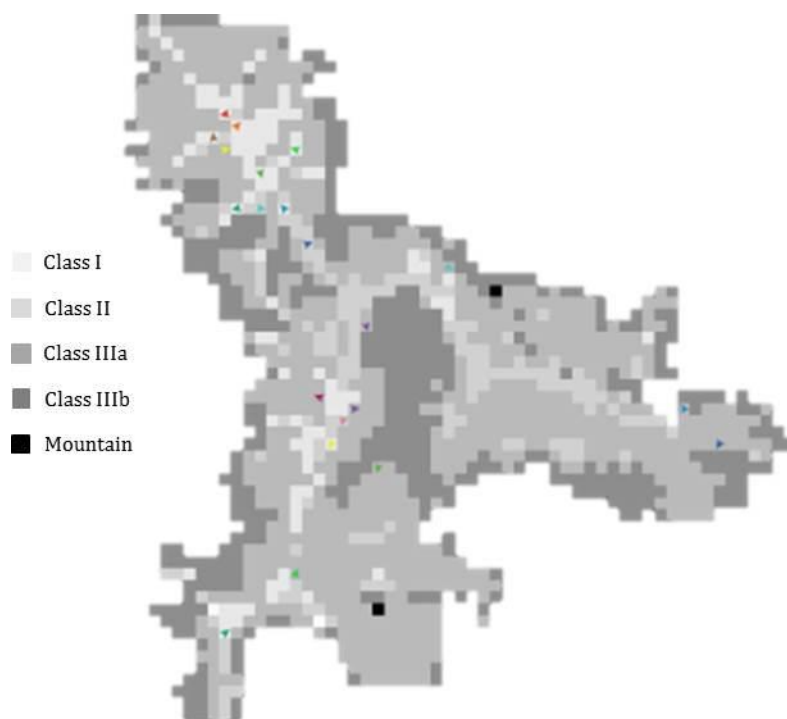


Figure 5.5 The landscape of Model 3 based on the Valley of Oaxaca environmental data (Figure 5.4). The shape of the valley is formed by importing a greyscale version of the land types map (Figure 5.4). The colour of each patch is determined by the colour of the image imported into NetLogo, which in this case gives the different types of land (described in Section 5.4.4). Black patches are considered mountainous and uninhabitable. The gradations of grey from dark to light correspond with increasingly productive areas of land (see Table 5.2 for land types). Increasing the number of patches will increase the resolution of the environmental areas, but I have kept the model environment to within a 61x61 grid. This means that the number of habitable patches (1454) is similar to the total number of patches in Model 2 in Chapter 4 (1681 patches); and the total population size (as constrained by the number of habitable patches) does not greatly exceed the maximum number of settlements observed in the archaeological record (Figure 5.6). The villages in this figure (coloured triangles) show the starting locations of the villages in the model, based on the sites of settlements during the Tierras Largas phase (see Supplementary Materials 3, Figure 5.18).

The total number of habitable patches in the model world was chosen to match the total number of patches tested in Model 2 (Chapter 4) as closely as possible (see Figure 5.5 for details). As each patch can only adopt one type of land, this means that some resolution in land types is lost. However, this also means that

the results from Model 2 are comparable with the results from Model 3 and that the overall population size of the valley does not exceed the population size reached by 200 CE.

5.4.5 Social conditions

To make the model output comparable with the archaeological record, the model needs to be situated in time as well as space. The model environment may be linked with the geography of the Valley of Oaxaca fairly accurately (Section 5.4.4). To link the model to the time period 1400 BCE to 200 CE, it is necessary to both replicate the starting conditions at 1400 BCE as closely as possible and determine how many years each time step should relate to. To address both of these questions, I have used the settlement survey data provided by Blanton, *et al.*, (1982) and Kowalewski, *et al.*, (1989a, 1989b). The location, size, and dates of occupation of settlements across the Valley of Oaxaca (within the boundary depicted in Figure 5.1) were recorded based on the spread and density of ceramic types associated with each phase. The intention of this survey was to gather surface-level information on settlement patterns in the valley from the beginning of the Tierras Largas phase (1400 BCE) to the end of Monte Albán V (1500 CE) for as far across the valley as possible (although permission and resources to survey was not always available, Kowalewski, *et al.*, 1989b, p19). What this information therefore provides us with is an indication of the location and proliferation of people living in the Valley of Oaxaca over nearly 3,000 years. The size and density of pot sherds combined with other recorded observations for the presence of monumental architecture at different settlements also provide us with an indication of the scale of settlements over this time. However, what this information does not provide us with is a more in-depth analysis of any individual settlement, nor any assurance that the sherds and structures spotted on the ground surface are truly representative of the number and scale of settlements in the past (O'Brien and Lewarch, 1992). I therefore supplement the survey data with additional archaeological findings wherever possible (see Section 5.2.1 for settlement hierarchy assessment with site area combined with other lines of evidence).

5.4.5.1 Starting population

There are 21 recorded settlements dating to the Tierras Largas phase (1400 – 1150 BCE), mostly located in the Etla subvalley (see map in Supplementary Materials 3, Figure 5.18 for the original settlement survey map). To compare the model output with the archaeological data (Experiment 1), I therefore start each village in a comparable location in the model world (see Figure 5.5 for an illustration of this).

5.4.5.2 Population growth

The measure of population growth I use for both the model output and archaeological data is the number of settlements rather than the number of individual people within those settlements. Estimates of the number of individuals living in the Valley of Oaxaca have been made based on the size and density of archaeological remains, but estimates can vary greatly (Blanton, *et al.* 1979; Marcus and Flannery, 1996). To avoid confusion in population estimates, I only plot the number of settlements and not their estimated area or population size (Figure 5.6). This does mean that any increase in population size within settlements is not accounted for, and is therefore not a completely accurate representation of the population size of the valley. However, focusing only on the number of settlements maintains scale of analysis at the settlement level, as has already been discussed for Model 1 and Model 2 in Chapters 3 and 4 respectively (see Chapter 2, Section 2.2.2 for a discussion on model scale).

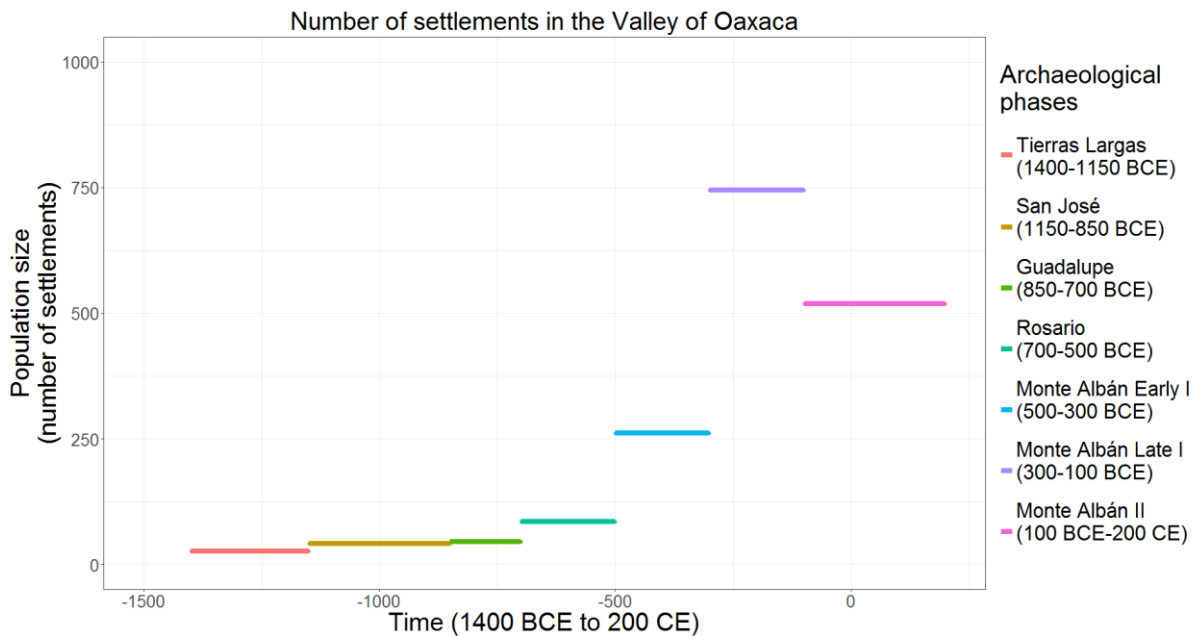


Figure 5.6 The number of settlements present in the Valley of Oaxaca over the first 1600 years of settlement data (settlement survey data from Kowalewski, et al., 1989a, 1989b) (see Supplementary Materials 3, Figures 5.18 and 5.19 for maps of the distribution of those settlements in the Tierras Largas and Monte Albán II phases). The phases after Monte Albán II have not been included here because the focus of the model is on the initial emergence of more complex societies rather than their maintenance or collapse. The population does not vary within phases because the ceramic information used to date the phases of occupation is limited by ceramic morphology which may not substantially change for one or more centuries. However, an exponential increase in population size can be seen after the Rosario phase (from around 700 BCE). This pattern of increase in population size (by number of settlements) has been used to tie the rate of population growth in the model with the archaeological record (see Section 5.4.5.2).

5.4.5.3 Scale of time

To link the timescale of the model with the timescale of the archaeological record, I have set the rate of population growth to be as similar as possible to that seen in the archaeological record. There are three reasons why I have chosen the rate of population growth to link the timescale of Model 3 with the archaeological timescale: (1) the pattern of population increase documented by the settlement survey occurs within a specified timeframe of 1600 years; (2) the emergence of hierarchy is the focus of Model 3, not the population dynamics resulting in the observed population increase over time; (3) population size must be controlled for (see Figure 5.7), given the results in Chapter 4 (Sections 4.5.1 to 4.5.3) indicating the effect of population size on hierarchy formation.

To control for population size, I link population growth in the model to the population (number of settlements) seen in the archaeological record over time (see Figure 5.7). Population growth in the model is determined by the availability of resources and unoccupied patches around villages in the model. To estimate a suitable value for the *probability.grow* parameter, I therefore ran several test experiments with different *probability.grow* values. In each experiment, villages were placed in locations corresponding to the archaeological distribution of settlements in 1400 BCE (see Figure 5.5). Each experiment was repeated for five iterations with *probability.grow* set between low (0.01) and high (0.4) values (see Figure 5.7). The archaeological data suggests that towards the end of the time period focused on here (300 BCE to 200 CE), there were between 500-750 settlements in the valley (Figure 5.6). I therefore chose a *probability.grow* value based on the time taken for the population size in the model to reach a similar size (see grey band, Figure 5.7). From these experiments, I concluded that each model time step should relate to 10 years in real-time if run for up to 200 time steps (see Table 5.2 for scaling of other time-dependent parameters).

Although the actual number of settlements at any given year cannot be replicated in Model 3, scaling the model in this manner will allow for a qualitative comparison of the emergence of hierarchy in the model with the archaeological record. Exact quantitative analysis cannot, and should not, in this case be made. This is particularly important to note, especially given that the limitations of the available survey data discussed above preclude accurate analysis of the archaeological data itself (O'Brien and Lewarch, 1992). However, a qualitative comparison may still provide useful insights and will provide a firm basis for more quantitative work (see Chapter 2, Section 2.2.2, for a discussion on useful types of models).

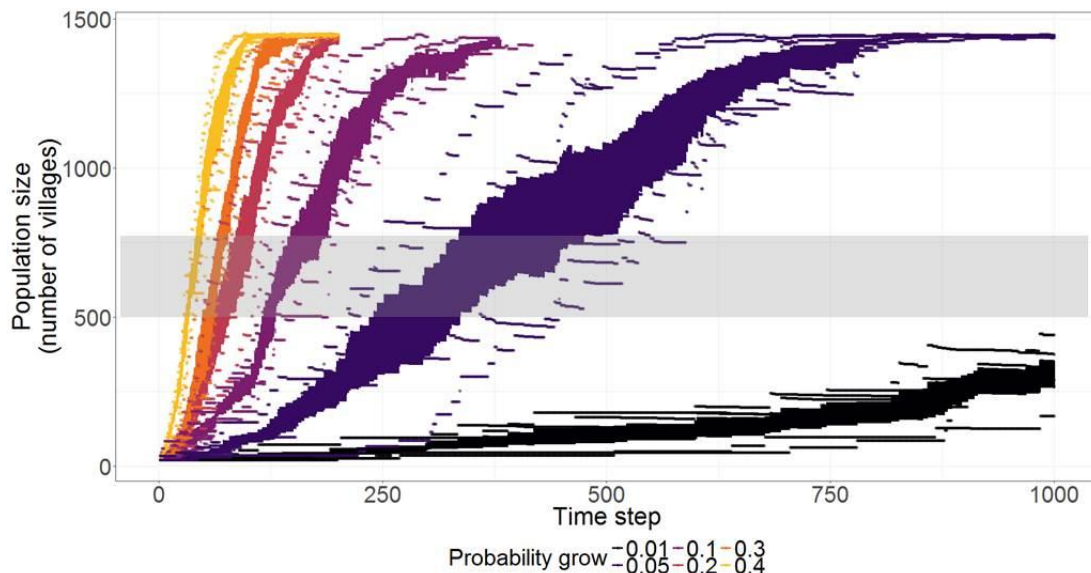


Figure 5.7 Trends in population growth to explore the `probability.grow` parameter space. This parameter space exploration was done using a model environment comparable to the land types of the Valley of Oaxaca (see Figure 5.4), to attempt to create a rate of population growth in the model that is comparable with the archaeological data (see Figure 5.6). All parameters are kept constant except for the `probability.grow` parameter, and each experiment was repeated 5 times and summarised by standard error bars. In the later phases of the archaeological record, the number of settlements in the valley of Oaxaca reaches 500-750 during the phases Monte Albán Late I (300 – 100 BCE) and Monte Albán II (100 BCE – 200 CE), which is roughly 1100-1600 years after the beginning of the Tierras Largas phase (1400 BCE). I have used this estimated population size to direct the population growth rate in the model, depending on how long each time step equates to in real-time. The faster the rate of population growth, the longer the amount of time that passes within each time step. Thus, when the probability of growing is relatively high (0.4, amber line), the population reaches between 500-750 settlements within 20-30 time steps, and therefore each time step roughly equates to 50 years in real-time. In the lowest population growth setting (`probability.grow` = 0.01), the population size does not reach 500-750 until after 1000 time steps. Each time step in this condition therefore relates to between one to two years. A medium population growth rate (`probability.grow` = 0.1, dark pink line) means that around 125-175 time steps are needed for the population in the model to reach 500-750 villages, which roughly means that each time step is the equivalent of 7.3 to 10.6 years. For the setting of the remaining parameters, I round this number to 10 for simplicity and therefore assume each time step is roughly equivalent to 10 years of time.

5.5 Simulation experiments

The simulation experiments are in two parts. In Experiment 1 (Section 5.5.1), I use real-world landscape data to inform the level of environmental circumscription in Model 3 in order to investigate the potential role of

environmental circumscription on the emergence of social complexity in the Valley of Oaxaca (see Figure 5.5). In Experiment 2, I use the distribution of resources to investigate the potential role of resource circumscription in combination with environmental circumscription in the Valley of Oaxaca (see Section 5.5.2, Figure 5.9). In both experiments, the rate of population growth is kept consistent and close to the rate of population growth seen in the archaeological record (Section 5.4.5.2).

All experiments are run for 200 time steps, but only the first 160 are plotted in Experiment 1 to correspond with 1600 years of archaeological time. Experiment 1 is repeated for 100 iterations, and Experiment 2 for 50 iterations.

5.5.1 Experiment 1: the effect of environmental circumscription on the formation of social complexity in the Valley of Oaxaca

In Chapters 3 and 4, we learned that environmental circumscription may increase the likelihood of hierarchy formation, but also that hierarchy formation is by no means inevitable as the rate of hierarchy formation is also determined by the availability of resources, the distribution of those resources, and rate of population growth (see Sections 3.5.2 and 4.5.3). I use Model 3 to test whether environmental circumscription (as imposed by mountains around the valley) could have had an impact on the likelihood of social complexity formation. The availability and distribution of resources are set to match the landscape of the Valley of Oaxaca, to show whether those specific conditions are sufficient to allow hierarchy formation. The rate of population growth is controlled for by replicating the increase in number of settlements seen in the archaeological record (see Section 5.4.5). All parameters are based on archaeological data where possible (see Table 5.2, Sections 5.4.4 and 5.4.5), including the initial starting location of villages (see Figure 5.5). The two exceptions are: *village.range* and *probability.attack*, which cannot be narrowed down based on the archaeological data alone. These two parameters are therefore varied between extreme (but plausible) values.

The levels of settlement hierarchy seen in the archaeological record are plotted as grey lines by phase (see Table 5.1 for values, and Section 5.2.1 for discussion of the archaeological data). The archaeological data recorded here

represents the range of maximum levels of settlement hierarchy of the polities in the Valley of Oaxaca for each phase from 1600 BCE to 200 CE (Table 5.1). The data does not include individual levels of settlement hierarchy for every settlement in the valley which means that the average hierarchy level used in previous experiments (Chapters 3 and 4) is unsuitable for comparison with the archaeological data. I have therefore recorded an average of the maximum levels of settlement hierarchy for each polity at every time step instead of the average level of hierarchy of all villages for this experiment.

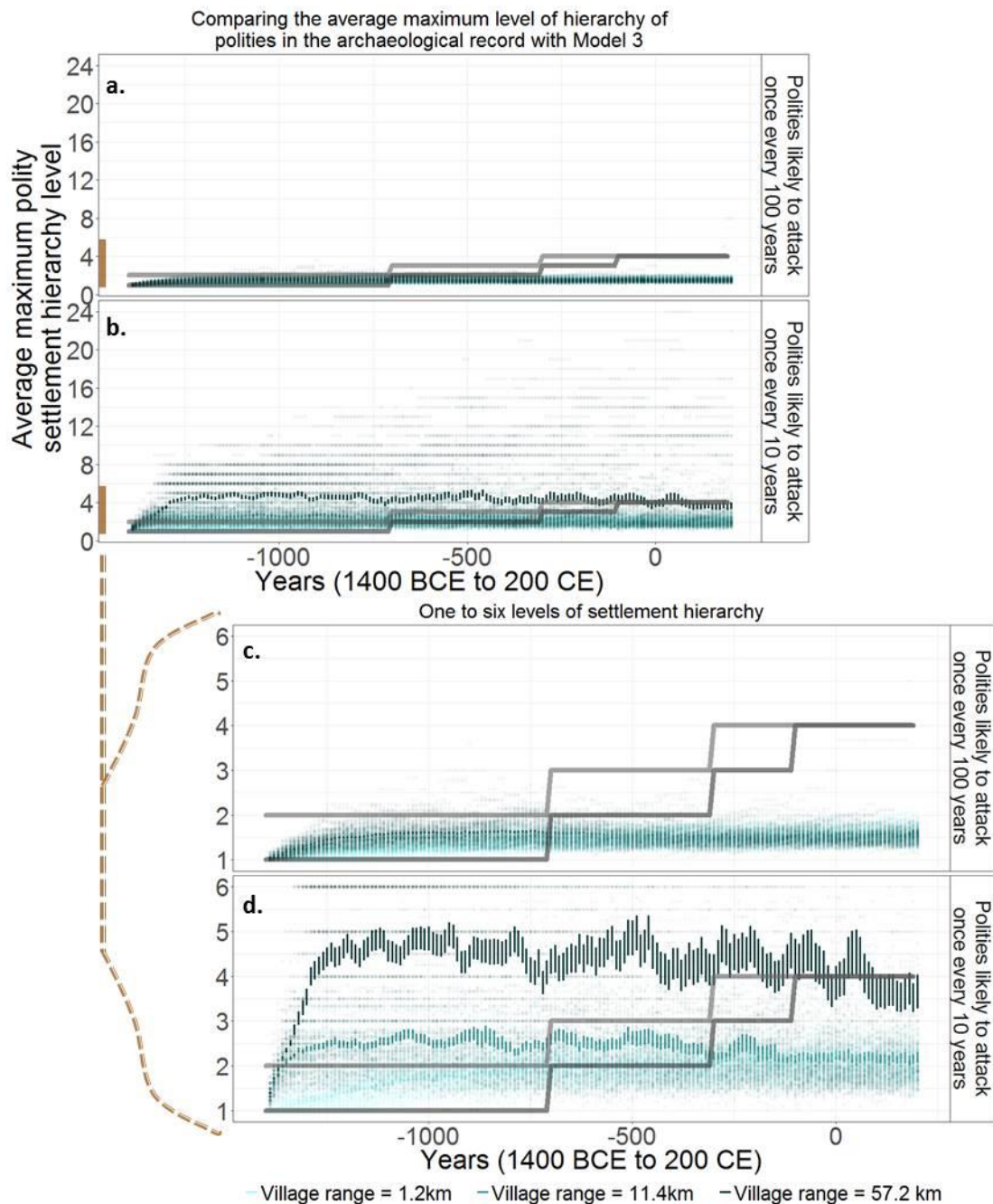


Figure 5.8 Graphs comparing the average maximum hierarchy per polity from Model 3 (shades of teal, translucent points) with archaeological upper and lower estimates for the levels of settlement hierarchy in polities in the Valley of Oaxaca for each phase (light grey and dark grey represent upper and lower estimates of the levels of settlement hierarchy respectively, see Table 5.1 and Sections 5.2.1.1 to 5.2.1.6). The results from repeat model runs are summarised by one standard error above and below the mean (darker coloured blocks). Two parameters are varied in Model 3: village.range and probability.attack (see Table 5.2 for parameter settings). The full data range is shown in panels a and b. A subset of up to seven levels of settlement hierarchy is shown in panels c and d.

The results in Figure 5.8 show that hierarchy does form in Model 3 within a timeframe comparable to the archaeological record. This supports the overall hypothesis that environmental circumscription could have increased the likelihood of the emergence of social complexity in the Valley of Oaxaca. However, the scale of hierarchy formation is dependent on both the range of village movement (*village.range*) and probability of attack (*probability.attack*).

When the probability of attack is low (once every 100 years per polity, *probability.attack* = 0.1, Figure 5.8, panels a and c), the average maximum level of settlement hierarchy between polities is between the upper and lower archaeological estimates for settlement hierarchy for the first 700 years, showing a good fit between the model and archaeological data. However, from the Rosario phase (700 BCE – 500 BCE) onwards, the level of settlement hierarchy in the archaeological record exceeds that seen in the model. If the rate of conflict is increased to once every 10 years per polity (*probability.attack* = 1, Figure 5.8, panels b and d), there is the potential for much higher levels of hierarchy in the model. With a higher rate of conflict, the range of village movement becomes the main factor influencing the similarity between model output and archaeological data.

If villages can only see 1.2km or 11.4km away from their current position (*village.range* = one patch and *village.range* = 10 patches, Figure 5.8, lightest two shades of teal) when there is a high rate of conflict (*probability.attack* = 1) both the model output and archaeological record show polity hierarchy between two and three levels between 700 and 300 BCE. Once the level of hierarchy increases in the archaeological record to four after 300 to 100 BCE, only for villages which can see almost across the whole extent of the valley (*village.range* = 50 patches, Figure 5.8 darkest teal, roughly equivalent to 57.2km) does the average polity hierarchy in the model reach comparable levels.

Given the knowledge that the *village.range* parameter can influence the rate of conflict (by determining the likelihood that a village will encounter another village) (see Chapters 3 and 4, Sections 3.5.2.2 and 4.5), we may conclude from the results in Figure 5.8 that the incidence of conflict will determine how well the model output fits the archaeological data. In the earlier phases, a low

incidence of conflict (though either a low probability of attack or small range of village movement) will show a similar pattern of low levels of settlement hierarchy formation. Increasing the probability of attack and range of village movement will increase the level of hierarchy formation in the model to levels comparable with the archaeological settlement hierarchy from around 700 BCE onwards.

5.5.2 Experiment 2: the effect of resource distribution in the Valley of Oaxaca

In Experiment 1 (Section 5.5.1), we saw that the level of hierarchy reached across all polities in the valley will roughly match the levels of settlement hierarchy seen in the archaeological record, if the rate of conflict is taken into account.

In Experiment 2, I build on these results to investigate the role of resource concentration within the valley on the likelihood of hierarchy formation. Carneiro (1970, 2012a) suggests that resource concentration may amplify conflict between groups of people and thereby increase the chance that social complexity will form. This hypothesis is largely supported by the results discussed in Chapters 3 and 4 (Sections 3.5.1 and 3.5.3), where we saw that increasing the difference in resources between land types could amplify the effect of environmental circumscription. Moreover, in the archaeological record we can see that the first indications of multiple levels of settlement hierarchy appear in the valley with the most resources (see Section 5.2.1). I therefore test the impact of resources by comparing the rate of hierarchy formation in each of the three subvalleys in Model 3. This experiment is intended as a comparison between subvalleys and not to be directly comparable with the archaeological data. I have therefore recorded the average hierarchy level of all villages rather than of all polities, as done for experiments in Chapters 3 and 4.

The division of the valley into three subvalleys is based on the regions suggested by Spencer and Redmond (2003), but adjusted here to ensure almost equal numbers of patches in each subvalley (Figure 5.9). A roughly equal number of patches between subvalleys will ensure that no subvalley has a greater opportunity for resources or population size through a higher number

of patches than the other subvalleys. This will therefore provide a fair test of the importance of any difference in land types on the emergence of hierarchy between the three subvalleys.

I then estimated the total potential resources of each subvalley as the sum of *land-resources* of each patch. As noted in Table 5.2, the *land-resources* of patches are based on the land type classifications of Kirkby (1973) and Nicholas (1989), with the resources for each land type set at the lower estimate of potential maize yield per hectare. The actual difference in resource potential between land types is therefore likely to be more pronounced than is suggested here.

All parameter combinations tested remain as described in Table 5.2 and Experiment 1. Each experiment is run for 50 iterations to 200 time steps. The average level of hierarchy for each model run is recorded as a translucent point for each time step, and summarised by one standard error above and below the mean (darker blocks) among model iterations.

Three separate tests are included here to control for settlement starting location. In Test 1, each village is placed in a position roughly equivalent to the locations of settlements in the Tierras Largas phase (see Figure 5.5). This experiment is the most direct comparison with the archaeological record. However, this also means that most villages are located in the northern Etna valley. The initial starting location may therefore bias the comparison between subvalleys.

In Test 2, each village is located at random on any patch of either Class I or Class II land (see Figure 5.4). Here I assume that people would prefer to occupy the most fertile land where possible, but do not control the specific starting location of each village. This experiment fits the assumptions of the resource circumscription hypothesis most closely, by assuming preference for areas richer in resources. However, the starting location bias towards the northern Etna valley persists as this valley contains the highest number of Class I and Class II patches.

In Test 3, villages are located at random on any Class I, Class II or Class IIIa land (see Figure 5.4). The archaeological starting locations of settlements

suggest that people did live on all of these land types during the Tierras Largas phase (see Figure 5.5). There are also a similar number of patches of the three land types in each subvalley, allowing for an equal chance of villages starting in each subvalley. This experiment therefore provides a control for starting location.

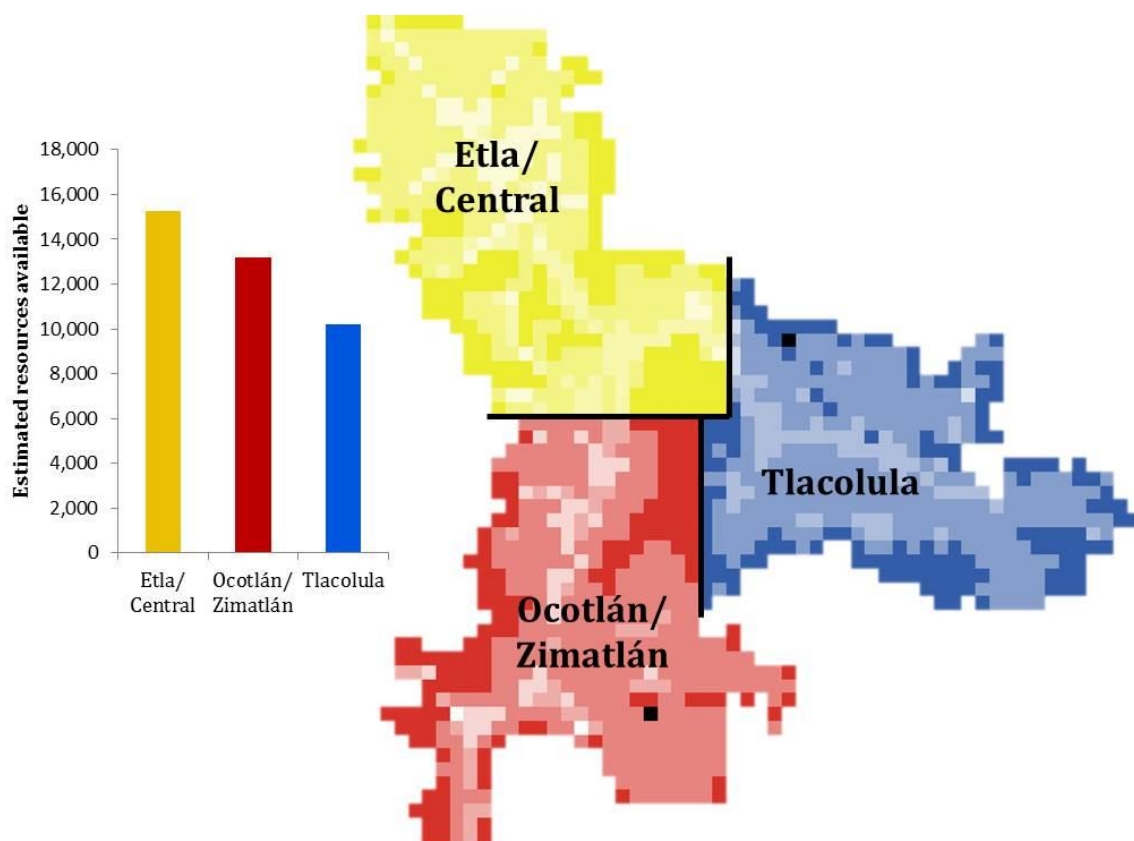


Figure 5.9 The three different subvalleys as delineated in Model 3. The divisions are based on the valley sub-divisions in Spencer and Redmond (2003, p57), but adjusted here to allow for an almost equivalent number of patches in each valley area (and therefore roughly equivalent maximum population size – see Section 5.4.5.2). The highest number of available resources are in the Etna/Central valley (northern valley, in yellow), where the total land-resources of each of the 498 patches is 15,280 (using the land type classifications discussed in Figure 5.4). In the Ocotlán/Zimatlán valley, there are 507 patches with a total of 13,180 land-resources; and in the Tlacolula valley there are 449 patches with a total of 10,220 land-resources.

5.5.2.1 Test 1: Archaeological starting locations

There is a clear distinction in the rate of hierarchy formation when the range of village movement is small (*village.range* = 1) and the probability of attack is high

(*probability.attack* = 1) (Figure 5.10, panel c). The region with the highest resources (Etna/ Central subvalley, yellow) shows the fastest rate of hierarchy formation, while the region with the lowest resources (Tlacolula subvalley, blue) shows the lowest rate of hierarchy formation (Figure 5.10, panel c). The difference between the rate of hierarchy formation in the three subvalleys is also discernible when the probability of attack is lower (*probability.attack* = 0.1, Figure 5.10, panels a and b) and if the range of village movement is increased (*village.range* = 10, Figure 5.10, panels b and d), but the distinction is less clear.

The results from Model 2 (Chapter 4, Section 4.5.3) suggest that a concentration of resources may have an effect on the rate of hierarchy formation insofar as the resources allow for a faster rate of population growth. In Figure 5.11 we can see that population size (in number of villages) does grow faster the more resources are available in a subvalley. However, the difference in rate of population growth between the subvalleys is much greater than the difference in rate of hierarchy formation when villages can range for up to 10 patches distant or when the probability of attack is low (compare panels a, b and d in Figure 5.10 and Figure 5.11). The results from Chapter 4 (Section 4.5) show that the proximity between villages is important in predicting the rate of hierarchy formation. I therefore suggest here that when villages can see further afield, they are more likely to find patches of higher resources to occupy, but also more likely to find unoccupied patches to move to if defeated. This may explain the difference in the rate of hierarchy formation and the rate of population growth seen in Figures 5.10 and 5.11, panels b and d.

These results show that when villages start in locations comparable to the first archaeological settlements, the predictions from both the resource circumscription hypothesis and spatial distribution of hierarchy formation in the archaeological record (Section 5.3) are supported if there is a high rate of conflict and villages do not move far from their original location. However, given that the original location of most villages is the Etna/ Central valley (Figure 5.5), this result may be driven by the initial close proximity of villages in the Etna/ Central valley.

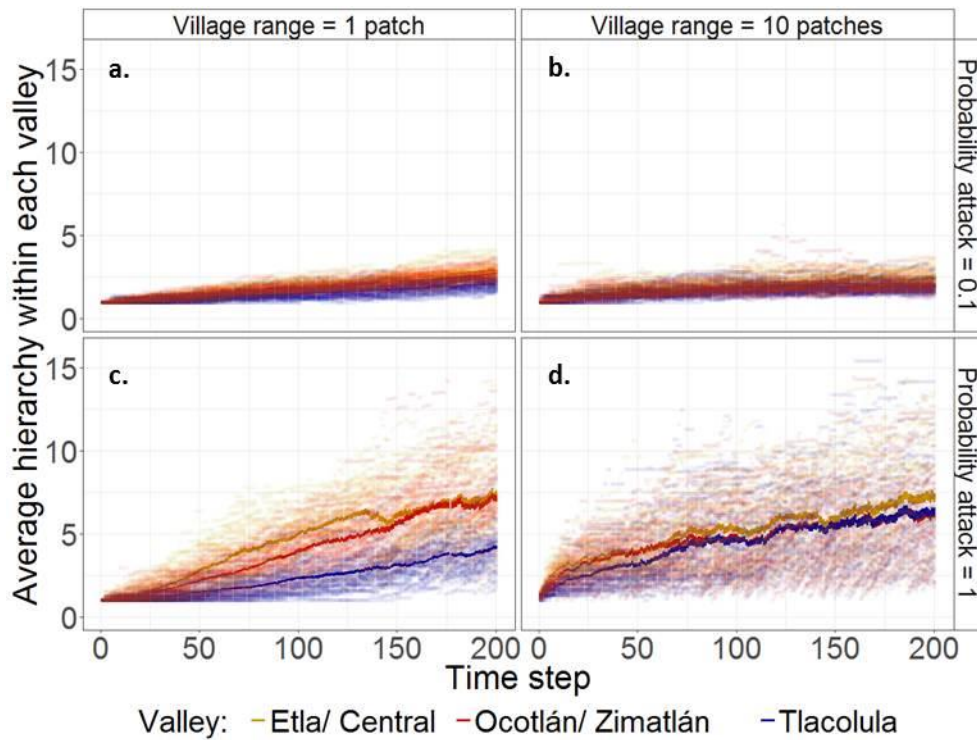


Figure 5.10 The average level of hierarchy among villages in the Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) subvalleys of the Valley of Oaxaca (see Figure 5.9). Villages are located in positions equivalent to those where the first settlements in the valley have been found (see Figure 5.5).

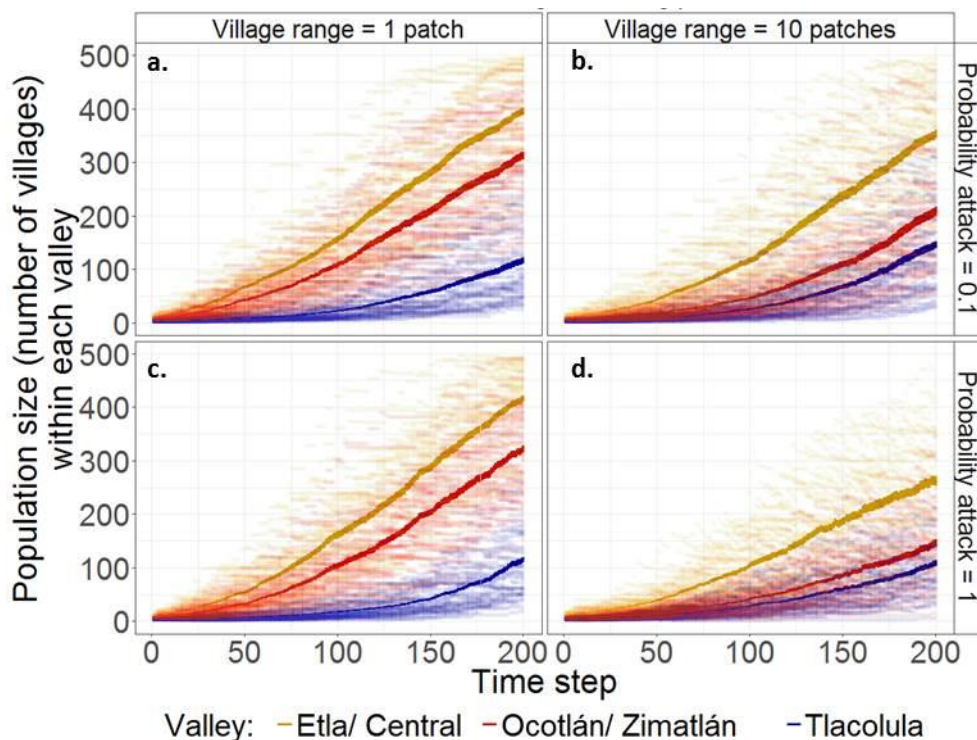


Figure 5.11 The population size (number of villages) of each subvalley: Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) (see Figure 5.9). Villages are located in positions equivalent to those where the first settlements in the valley have been found (see Figure 5.5).

5.5.2.2 Test 2: Class I and Class II land type starting locations

Test 2 shows that the rate of hierarchy formation remains higher in the Etlá/Central subvalley even when villages are not located in specific archaeological positions (Figure 5.12, panel c). However, there is much less distinction between the three subvalleys compared to the results in Test 1, and there is no discernible difference if the village range is wide (*village.range* = 10 patches, Figure 5.12, panels b and d) or if the probability of attack is low (*probability.attack* = 0.1) (Figure 5.12, panels a and b). The difference in rate of population growth between the subvalleys also persists (Figure 5.13), but again, the difference is less pronounced than in Test 1.

We can conclude two things from these results. Firstly, that the population size is more likely to increase more rapidly in areas richer in resources (which in the Valley of Oaxaca is the Etlá/Central valley, Figures 5.13, yellow line), if we assume that people would have chosen more fertile land to occupy by preference. Secondly, that the difference in rate of population growth can increase the likelihood of hierarchy formation, but the effect is most strongly seen when villages cannot move far (*village.range* = 1) and the probability of attack is high (*probability.attack* = 1) (Figure 5.12 and Figure 5.13 panel c). As discussed in Test 1, the difference in hierarchy formation between conditions where villages can see further away or not is likely due to villages being more likely to find unoccupied patches to move to if defeated when *village.range* = 10, despite the more rapid population growth in areas with more resources.

These results are consistent with the results discussed in Test 1 which suggest that multiple levels of settlement hierarchy are more likely to emerge in the Etlá/Central subvalley, albeit less strongly if villages are more evenly distributed across the valley than when they are placed in the archaeological locations. However, the starting location of villages in Test 2 remain biased towards the Etlá/Central subvalley because a greater number of Class I and Class II patches are located there (Figure 5.9).

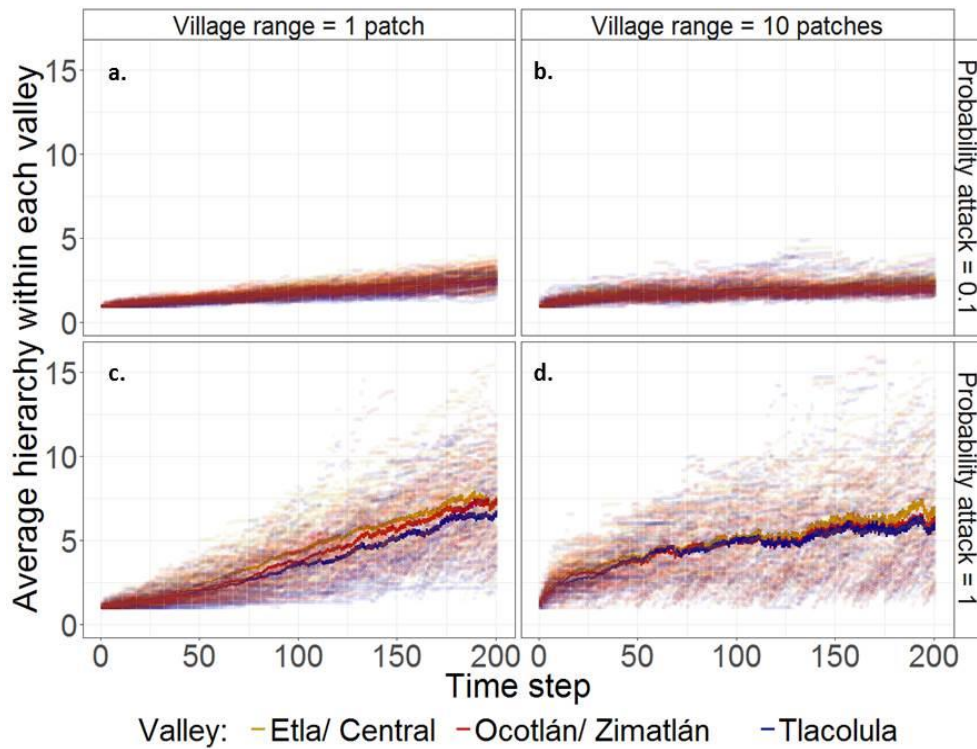


Figure 5.12 The average level of hierarchy among villages in the Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) subvalleys of the Valley of Oaxaca (see Figure 5.9). Villages are located at random on any patch of Class I or Class II land.

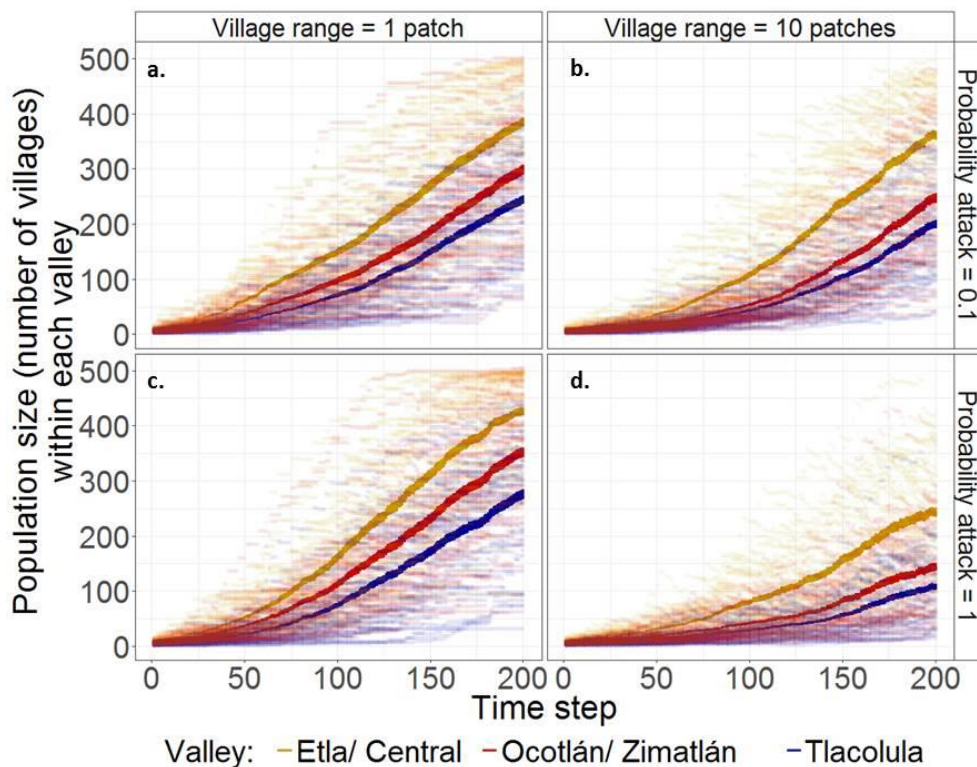


Figure 5.13 The population size (number of villages) of each subvalley: Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) (see Figure 5.9). Villages are located at random on any patch of Class I or Class II land.

5.5.2.3 Test 3: Class I, Class II, and Class IIIa land type starting locations

Test 3 shows that if there is an almost equal chance that the first villages will be placed in each subvalley, the difference in the rate of hierarchy formation between the subvalleys diminishes considerably (Figure 5.14). When the range of villages is small (*village.range* = 1) and probability of attack high (*probability.attack* = 1) (Figure 5.14, panel c), the rate of hierarchy formation is slightly faster in the Etlá/ Central subvalley (yellow line) after 100 time steps, but the difference is very small compared to the results shown in Test 1 (Figure 5.14, panel c). There is no discernible difference in the rate of hierarchy formation between subvalleys when the range of village movement is wider (*village.range* = 10, Figure 5.14, panels b and d) or when the probability of attack is low (*probability.attack* = 0.1, Figure 5.14, panels a and b). However, population size in each subvalley does show a faster rate of growth in the subvalleys with more resources (Figure 5.15, yellow and red lines), particularly if the range of village movement is high (*village.range* = 10, Figure 5.15, panels b and d). This suggests that even though villages are equally likely to be placed in any subvalley, villages are more likely to move to or create villages in areas higher in resources.

From these results we may conclude that when villages are placed equally across the valley but unable to move far (*village.range* = 1, Figure 5.14 and Figure 5.15, panels a and c) there is an almost equal rate of population growth which makes the effect of clustering of villages in each subvalley almost equal. This results in similar levels of hierarchy formation (Figure 5.14, panels a and c), despite a faster overall rate of population growth where more resources are available. However, if villages can move further afield (*village.range* = 10, Figure 5.14 and Figure 5.15, panels b and d), they are much more likely to find the patches of the highest resources and relocate there, resulting in a higher rate of population growth in the subvalley with the highest resources (yellow line). As in Test 1 and Test 2, this does not translate into a higher rate of hierarchy formation because villages are more likely to find unoccupied patches to move away to if defeated.

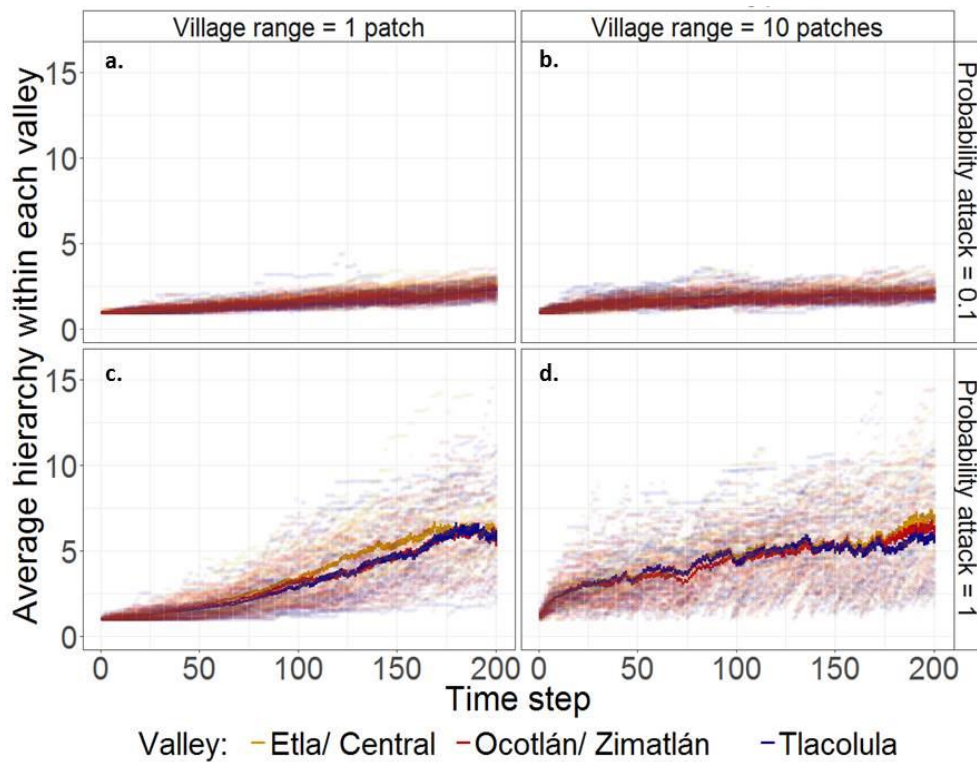


Figure 5.14 The average level of hierarchy among villages in the Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) subvalleys of the Valley of Oaxaca (see Figure 5.9). Villages are located at random on any patch of Class I, Class II, or Class IIIa land.

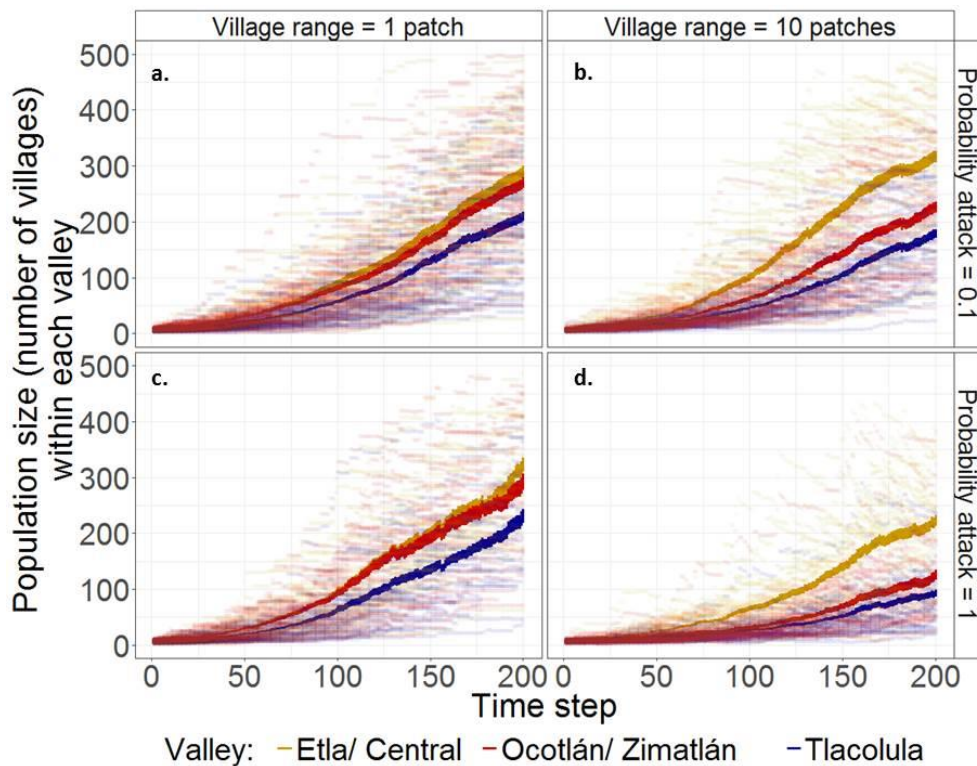


Figure 5.15 The population size (number of villages) of each subvalley: Etlá/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) subvalleys of the Valley of Oaxaca (see Figure 5.9). Villages are located at random on any patch of Class I, Class II, or Class IIIa land.

The results from these three tests show that the concentration of resources can have an effect on the rate of hierarchy formation, as predicted by the resource circumscription hypothesis (Section 5.3), but that the starting location of villages is important in determining where social complexity is most likely to emerge. If we assume that people would by preference occupy the most resource-rich areas, then social complexity is more likely to form in the Etna/ Central valley, as occurred in the archaeological record.

5.6 Discussion

In this chapter I have used an agent-based model to test the extent to which the circumscription hypothesis (described in Chapter 1, Section 1.5) may explain the emergence of social complexity in an area highly circumscribed by surrounding mountains. The Valley of Oaxaca is a known location of the early appearance of multiple levels of settlement hierarchy (Section 5.2.1), and is therefore an ideal test case for the circumscription hypothesis. The agent-based model used here builds on the results discussed in Chapters 3 and 4 from Model 1 and Model 2, which test the circumscription hypothesis in an abstract environment. Archaeological and environmental data were used to tie the model to the conditions seen in the Valley of Oaxaca as much as possible.

The purpose of Experiment 1 was to see whether Model 3, built on the assumptions of the circumscription hypothesis (see Chapters 3 and 4), would produce a pattern of hierarchy formation comparable to that seen in the archaeological record (Section 5.2.1). The results show that similar levels of settlement hierarchy were indeed produced by the model when run for a comparable timeframe, but that the fit depended largely on the incidence of conflict between polities. This shows support for the impact of environmental circumscription on social complexity formation in the Valley of Oaxaca, but also highlights conditions under which environmental circumscription will not have the predicted effect on social complexity formation. Given the current lack of detailed archaeological information on the frequency and intensity of conflict between people in the Valley of Oaxaca, the actual rate of conflict in the past may not have been high enough to produce the levels of settlement hierarchy produced by this model. The results in Section 5.5.1 suggest that conflict may

have occurred relatively frequently (between polities every 10 years) in order to produce the levels of settlement hierarchy seen in the archaeological record (if the assumptions of the role of warfare in the circumscription hypothesis is correct). It may not be possible to further refine information about the frequency of conflict in the past, but doing so would provide firmer conclusions about the role of environmental circumscription and warfare on social complexity formation in the Valley of Oaxaca.

These results also show a potential limitation of the model itself. In Model 3, the distance that villages can see and move is set to a single value within model runs, which does not allow for a more dynamic range of village movement across the valley. The distribution of settlements across the valley in the archaeological record suggests that people preferred to live in clusters, but that they were also willing to move greater distances to unoccupied areas of land to build new settlements. Moreover, archaeological evidence suggests that people were aware of and traded with people from areas outside of the valley (Spencer and Redmond, 2003). This suggests a much wider worldview than villages in Model 3 are currently allowed. Further work on Model 3 may include allowing villages to 'see' much further afield, but with a preference for interactions much closer to their current location. The amalgamation of the different ranges of village movement may produce an even closer fit in the rate of hierarchy formation with the archaeological record, given that the three levels of *village.range* tested here span the full range of archaeological settlement hierarchy (Figure 5.8).

One further limitation highlighted in Experiment 1 is in the process of hierarchy formation itself in the model. As discussed in Chapter 3 (Section 3.2, Figure 3.1), hierarchy will form when one polity conquers another, with the newly subordinate villages maintaining their internal hierarchical structure ranked directly beneath the head-village of the victorious polity. This will in most cases produce polities of up to five levels of settlement hierarchy (see Figure 5.8, panel d), but can sometimes result in vast chains of villages in the same polity, each ranked directly below the other (see Figure 5.8, panel b). Although the overall pattern of hierarchy formation appears similar to that seen in the archaeological record, the model may be improved by allowing for more realistic consequences of conquest. In the Valley of Oaxaca, the majority of settlements

are small in scale with only a few, larger, primary centres between polities (Kowalewski, *et al.* 1989a, 1989b). We may therefore assume that the majority of settlements in a polity are at a lower rank of settlement hierarchy, with a few larger settlements ranked at a higher level of settlement hierarchy within the polity (see Section 5.2.1 for a discussion on settlement hierarchy in the valley). A potential avenue to explore is the growth of individual settlements within the model. When conquered, the newly subordinate villages could be ranked based on their relative size to other villages in the conquering polity, therefore only allowing for multiple levels of settlement hierarchy to form if some villages are substantially larger than others. A system of settlement hierarchy formation linked to settlement size may replicate the processes of settlement hierarchy formation more closely and would allow for a more detailed comparison with the archaeological record. However, this would entail further assumptions about the factors leading to an increase in settlement size and the division of levels of settlement hierarchy. Variations in settlement size have therefore not been included in Model 3.

The purpose of Experiment 2 was to test the assumptions of the circumscription hypothesis more rigorously within the Valley of Oaxaca by analysing the effect of resource distribution across the valley. The first evidence for social complexity formation is found in the ETLA/ Central subvalley, which also contains the highest concentration of more fertile land (see Section 5.4.4 and Figure 5.9). The results of Experiment 2 show that the rate of hierarchy formation is more likely to be higher in the ETLA/ Central valley if the first villages are placed where they are known to have been during the Tierras Largas phase, or if we assume a preference for the most fertile land (Test 1 and Test 2 respectively). However, there may be many reasons why people living in the Valley of Oaxaca chose to settle where they did which are not easily fathomable to us today. Not every settlement location may be directly related to the ease of cultivation (Nicholas, 1989). If villages are distributed more evenly across the valley, the effect of resource concentration on the rate of hierarchy formation disappears even though the rate of population growth is higher in areas richer in resources (Test 3). From these results we may conclude that a higher concentration of resources may increase the likelihood of hierarchy formation, but only if we

assume that people in the past were more likely to choose to settle on fertile land.

There are two further avenues to explore in order to test the impact of resource circumscription on the formation of social complexity. The first is to identify other types of resources and therefore other reasons for settlement location. A preference for location may be determined by access to non-edible resources (such as building materials or metals), or by other, less material reasons, such as proximity to kin or defensibility of the location. A full test of resource concentration in the Valley of Oaxaca requires a more complete understanding of what people in the past considered valuable, and therefore what may have driven their choice of settlement location. The second avenue is to test the impact of resource concentration in other areas of the world, particularly areas such as Mesopotamia, highlighted by Carneiro as locations where the concentration of resources may have had a significant circumscribing impact (see Chapter 1, Section 1.5). By comparing the results from Model 3 here, where the model landscape has a high degree of environmental circumscription, with other areas of the world which may have higher degrees of resource circumscription, it may be possible to compare the impact of environmental and resource circumscription more fully.

Two final limitations of Model 3 relate to both the results in Experiment 1 and Experiment 2. Both relate to the scale of the model. The first limitation is time. To compare the results of Model 3 with the initial formation of social complexity in the archaeological record, I limited the timescale to 1600 years and set the rate of population growth by the population size seen in the archaeological record towards the end of this time period. The number of habitable patches in Model 3 limits the population size to 1454 (see Figure 5.5), but 2455 settlements are present in the valley during Monte Albán V phase (900 – 1500 CE) (Kowalewski, *et al.* 1989a, 1989b). The population of the valley continues to increase after 200 CE, even though the Zapotec polity (the first to unify all inhabitants of the valley) began to decline in size (Balkansky, 1998). A longer timescale may be useful to further investigate the role of population size on the increase of social complexity, and the role of political instability on the persistence of large scale societies over time. The maximum population size allowed in Model 3 does not allow for comparison with the archaeological record

beyond the Monte Albán II phase (100 BCE – 200 CE). In order for a longer timescale to be analysed by this model, the valley must either be divided into smaller patches or multiple villages must be allowed to occupy the same patch of land.

The second limitation is geographical scale. Model 3 includes only the surveyed area of the Valley of Oaxaca (see Figure 5.5), with the assumption that the land surrounding the surveyed boundaries consists of uniformly inhospitable mountains. Although the mountains around the Valley of Oaxaca were formidable, rising to over 3,000m above sea level (Flannery and Marcus, 1976), they were not impassable. The Zapotec polity, which grew during the Monte Albán phases, conquered people occupying valleys outside of the Valley of Oaxaca (Spencer and Redmond, 2003). An additional test of the emergence of social complexity in the Valley of Oaxaca could therefore allow for some movement of people and resources across the mountains to access neighbouring valleys. However, as discussed in Chapter 2 (Section 2.2) it is important to keep the model as simple as possible and to set the scale of the model to match the defined purpose. In Model 3, I chose to limit the geographical extent of the model to cover only the surveyed region of the Valley of Oaxaca to allow comparison with the available archaeological data. Further elaborations of the model may increase realism but will not necessarily offer additional insights on the effect of circumscribing conditions in the Valley of Oaxaca.

5.6.1 Conclusion

The purpose of Model 3 was to test the findings of the abstract agent-based Models 1 and 2 (discussed in Chapters 3 and 4) against an example of social complexity formation in the archaeological record. The results confirm that the mountainous surroundings of the Valley of Oaxaca may have increased the likelihood of social complexity formation. Moreover, the model confirms that the Etlá/Central subvalley was the most likely region for an increase in social complexity, if we assume that people at the time would have occupied more fertile land where possible.

However, the effects of environmental and resource circumscription alone are insufficient to explain the formation of social complexity. The results from Model

3 also show that the likelihood of social complexity formation is greatly dependent on the incidence of conflict and on the distance that people were willing to travel from their original location. Without further archaeological evidence to confirm the continuous prevalence and intensity of warfare in the Valley of Oaxaca over this time period, or the factors behind choice in settlement location, we cannot conclusively say that circumscribing conditions did lead to an increase in social complexity.

Chapter 6: Conclusion



The evolution of complex human societies was not inevitable, and perhaps also not predictable until relatively recently in our past. At the start of this thesis, I discussed archaeological evidence for the initial emergence of social complexity in human societies. Our understanding of the past, as seen only through the lens of the archaeological record, will always be incomplete. But this does not and should not diminish our attempts to interpret it. In Chapter 1, I drew attention to one particular line of thought to explain why social complexity emerged in some areas of the world before others. The circumscription theory described by Robert Carneiro (1970, 2012a) suggests that warfare is at the heart of the formation of complex societies, and that any conditions which limit population dispersal (be it through environmental barriers, concentration of resources, or social boundaries) would intensify the effect of warfare. The theory sounds plausible in verbal form, and can even be used to explain the emergence of specific societies in a few highly circumscribed areas in the world. However, a verbal formulation of any hypothesis may mask assumptions and logical inconsistencies which are difficult to identify. Finding another's assumptions, on top of our own inherent biases, requires a great deal of self-reflection and rigorous thought. In Chapter 2 I described the role of formal models in aiding efforts to find those implicit assumptions in a way that can be understood by others.

A successful model will simplify reality in a way which allows us to better understand some part of the immense complexity of our own world. Agent-based models are a particularly useful tool to use in archaeology because these models can allow for complex phenomena to emerge from relatively simple rules, with elements of stochasticity to allow for the many unknowns in our knowledge of the past. In Chapter 2, I discussed the benefits of building a

model up from the simplest components, both for our understanding of the processes we want to investigate and to reduce the scope for human error in the code. I continued on to discuss previous modelling work which had been done to aid our interpretation of the archaeological record, particularly those models which relate to parts of the circumscription theory outlined in Chapter 1. The following three chapters (Chapters 3, 4, and 5) followed the principles outlined in Chapter 2 to test the circumscription theory from the simplest components up to a model which could be compared with the archaeological record.

In the first and simplest model (Chapter 3, Model 1), I simplified the circumscription theory down to the core parts to include agents (in this case villages) which could enter into conflict with one another situated within model landscapes of high or low levels of environmental and resource circumscription. Additional parameters (the level of tribute extraction, the internal stability of polities, the distance that villages could 'see', and the distribution of fertile patches) were included in the model to clarify implicit assumptions of the circumscription theory. From this model, we learned that the degree of environmental and resource circumscription could indeed have an impact on the rate of hierarchy formation, if we assume warfare between villages was present. An additional and unexpected result was the importance of the layout of land types. This made it clear that conditions of environmental and resource circumscription are not sufficient to increase the rate of hierarchy formation if villages are not able to detect these circumscribing conditions, or detect rival villages within the landscape. This laid the foundations for the importance of the proximity between villages found in Chapter 4 (Model 2), where I added population growth to the model.

Social circumscription, specifically population pressure, is another core part of the circumscription theory. I did not include population growth in Model 1 in an effort to understand the effect of environmental and resource circumscription with as few complicating factors as possible. In Model 2, I unpicked what exactly population pressure means in the context of the circumscription theory, and therefore what effect population growth would likely have on the rate of hierarchy formation. The results confirmed the importance of the proximity between villages suggested by both the circumscription theory and the results

from Model 1, but in some surprising ways. Instead of a clear distinction between the effects of high and low levels of environmental and resource circumscription suggested by Model 1, Model 2 showed that an extremely fertile and uncircumscribed landscape can result in a very rapid rate of hierarchy formation if the population is allowed to grow. With more villages in the world, there were ever more opportunities for conflict between rival villages and therefore much greater potential for hierarchy formation. The effect of population size notwithstanding, the model also showed that confining villages to a small initial area, or allowing villages to roam across inhospitable land to pockets of isolated resources, would increase the rate of hierarchy formation as villages were more likely to come into conflict with one another. These results therefore confirm the importance of environmental, resource, and social circumscription on the emergence of social complexity, but with additional insights into the landscape conditions most likely to increase the effect of each. From these conclusions, I suggest that environmental circumscription would most likely have an effect if: settlements were faced with a harsh circumscribing border, if those villages were hemmed in together, and if that same area also had sufficient resources to allow population growth.

As a final test of the circumscription theory in this thesis, I adapted the abstract models of Chapters 3 and 4 to the landscape seen in the Valley of Oaxaca in Mexico, a fertile valley circumscribed by mountains. From the archaeological record in this valley we can trace the emergence of social complexity from a few small villages to the formation of a polity with enough power to unify the whole valley. Model 3 showed that similar levels of settlement hierarchy could form in the model within a comparable timeframe, given the environmental, resource, and social conditions of the valley as seen in the archaeological record. But more importantly, Model 3 also showed us the conditions under which settlement hierarchy was much less likely to form: if there was little conflict, or if villages are not able to venture more than just over a kilometre from their original location. Archaeological evidence from the valley can only tell us with some certainty that conflict did occur, and that people were aware of places far beyond their current settlement. Further detail on the frequency of conflict and the distance over which people would reasonably move or conduct warfare is less precise. I therefore conclude that further archaeological research is needed

to confirm whether or not the circumscription theory could explain the emergence of social complexity in the Valley of Oaxaca.

An additional insight from Model 3 is the importance of settlement location in predicting where settlement hierarchy is most likely to increase. If we assume that people are more likely to initially occupy, or live near to, the most fertile land available, the model results show that hierarchy is more likely to emerge in the northern ETLA subvalley, where the majority of the richest land is located in the Valley of Oaxaca.

To apply the insights from Model 3 more broadly, we may expect social complexity to have emerged in areas rich enough in resources to support a growing population, but bounded by a sharp border of less habitable land. To further test whether circumscribing conditions may be an underlying factor in other cases of the emergence of social complexity, I propose using archaeological and environmental data from other parts of the world to parameterise Model 3. Ideally, these locations would cover a range of different circumscribing and non-circumscribing conditions, to complement the insights gained from one highly environmentally circumscribed valley.

Overall in this thesis, I have used agent-based models to test the logic and applicability of the circumscription theory to explain the emergence of complex human societies in the past. In doing so, I have also demonstrated the benefits of using formal modelling methods, such as agent-based models, to confront our assumptions and biases when interpreting archaeological data.

Supplementary Materials 1 (Chapter 3)

3.7 Supplementary Materials

The NetLogo model script for Model 1 can be seen as 'Model_One.nlogo' at: https://github.com/ajw246/Thesis_code.git

3.7.1 ODD protocol sections in addition to those discussed in the main text

3.7.1.1 Design concepts

3.7.1.1.1 *Basic principles*

This model has been built to test the logic of Carneiro's environmental circumscription hypothesis in an abstract environment. The aim of the model is therefore to observe the impact of varying the severity of environmental conditions on polity formation over time.

3.7.1.1.2 *Emergence*

The size of polities (determined by the number of villages within the polity) and number of levels of hierarchy connecting those villages in the same polity are emergent phenomena in this model. The pattern of polity size increase and average level of hierarchy increase begins to emerge from the end of the first time step.

3.7.1.1.3 *Adaptation*

Villages will weigh up the costs and benefits of whether to become subordinate or potentially lose resources by moving to a new area if they are defeated in conflict. Villages, and polities as collections of villages, therefore adapt to the situation they find themselves in. As a side effect, polities which are larger (include more villages) are more powerful in conflict and so are more likely to defeat and subsume other polities. Larger polities therefore tend to emerge.

3.7.1.1.4 Objectives

The objective of all individual villages is to maximise their resource gain, through either conquering neighbouring villages or deciding on their most cost effective option if defeated.

3.7.1.1.5 Learning

Villages do not learn or alter their behaviour over time. They respond to the environmental and social conditions they are presented with.

3.7.1.1.6 Prediction

Villages predict the costs of becoming subordinate by subtracting the cost of tribute as a proportion of their current resources. The villages do not pay the cost if they become subordinate but will make the decision of moving or staying assuming they will have to pay the cost of tribute. Villages cannot look further ahead to assess the potential cost of being subordinate over time.

3.7.1.1.7 Sensing

Villages can locate other villages within the radius *conquering.area* (see Figure 3.5 for an illustration of this distance). Villages are also aware of the resources contained and occupancy of the four directly adjacent patches to their current location.

3.7.1.1.8 Interaction

Polities will interact through conflict. In each time step, one village from each polity will find a village of a rival polity within the radius *conquering.area* to attack. All other villages in the polities of the attacking and defending villages become involved. If the defending polity is defeated, the whole polity becomes subordinate to the attacking polity, with the highest-ranking village of the defending polity ranked directly below the highest-ranking village of the attacking polity. The internal hierarchy of the defending polity remains the same within the new polity (see Figure 3.1 for an illustration of this process).

3.7.1.1.9 Stochasticity

Villages are initially located at random on any green patch (patches with *land.resources* = 5). One village within a polity will be chosen at random to check its surrounding environment within a radius of *conquering.area* for neighbouring villages of a different polity to attack. One subordinate village within a polity will also be chosen at random to decide whether to rebel from the polity or not.

3.7.1.1.10 Collectives

Villages form collectives as polities. This is emergent to the extent that the size of polities can change over time, but the total number of independent polities possible at any one time is equal to the total number of villages (*initial.villages*) because each village can form a polity of one village.

3.7.1.1.11 Observation

The levels of hierarchy of each village is recorded over time. The average level of hierarchy for all villages at the end of each time step is recorded for model analysis.

3.7.1.2 Initialisation

The model world is set up by dividing patches into either more or less fertile land, with the difference in resources between the two types determined by the *resource.difference* parameter. The resources owned by each patch does not change over one model run. The spatial distribution of green patches is either concentrated in a continuous band or random spread across the model world. The number of more fertile patches is varied between model runs by the *land.width* or *number.fertile* parameters, depending on the patch distribution (see Table 3.2 for details). Villages are then created to populate the model world to the number set in *initial.villages*, and placed on a randomly chosen, unoccupied patch with the highest proportion of resources. Each village starts as an independent polity.

3.7.1.3 Input data

The model does not use input data to represent time-varying processes.

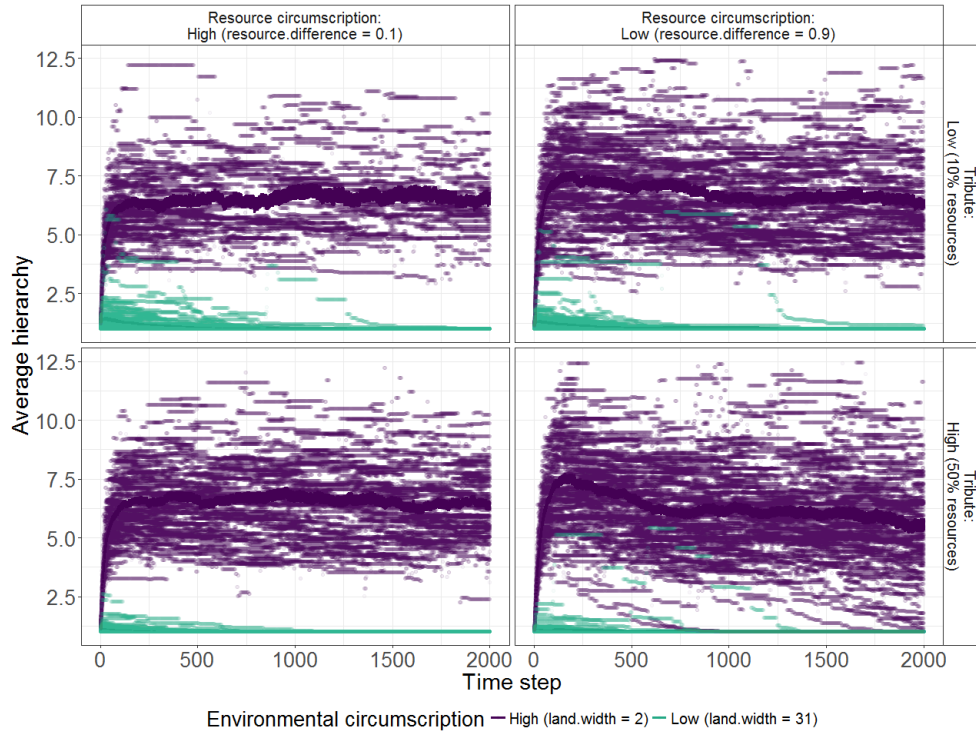
3.7.2 Additional model runs with 2000 time steps

Example experiments, run for 2000 time steps. The average hierarchy level of all villages is recorded at the end of each time step, and summarised by standard error bars. Parameter settings are in Table 3.4.

Table 3.4 Parameter settings for the experiments run for 2000 time steps for Model 1. Results are in Figure 3.11.

Parameter	Parameter values
<i>land.width</i>	2, 31
<i>number.fertile</i>	66, 1023
<i>resource.difference</i>	0.1, 0.9
<i>tribute</i>	0.1, 0.5
<i>initial.villages</i>	50
<i>conquering.area</i>	1
<i>probability.fragment</i>	0.01
<i>probability.attack</i>	1

Concentrated patch distribution



Random patch distribution

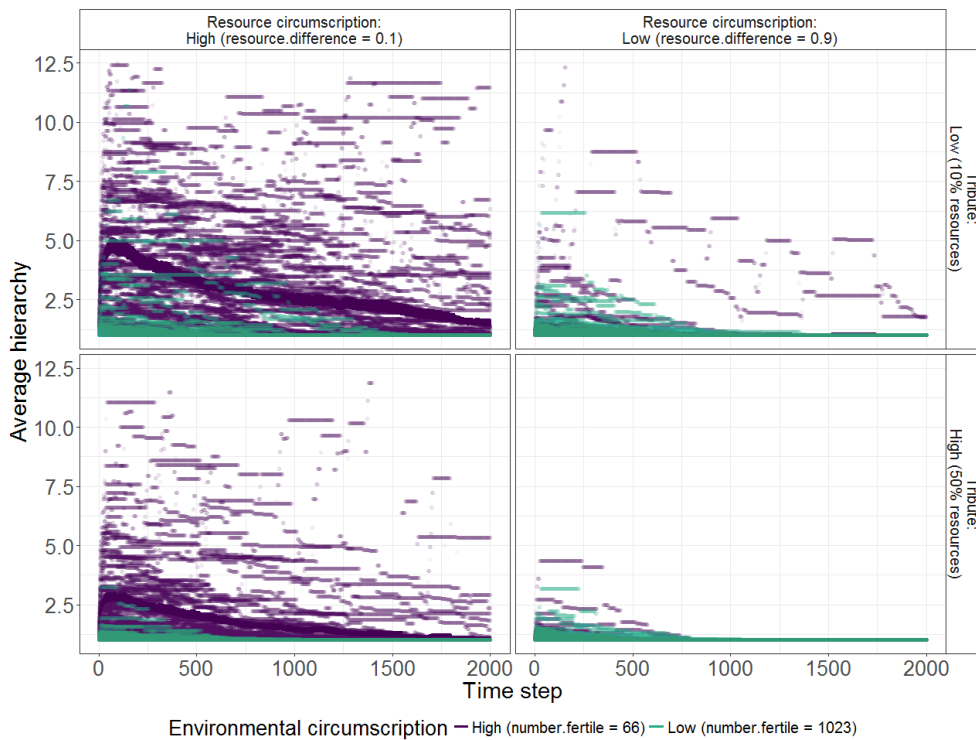


Figure 3.11 Graphs showing results from 100 iterations of the experiment in Table 3.4, for 2000 time steps.

3.7.3 Additional parameter settings of concentrate and random patch environments

3.7.3.1 Concentrated patch distribution

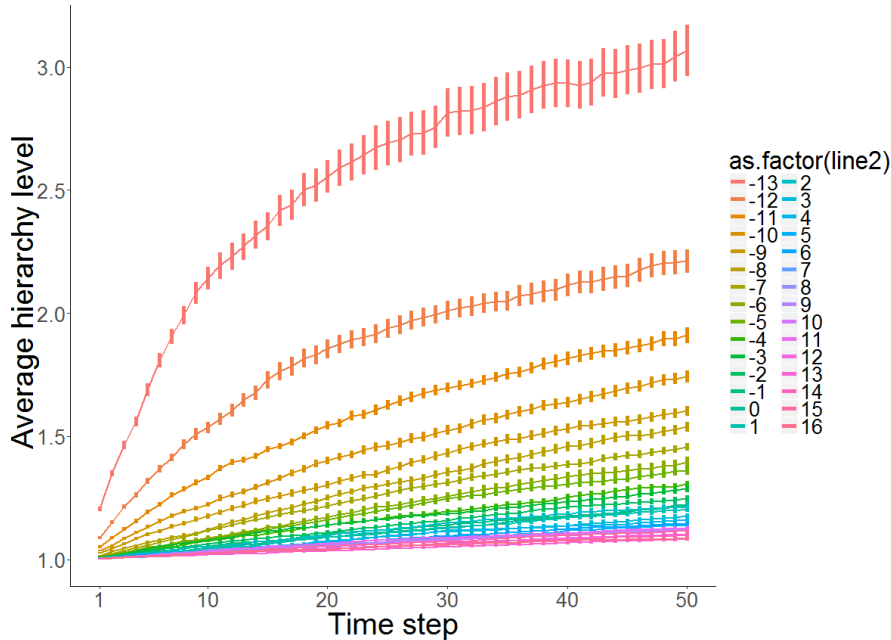


Figure 3.12 Graphs showing the results from additional settings for the *land.width* parameter (here labelled *line2*). Experiments were repeated for 50 iterations and summarised with standard error bars. Total villages = 40; *resource.difference* = 0.1; *probability.attack* = 1. These results show how there is a great difference in the rate of hierarchy formation when the area of fertile land is small (*line2* = -13 to -10), but there is very little difference in the rate of hierarchy formation when the area of fertile land is large (*line2* = -3 to 16). This suggests that the most important factor in the rate of hierarchy formation here is whether a village is located next to a border between more and less fertile areas. In model environments where there is a wide area of fertile land, more villages are likely to be located away from the less fertile patches and so are free to move.

3.7.3.2 Random patch distribution

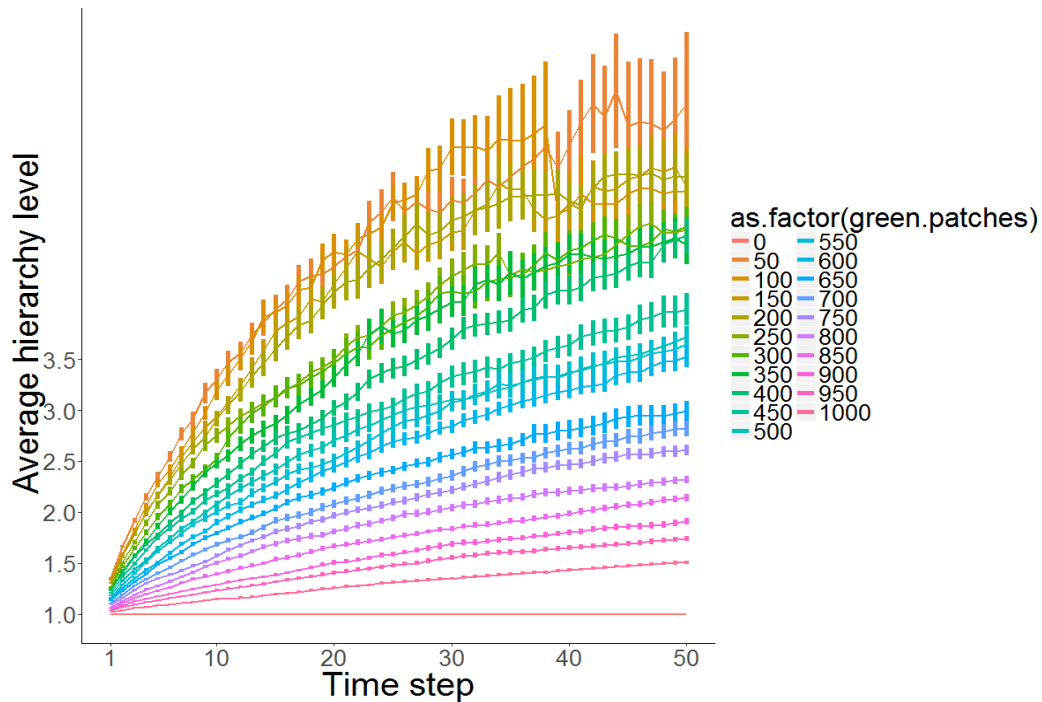


Figure 3.13 Graphs showing the results from additional settings for the number.fertile parameter (here labelled green.patches). Experiments were repeated for 50 iterations and summarised with standard error bars. Total villages = 40; resource.difference = 0.1; probability.attack = 1. The conclusion that the borders experienced by villages (as opposed to the absolute area of fertile land) is more important in determining the rate of hierarchy formation is supported by the random patch distribution results. Here, villages are more likely to be located next to a less fertile patch even in the low circumscription environments. The effect of increasing the area of fertile land produces a more consistent pattern of decreasing the rate of hierarchy formation.

Supplementary Materials 2 (Chapter 4)

4.7 Supplementary Materials

The NetLogo model script for Model 2 can be seen as 'Model_Two.nlogo' at: https://github.com/ajw246/Thesis_code.git

4.7.1 ODD protocol sections in addition to those discussed in the main text

Many of the points discussed here are similar to those for the first model in Chapter 3 (see Section 3.7.1 for ODD sections for the model in Chapter 3).

I will only add that in Section 3.7.1.1.3, villages also assess surrounding patches for the suitability of a newly created village; in Section 3.7.1.1.7, villages can 'see' within the radius *village.range*; in Section 3.7.1.1.9, the *land.resources* of patches ranges from 0-100; and, in Section 3.7.1.1.11, the level of experienced social and environmental circumscription, and the population size (in number of villages) is recorded in addition to the average hierarchy level of all villages in each time step.

Supplementary Materials 3 (Chapter 5)

5.7 Supplementary Materials

The NetLogo model script and map used in Model 3 can be seen as 'Model_Three.nlogo' and 'LandTypesBW3.jpg' at:
https://github.com/ajw246/Thesis_code.git

5.7.1 ODD protocol sections in addition to those discussed in the main text

Many of the points discussed here are similar to those for Model 2 in Chapter 4 (see Section 4.7.1 for ODD sections for the model in Chapter 4).

In Model 3, there are five land types, as opposed to the two included in Model 1 and Model 2. I have therefore adjusted the code whereby a village chooses a new location to move to if defeated. In Model 3, the village will randomly choose a patch within range, but is more likely to choose a patch with a greater number of *land-resources*. This section of code was adapted from the NetLogo Lottery Example in the Models Library (available in the downloaded NetLogo software package, version 6.0.1, written by Uri Wilensky). In the population-growth submodel, villages will choose any patch within range which has some *land-resources* ($land-resources > 0$), but the likelihood of creating a new village is determined by the number of *land-resources* the chosen patch has. If the chosen patch has the highest possible resources ($land-resources = \text{Class I}$), a new village will be created. If the chosen patch has half as many resources as a Class I patch, then there is a 50-50 chance that a new village will be created there.

5.7.2 Land type maps

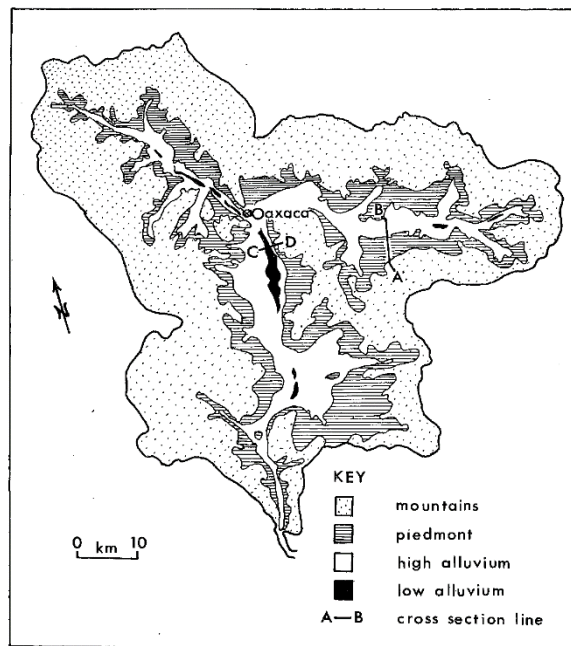


Figure 5.16 Kirkby (1973, Figure 3, p10), map showing the different environmental zones of the valley, as recorded by Kirkby (1973).

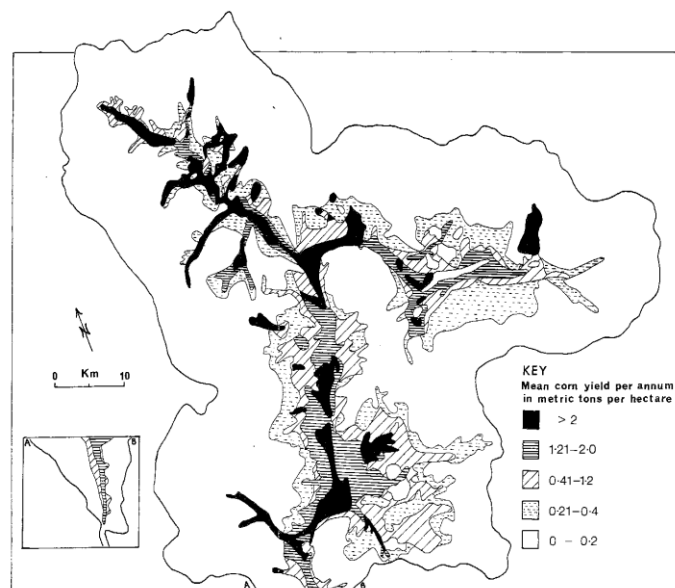


Figure 5.17 Kirkby (1973, Figure 25, p66) Map showing the distribution of maize corn yield per hectare in the Valley of Oaxaca. Key: black = >2 metric tons per hectare; horizontal stripes = 1.21 – 2.0 metric tons per hectare; diagonal stripes = 0.41 – 1.2 metric tons per hectare; dots = 0.21 – 0.4 metric tons per hectare; and white = 0 – 0.2 metric tons per hectare.

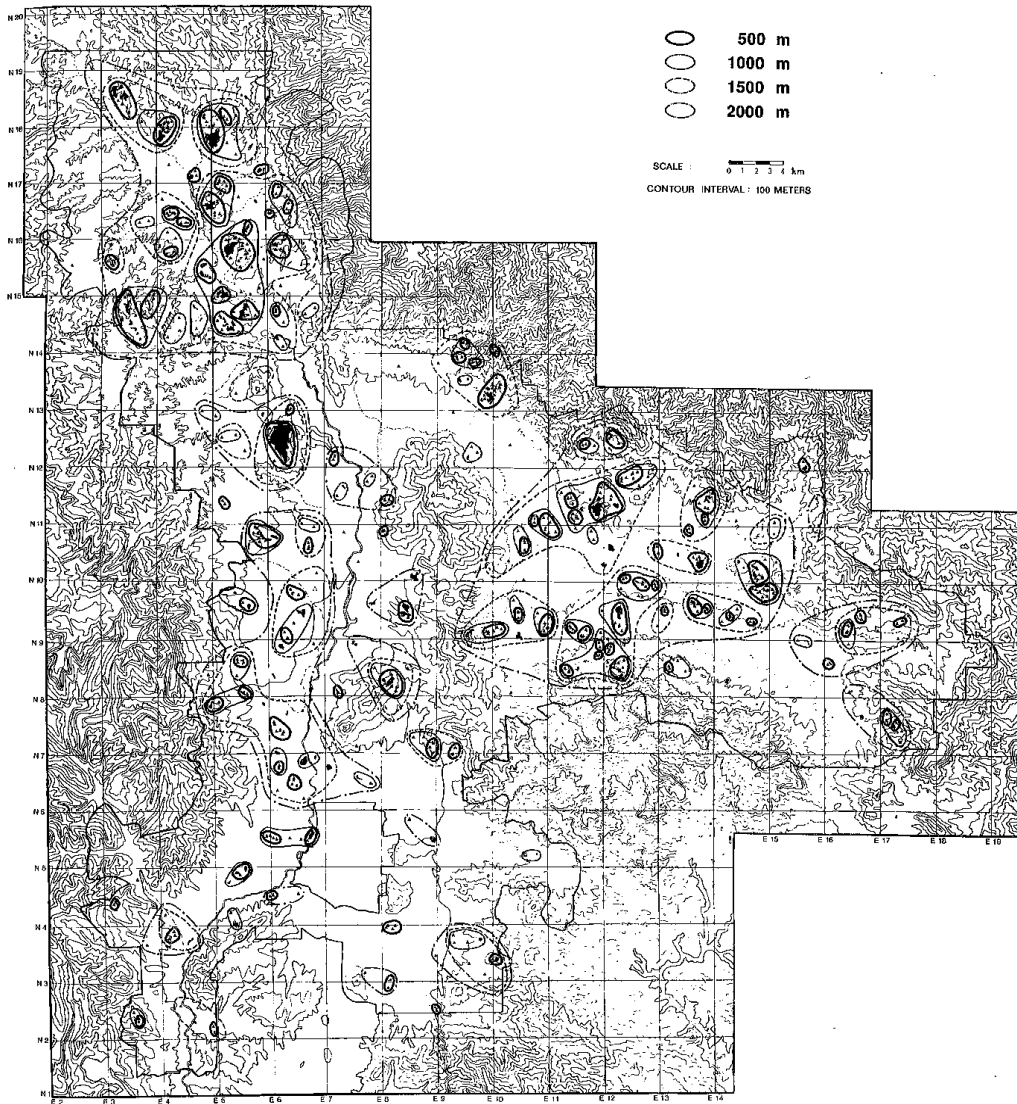
5.7.3 Archaeological settlement distribution

Two maps (Figures 5.18 and 5.19) showing the distribution of settlements across the Valley of Oaxaca at the beginning and end of the time period I focus on in this chapter, from Kowalewski, *et al.* (1989a, Figures 3.1, p56; and Figure 7.2, p163). Black triangles and dots represent settlements. The settlement locations in the Tierras Largas phase are used to locate the initial villages in the model (see Section 5.4.5.1). In the later phase (Monte Albán II), circles are drawn around clusters of settlements at distances of 500 to 2000m.

Figure. 5.18, Tierras Largas phase (1400 - 1150 BCE)



Figure 5.19, Monte Albán II phase (100 BCE - 200 CE)



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