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A formal test using agent-based models of the circumscription theory for the evolution of social complexity

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ABSTRACT

The emergence of social complexity in human societies is a long-debated topic in archaeology, with competing hypotheses proposed and argued for using archaeological evidence. However, formal testing of these hypotheses is generally lacking. Here, we present and analyse an agent-based model to test the effect of environmental, resource, and social barriers to population movement – collectively known as 'circumscription' – on the rate of hierarchy formation. The results show that social circumscription is the largest driver of social complexity by increasing proximity between settlements. Environmental and resource circumscription can negatively impact the emergence of social complexity when the conditions separate the population spatially but can amplify social complexity when the conditions increase proximity between settlements. In providing a detailed test of the assumptions and predictions of circumscription theory, our abstract model provides insight into the conditions that are most likely to result in the emergence of social complexity in the real world.

1. Introduction

The rise of complex human societies, characterised as populous, centralised, sedentary, and territorially expansive, within the last 6000 years, has long puzzled archaeologists and anthropologists (Trigger, 2003; Flannery and Marcus, 2012). Debates surrounding the likely causes of the emergence of these characteristics of social complexity draw on a wide range of evidence and interpretation, from the collective necessity of organisation for subsistence (Boserup, 1965; Wittfogel, 1957; Johnson and Earle, 2000; Earle, 2002), to trade (Rathje, 1971; Helms, 1988, 1993; Sherman et al., 2010), and elite ideology and charismatic individuals (Mann, 1986; Marcus and Flannery, 2004; Flannery, 1972). Specific pathways and patterns of socio-political change have been well described but there may be general similarities in processes that are common between cases across different times and locations. Recent research has adopted a cultural evolutionary perspective looking at the evolution of complex human societies (e.g. Turchin et al., 2013).

One influential attempt to unify the environmental and social factors affecting socio-political organisation into a single, coherent theory for the formation of social complexity was provided by Carneiro (1970, 1988, 2012a). His *circumscription theory* suggests that conditions which circumscribe, or limit, population movement intensify conflict between groups of people and increases the likelihood of the emergence of complex societies. Competition over limited resources or space will lead to increased incidence of conquest warfare (Carneiro, 1970, 1988, 2012a, 2012b). It is assumed here that the conflict caused by circumscribed conditions will result in the conquering or subjugation of one group of people over another, thus increasing the size of one polity (in population and territory size) with the loss of autonomy of the other.

Carneiro suggests that circumscribing conditions may take three main forms: (1) environmental, where there are geographical barriers to population movement; (2) resource, where resources are concentrated in certain areas; and (3) social, where surrounding land is already occupied by neighbouring groups of people (Carneiro 1970, 1988, 2012a, 2012b).

Locations circumscribed by geographical barriers to population movement, such as the deserts along the River Nile in Egypt and along coastal Peru, mountains along sections of the Yangtze River in China and surrounding the Valley of Oaxaca in Mexico, and ocean surrounding Pacific islands, show evidence for both environmental circumscription and the early formation of complex societies (Carneiro, 1970, 2012b; Sandeford, 2018; Schönholzer, 2017; Gayubas, 2015; Hauer, 1988; Kirch, 1988; Kirkby, 1973; Nicholas, 1989; Yi, 2012; Deflem, 1999).

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Other areas with less extreme environmental circumscription may nonetheless limit population movement through the concentration of resources in certain areas, such as along the Amazon and Yangtze Rivers and lowland Mexico, where resources are concentrated in areas of highly fertile alluvial soil or sources of raw materials (Carneiro, 1970, 2012a, 2012b; Yi, 2012).

However, we find there to be substantial overlap between the environmental and resource circumscription hypotheses as both describe environmental limitations to subsistence and mobility. We suggest instead that environmental and resource circumscription can be grouped together into a measure of 'geographical circumscription', following Perret and Currie (2023). Consequently, the more inhospitable the surrounding landscape (i.e. the greater the geographical circumscription), the less likely it is that people will opt to move there away from conflict over the resources available in their current location. This is based on a cost/benefit assumption: it may be overall less costly for a group of people to remain put and pay the costs of being conquered, such as a tribute payment or tax, than to move to a new location where resources are less accessible. We acknowledge that the costs of being conquered may be manyfold larger than payment of a portion of produce. The cost is intended to be a catch-all term that could encompass any cost or harm incurred during conflict or any cost of moving away.

Carneiro (1970, 2012a) also suggests that social barriers can create boundaries as effective as impenetrable environmental barriers. The social circumscription hypothesis suggests that occupied neighbouring territories may limit population movement if people cannot move into, or through, areas defended by other societies. Circumscription could therefore be created by neighbouring societies even if the surrounding landscape is rich in resources and otherwise beneficial to move to. Territorial borders are much more difficult to reliably identify in the archaeological record because they may be permeable or shift over time as political allegiances change. Carneiro relies on the idea of social circumscription to explain the formation of complex societies in areas which have no clear conditions of geographical circumscription, such as the broadly uniform and expansive landscape of the Eurasian steppe (Carneiro, 2012a, 2012b). However, none of the areas where complex societies first formed show evidence only for social circumscription without environmental circumscription (Carneiro, 2012a, 2012b; Sandeford, 2018). Nor does Carneiro explicitly define how population pressure may arise, or how populations may become clustered. Population pressure may occur when population size reaches or exceeds the carrying capacity of resources within the environment. However, carrying capacity is notoriously difficult to calculate for human populations because yield can change with cultivation methods or available labour force and trade can transfer resource supplies over long distances (Thurston and Fisher, 2007).

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 (Aldenderfer, 1991; Lake, 2015; Smaldino, 2017). 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 or rival societies (Schacht, 1988; Marcus, 2012; Peregrine, 2012). Arguments against the circumscription theory have also been made by criticising the reliance on warfare as a main mechanism of change (Stocker and Xiao, 2019); the relative absence of conquest warfare between independent communities and chiefdoms in cross-cultural data (Zinkina et al., 2016); the lack of evidence for hard geographic barriers or population pressure in areas of state formation including the Valley of Oaxaca, Egypt, and Uganda (Gibson, 2012); and criticisms that the conditions of circumscription require more precise definition (Schacht, 1988; Graber, 1988; Scott, 2011).

Critics of the circumscription theory raise important points, but often rely on citing particular case studies that do not appear to align with the predictions of the circumscription theory. However, recent work has started to shift the focus from case studies to biological and mathematical modelling of the circumscription theory to assess the extent to which it could explain social complexity. Perret and Currie (2023) adapt reproductive skew models to simulate the evolution of inequality in conditions of geographical circumscription. Other modelling work has been used to investigate the evolution of social complexity on a similar scale of individual decision-making (Daems, 2019, 2021); the effect of circumscription and environmental conditions (Scott, 2011; Turchin et al., 2013); and the effect of conflict (Gavrilets and Fortunato, 2014; Gavrilets et al., 2010).

We aim to test the circumscription theory, as described by Carneiro, as an agent-based model (ABM) and explore the conditions under which social complexity increases most rapidly. By using the explicit assumptions described by Carneiro to build the ABM, we are forced to define the implicit assumptions of the theory that have not been discussed previously yet are integral (Table 1). Our objective is to test whether circumscribing conditions may lead to the predicted increase in social complexity formation, even when the implicit assumptions of the theory are accounted for. We can then compare which conditions in the ABM have the greatest effect and assess whether they correspond with any real-world conditions, and therefore whether circumscribing conditions *could* have contributed to the initial emergence of social complexity in human societies. Our ABM forms a firm foundation for future testing of specific places known to have early evidence of social complexity formation with a tool to explore the relative impact of the different circumscribing factors involved. By extension, future archaeological research may also use our model to identify the data needed to support or refute the circumscription hypothesis.

2. Methods

We build on previous modelling approaches to create an agent-based model (ABM) designed to simulate the effects of circumscribing conditions, as described by Carneiro, at the scale of settlements to compare patterns of change directly with archaeological data. We use an agent-based approach to include the flexibility of individual decision-making within the model while controlling the environment and parameter space for sensitivity analysis and comparison with archaeological data, following Romanowska's (2015) ABM guidelines for archaeology. The conditions tested within the model are intended to represent the full range of possibilities that could occur within the real world to fully explore the implications of the circumscription theory. Future work may set parameters within feasible boundaries with known archaeological information for regions and time periods of interest for further archaeological investigation.

The model was written using NetLogo (version 6.0.1; Wilensky, 1999). The model code, output data, and R script for the graphs presented here are available online on GitHub (https://github.com/ajw246/Circumscription_ABM). A full model description following the ODD protocol (Grimm et al., 2006, 2010) is in Supplementary Materials 1.

2.1. Verbal outline of the model

Agents in this model can be thought of as individual settlements, or *villages*. Villages are independent *polities*, until they either conquer or are conquered by another polity. At this point, hierarchically organised, multi-village polities begin to form. The environment is divided into *patches*, which can be occupied (contains a village) or unoccupied (does not contain a village) and contain a set number of *resources*. Patches are set to be one of three types: (1) extremely fertile, with the maximum number of *resources* in each patch, (2) quite fertile, with 90% of the maximum number of *resources,* and (3) minimally fertile, with only 10% of the *resources* in each patch. A patch cannot contain more than one village. Every village owns a single patch of land and its resources. We assume that the most fertile land would be occupied by preference,

Table 1
The core assumptions of Carneiro's circumscription theory (1970, 2012a) compared with the implicit assumptions of the circumscription theory that we included in our model, the strategies we used to model both the explicit and implicit assumptions of the theory, the variables relating to each, and the assumptions of the circumscription theory that are not included in this model.

Circumscription Theory	Implicit assumptions included in our model	Modelling Strategies	Variables
Barriers to population movement can be environmental, resource-based, or social.	The landscape layout may affect the degree of circumscription. Environmental and resource-based barriers can be collectively defined as geographical circumscription. 'Resources' can be any resource that is considered necessary or valuable	Distribution of two land types varied between two extremes (concentrated and random). Potential resources in the land types differ. Villages cannot move into a patch already occupied by a village.	*land.width/number.fertile* *resource.difference* Level of circumscription measured by *experienced geographical circumscription* and *experienced social circumscription*
Conflict may occur without circumscription, but movement barriers may amplify conflict by increasing population pressure.	Population pressure can be affected by population size, growth rate, and clustering.	Conflict can occur with any village within range. Starting population size, population growth, and the range of village movement are parameters that can affect population size and population clustering.	*probability.attack* *initial.villages* *population.growth* *village.range*
	A decision to move is affected by the relative costs or benefits of moving or not moving.	Villages calculate the potential resource gain from moving compared to staying in their current location and paying a cost.	*tribute*
	Polities may also fragment into smaller groups for any reason.		*probability.fragment*
Conflict causes an increase in social complexity.	The larger the polity, the greater the chance of winning a conflict.	Villages become directly subordinate if defeated in conflict. All villages subordinate to a defeated village will join the conquering polity.	Social complexity measured as settlement *hierarchy*

Assumptions not included in in our model:

- Role of charismatic individuals, or '*pendragons*', in leading a population in conflict and polity organisation (Carneiro, 2012a).
- Social dynamics, individuals, and population growth within villages.
- Maintenance of social complexity beyond initial formation.
- Non-conflict-based alliance formation between groups.
- Reasons for conflict.
- Variation of the availability of resources over time, e.g. depletion of produce or raw materials.
- Population decline due to natural variation or depletion of resources (although the parameter for village death is included in the model and can be varied in future experiments).

therefore villages are initially located on patches with the highest resources. Figure SM 2 shows a flow diagram of the processes that occur during each timestep of the model.

Villages may create new villages in unoccupied neighbouring patches, representing population growth. The spread of villages into unoccupied patches is more likely if the patches are high in resources, but population growth is curtailed by the *probability.grow* parameter. To model population pressure, we simplify carrying capacity by not allowing more than one village to occupy an area and measuring the number of neighbours each village has. To model population clustering, we assume here that as a population grows, new settlements may be placed close to original settlements, leading to population clustering in the absence of resource concentration.

Polities attack other polities and attempt to conquer their neighbours. The probability that an attacking polity defeats another polity (P_{win}) is dependent on polity size: the more resources across all villages in the attacking polity (R_a), the more likely it is to win against the defending polity (R_d), as per Equation (1).

$$P_{win} = R_a \; / \; (R_a + R_d) \tag{1}$$

Polities that are defeated in conflict become subordinate to the attacking polity if they decide not to, or cannot, escape to a new location. Villages search for a new location within a defined area (*village.range*). If defeated, the highest-ranking village of the defeated polity becomes directly subordinate to the highest-ranking village of the attacking polity, while maintaining the same internal hierarchical structure (see Supplementary Materials 1: ODD). To decide whether to move, each village within the defeated polity will calculate the potential cost or gain of resources by identifying their richest, unoccupied neighbouring patch. The total resources of the potential new patches (R_n) is then compared to the total resources of patches currently occupied by the villages in the defeated polity (R_c), minus the cost of *tribute* (T). A polity is more likely to move if there will be a gain in resources (P_{mov}), as per Equation (2). Polities containing multiple villages act as a whole entity, even if the decision taken means that individual villages within the polity are consequently worse off.

$$P_{mov} = R_n \; / \; (R_n + R_c - T) \tag{2}$$

Finally, villages that are subordinate within a polity have a chance of rebelling (*probability.fragment*), in which case they and all their subordinate villages form a new, independent polity.

2.2. Parameter space

We increase the level of geographical circumscription in two ways: (1) by reducing the proportion of most fertile patches in the model landscape to reduce the area of most attractive land and (2) by reducing the resources available in the less fertile patches to steepen the resource gradient between patches. We increase social circumscription by increasing population growth to reduce the area of free patches for villages to move into. Two landscape layouts are used to test two extremes of environmental distribution: a concentrated and narrow distribution of patches, simulating a hypothetical river valley; and a random distribution of patches, simulating islands of resource-rich land between uninhabitable hypothetical mountains or oceans (Fig. 1). Most real-world environments will lie in between these two extremes, allowing our model to account for a wide range of potential landscapes.

We present the results of varying parameters for geographical circumscription in the two different landscapes while assuming a constant likelihood of population increase, conflict, and fragmentation, as well as a constant range of movement and cost of becoming subordinate (Table 2). Additional parameter effects from varying these parameters have been previously explored (Williams, 2019).

We measure the level of social complexity through the proxy of settlement hierarchy. This has the dual advantage of being detectable in the archaeological record through the comparison of settlements

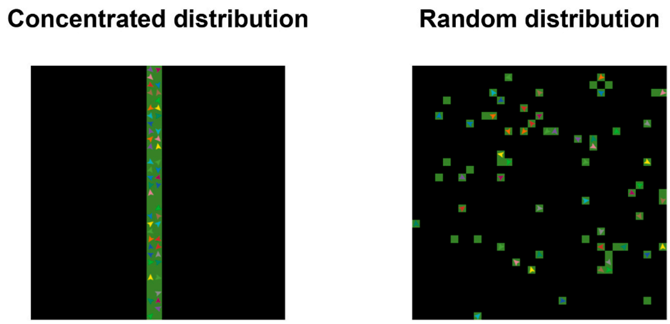

Fig. 1. The model environment showing the two landscape distributions of the two different land types (highly fertile in green and less highly fertile in black). The coloured triangles represent individual villages. See SM Fig. 6 for more detail. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Spencer and Redmond, 2004), and of reflecting other measures of social complexity, including wealth concentration, the extent of political influence, and the internal specialisation of roles (Turchin et al., 2013).

We also plot the level of experienced geographical and social circumscription to show the circumscription pressure being exerted on villages. 'Experienced geographical circumscription' is calculated as a proportion of the sum of visible resources compared to the maximum potential resources of each patch. 'Experienced social circumscription' is calculated as the proportion of visible land around each village that is occupied by other villages.

Experiments were run for 100 time steps and repeated 50 times to allow differences between parameter conditions to emerge and diverge. The level of hierarchy is averaged across all villages for each time step. We report the mean level of hierarchy at each time step across the 50 iterations, summarised between model runs by the median and interquartie range at each time step.

2.3. Predictions

2.3.1. Social circumscription

Carneiro (1970, 2012b) suggests that social circumscription occurs when population size increases, leading to an increase in population pressure where resource demand begins to outstrip supply. Warfare may intensify as people compete over the limited resources. Population pressure may therefore both increase the incidence of conflict and limit the area of unoccupied neighbouring territory to escape to in conflict.

Given the original verbal formulation of the social circumscription hypothesis and the caveats discussed in Section 1, we predict that increasing population pressure, defined as having more villages in the surrounding patches, 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 hierarchy formation. To show this we measure both the mean level of hierarchy reached and the level of 'experienced social circumscription', calculated as the proportion of occupied patches within the area that a village could move to if defeated (*village.range*). If the prediction that social circumscription leads to a greater rate of social complexity formation is supported, we expect the rate of hierarchy formation to increase with the level of experienced social circumscription.

Table 2
The parameter conditions tested in the experiments. Parameters affecting the degree of geographical circumscription are varied between high and low values. See Supplementary Materials Table 2 for full list of parameters and descriptions relating parameters with model code.

	Parameter	Low	High
Proportion of area consisting of the most fertile patches	*land.width* (concentrated distribution)	5%	95%
	number.fertile (random distribution)		
Resource availability	*resource.difference*	0.1	0.9
Population dynamics	*village.range*	1	10
	probability.grow	0.1	0.5
	initial.villages	10	
Polity conditions	*tribute*	0.1	
	probability.fragment	0.01	
	probability.attack	1	

2.3.2. Geographical circumscription

In the verbal formulations of the circumscription hypothesis, Carneiro (2012b) suggests that social circumscription will be felt more keenly where environmental conditions also restrict population expansion. A growing population is assumed to 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. Here, we model geographical circumscription by lowering the resource availability in a portion of the total land area in the model. The amount that the resources were lowered by and the total area of land that this applied to were varied to simulate varying levels of geographical circumscription (Fig. 1).

To show the extent to which villages are enclosed by the conditions of their surroundings, we include a measure of 'geographical circumscription'. This is a measure of the resource availability surrounding a village. A village in a uniform, fertile environment will have a geographical circumscription measure of zero, while a village surrounded by patches with fewer resources will have a value closer to one. If the prediction that environmental circumscription leads to a greater rate of social complexity formation is supported, we expect the rate of hierarchy formation to increase with the level of geographical circumscription.

3. Results

3.1. The effect of geographical circumscription on hierarchy formation is dependent on the range of village movement

Geographical circumscription is not associated with higher rates of hierarchy formation when the village range is small (Fig. 2, Figure SM 8). Both plots A and B in Fig. 2 show a lower level of hierarchy formation in the harshest condition (geographical condition 1) where the majority of patches are resource poor, while the same geographical condition shows the highest level of 'experienced geographical circumscription' in plots C and D. The final median hierarchy level at time step 100 is 4.66 and 1.47 for the harshest geographical conditions (1), while the final median hierarchy level is substantially higher (7.83–8.55) for all other geographical conditions (Fig. 4, Table SM 3).

However, increasing the village range to 10 (Fig. 3) reduces the difference between the geographical conditions. In Fig. 3, while the level of experienced geographical circumscription remains highest in the harshest geographical condition (1), the rate of hierarchy formation is very similar between all geographical conditions. Fig. 4 shows that the final median level of hierarchy is between 3.29 and 4.71 for all geographical conditions where the range of village movement is 10 patches.

3.2. Hierarchy formation is associated with social circumscription when the village range is low

High levels of social circumscription are associated with higher rates of hierarchy formation in almost all conditions when the village range is small (Fig. 2, Figure SM 8). The impact is strongest when the environment is rich in resources. The highest rates of hierarchy formation (plots A and B) and 'experienced social circumscription' (plots E and F) occur

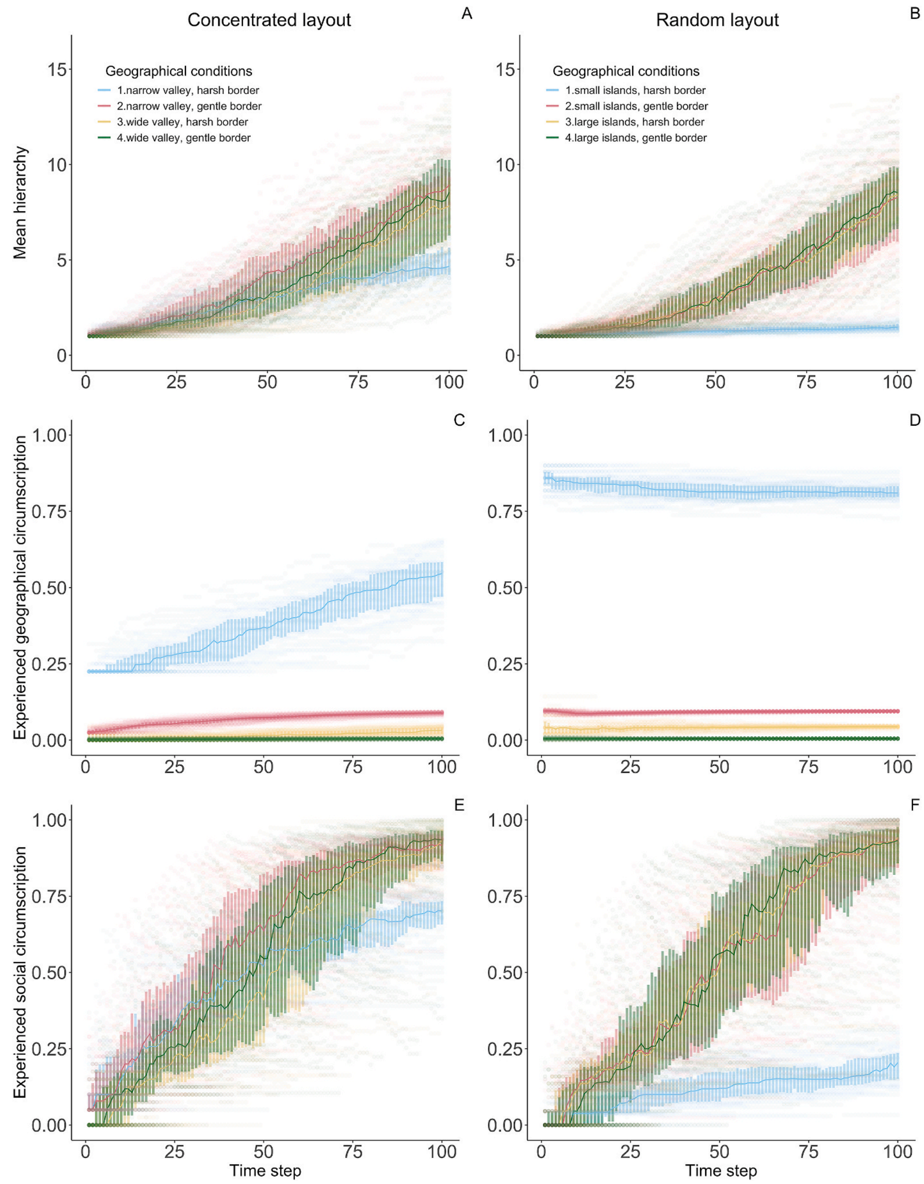

Fig. 2. Parameter village.range = 1. Plots A (concentrated landscape) and B (random landscape) show the mean hierarchy level across all villages. Plots C (concentrated landscape) and D (random landscape) show the level of geographical circumscription experienced by villages. Plots E (concentrated landscape) and F (random landscape) show the level of social circumscription experienced by villages. All plots show the mean value across all villages at each time step (pale dots) and are summarised across iterations by the median (line) and inter-quartile range (dark bars) at each time step. The harsh and gentle borders correspond to high and low resource.difference parameter settings respectively (Table 2) and are described in more detail in Table SM 2 and Figure SM 6. Further comparison of experienced circumscription is shown in Figure SM 8.

in geographical conditions 2–4, where there is either a larger proportion of the most fertile land or where the land doesn't have any very resource poor areas.

There is no effect of social circumscription on hierarchy formation when the village range is larger. The rate of hierarchy formation is very similar between all geographic conditions and the final median hierarchy level varies between the conditions by only 1.42 (Fig. 3, compare plots A and B with E and F; Fig. 4), despite substantial levels of experienced social circumscription in geographic conditions 2–4.

However, hierarchy does form in geographic condition 1 even though the level of experienced social circumscription is very low (Fig. 2, plots B and F, and Fig. 3).

3.3. *A concentrated layout of patches is associated with a higher rate of hierarchy formation than a random layout when the village range is small*

The rate of hierarchy formation and level of 'experienced social circumscription' is higher in the harshest conditions (geographical condition 1) in the concentrated layout (Fig. 2, plots A and E) compared to the random layout (plots B and F). Hierarchy formation in geographical condition 1 in the concentrated layout is very similar to that seen in conditions 2–4 for the first 75 time steps, whereas hierarchy doesn't increase at all in condition 1 in the random layout. Hierarchy formation and experienced geographical and social circumscription are very similar between the concentrated and random landscape layouts if the village range is larger (Fig. 3).

Additional parameter space results with an increased rate of population growth are presented in Supplementary Materials 2.

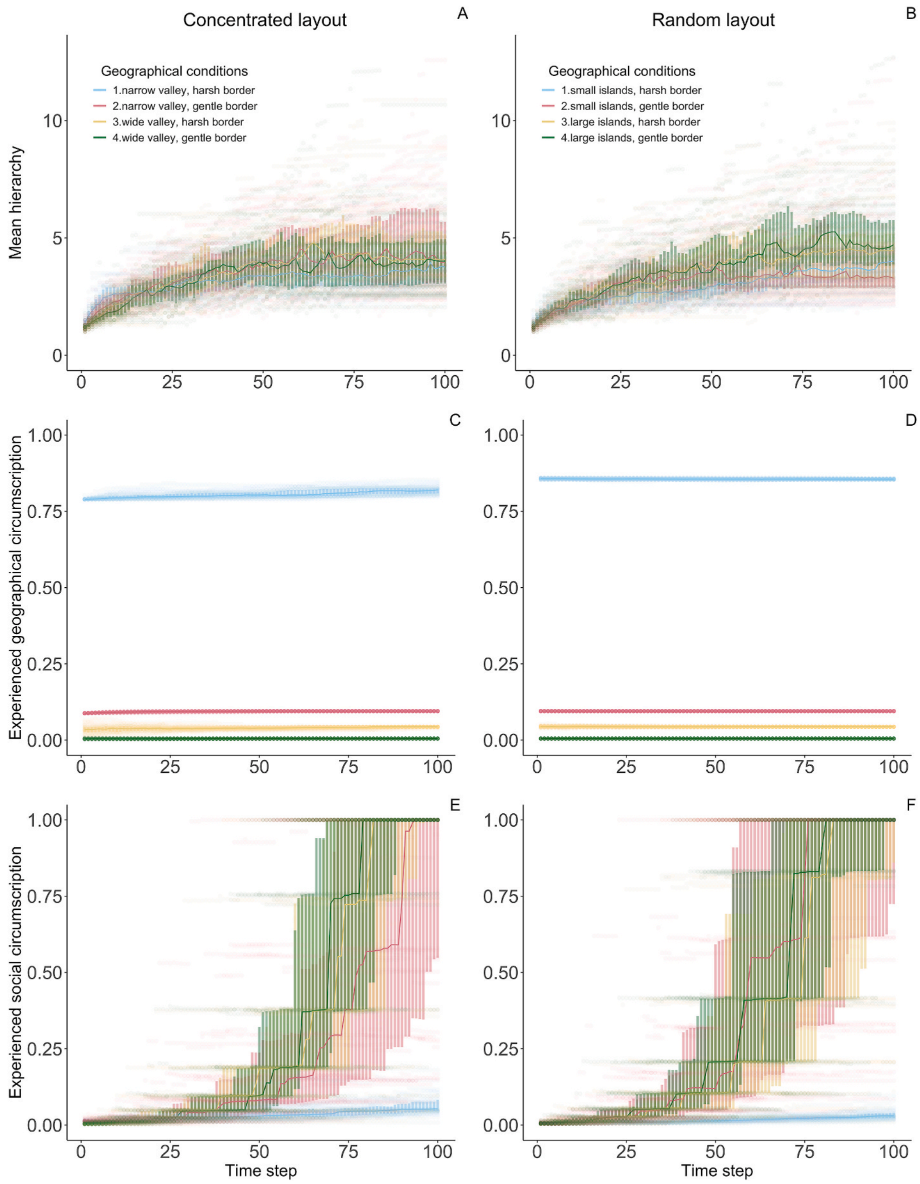

Fig. 3. Parameter village.range = 10, all else as in Fig. 2.

4. Discussion

In his circumscription theory, Carneiro (1970, 1988, 2012a, 2012b) suggests that social complexity is more likely to form in conditions where warfare between people is intensified. The results of our model show that increasing social circumscription through a growing population size increases social complexity. However, Carneiro also suggests that environmental barriers to population movement (e.g. areas with fewer resources) will intensify the effect of social circumscription by causing people to cluster in resource-rich areas. The results from this agent-based model do not fully support the assumptions of geographical circumscription. Increasing the levels of geographical circumscription can decrease the likelihood of social complexity formation if these conditions restrict access to neighbouring populations or stunt population growth by restricting the availability of resources. In real-world situations, areas of initial social complexity formation tend to be associated with a substantial increase in population size (Sandeford, 2018). The model results therefore present an important clarification of the circumscription hypothesis: geographical barriers will not lead to an increased likelihood of social complexity formation if the area contained is not rich enough in resources to support a growing population.

The discrepancy between the predicted effect of geographical circumscription is particularly apparent if villages are more isolated in an environment in which high resource patches are distributed randomly rather than concentrated together. Severe geographical circumscription may isolate populations and therefore halt the formation of social complexity. Increasing the intensity of geographic barriers will only increase social complexity formation if these conditions cluster the population into the same area. Carneiro hints at the insufficiency of geographical circumscription alone in driving the formation of social complexity when discussing the apparent lack of social complexity in the highly circumscribed Apa Tani valley in north-eastern India (Carneiro, 2012b, responding to criticisms by Toon van Meijl, p164-5), and the difficulties in unifying the Greek city-states in separate small valleys (Carneiro, 2012b, responding to criticisms by David Small, p160-161). The results from our model confirm that environments may be too geographically circumscribed for social complexity to form if barriers isolate populations. If the level of geographical circumscription is minor,

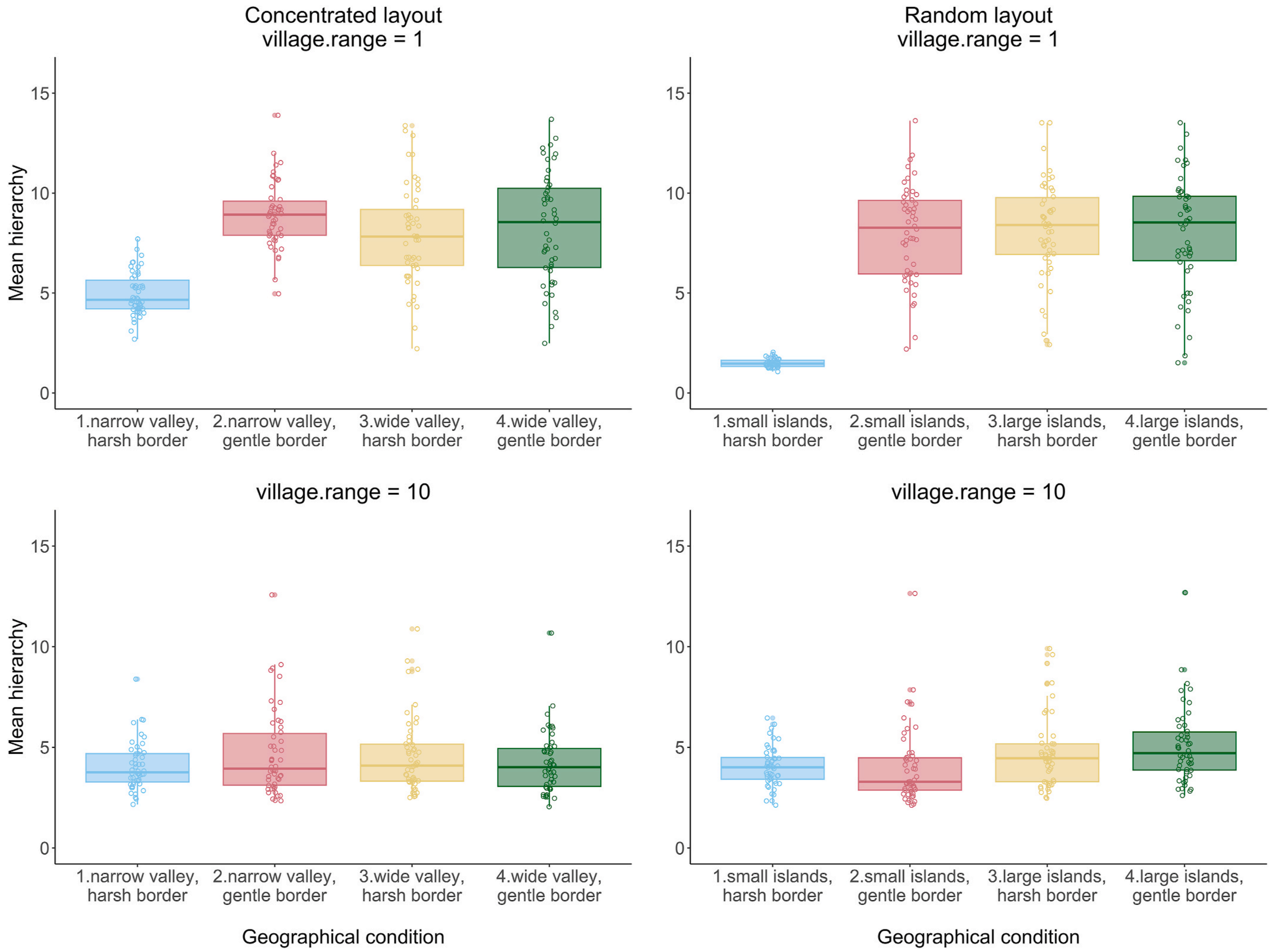

Fig. 4. Boxplots of the mean hierarchy across all villages at time step 100, parameter values are as described in Fig. 2.

the availability of resources may initially allow the population to further spread to avoid conflict and therefore slow the formation of social complexity. However, this effect rapidly disappears as the population grows into these areas of abundant resources.

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. If a population has greater access to resources, such as an area with fewer geographical 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 in which 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, severe barriers to population movement may result in a faster emergence of social complexity but may not necessarily be the same areas in which the highest levels of social complexity can be built or sustained. However, population mobility has an important negating effect of the circumscribing conditions: where villages can move greater distances, hierarchy formation becomes very similar between all conditions.

The model presented here does not explicitly test how social hierarchy is created and maintained between individuals within villages and polities but assumes that these mechanisms were present. Further work focusing on individual people or households as agents may complement this model (see Daems, 2019; Hooper et al., 2010; Powers and Lehmann, 2013).

Core features of the model based on the original circumscription theory include assumptions about human behaviour that could be further validated and quantified. We assume conflict between villages is present and key to the formation of hierarchy between settlements. This is based on archaeological evidence for warfare associated with early complex society formation, such as seen in the Valley of Oaxaca (Flannery and Marcus, 2003). A low-level of conflict between polities in this model can still result in hierarchy formation (Williams, 2019). We also assume that defeated populations will become subsumed into the conquering polity if they don't move away. This is a generalisation of what may be many different ways in which two polities can interact, including building a heterarchical relationship (Crumley 1995) or one based on mutual aid or trust. However, conquest warfare is a core assumption of the circumscription theory that we are testing with this model. Further work to parameterise this model based on archaeological and environmental evidence will provide more precise quantitative estimates for the effects of circumscription on the formation of social complexity. This will allow for both more explicit testing of whether the circumscription theory can explain the rise of social complexity in particular locations, given the social and geographical conditions of those cases, and further refinement of the circumscription theory by precisely quantifying the conditions under which social complexity is more likely to arise and persist.

5. Conclusion

The agent-based model presented here was built to test the logical consistency of Carneiro's circumscription theory by focusing on the effects of geographical and social conditions on the formation of social complexity. The model supports the circumscription theory insofar as population crowding within an area can result in faster social complexity formation than among populations that are isolated by geographical boundaries. However, increasing the circumscription of the landscape is not associated with an increase in social complexity formation, and a very highly circumscribed environment that isolates populations will stall complexity formation. This model provides a logical test of Carnerio's circumscription theory and further insights into the geographical and social conditions that may feature in the formation of the earliest complex human societies.

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CRediT authorship contribution statement

A.J. Williams: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology. **A. Mesoudi:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Model code is available online (https://github.com/ajw246/Circumscription_ABM).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2024.106090.

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