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Testing the effect of circumscription on the evolution of social complexity in the Valley of Oaxaca, Mexico, using agent-based models

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ABSTRACT

The initial emergence of complex societies in the archaeological record has often been explained by cultural and environmental conditions. In this paper, we formally test whether the conditions of the highly circumscribed region of the Valley of Oaxaca in highland Mexico could have intensified the formation of social complexity. The Valley of Oaxaca shows some of the earliest evidence for territorial expansion and multiple levels of internal organisation, or social complexity, in Mesoamerica and is considered a classic example of the effects of environmental circumscription. We build on our previous abstract agent-based model (Williams and Mesoudi, 2024) by incorporating real-world archaeological and environmental data from the Valley of Oaxaca to explore social complexity formation and test the impact of factors for which there is little archaeological evidence. The model results suggest that the mountainous surroundings of the valley could have contributed to social complexity formation, if we assume warfare was present throughout the time periods. However, the model also suggests that observed differences in social complexity formation between the three subvalleys of the Valley of Oaxaca were unlikely to be due to differences in circumscribing conditions. The model highlights key forms of archaeological evidence that might confirm or reject the effect of geographical circumscription in the Valley of Oaxaca.

1. Introduction

The initial emergence of complex societies in the archaeological record has inspired many competing theories to explain how, why, and where these societies appeared (Flannery and Marcus, 2012). Robert Carneiro (1970, 2012a) proposed a unifying theory explaining how and why complex societies formed around the world, with a particular focus on circumscribing environmental conditions. Carneiro's circumscription theory suggests that conditions that intensify warfare by either limiting population movement through environmental or social barriers (such as mountains or rival territories) or increasing competition over concentrations of resources (such as areas of more easily cultivatable land) may increase the likelihood that complex societies will form. Previous work has drawn extensively on archaeological and environmental evidence in support of the circumscription theory, as described by Carneiro (1970, 1988, 2012a), but the theory has also been heavily criticised (Stocker & Xiao, 2019; Zinkina et al., 2016; Gibson, 2012; Gayubas, 2015).

The Valley of Oaxaca in highland Mexico is used as a classic example of the effect of environmental circumscription due to the early formation of large settlements and a territorially expansive society within a mountain-range valley (Carneiro, 2012a, 2012b). However, research comparing potential population size with the agricultural potential of settlement locations across the valley suggest that not only was there an absence of population pressure but many settlements after 500 BCE were located outside of the most agriculturally productive areas despite ample space, including the key centre Monte Albán (Nicholas and Feinman, 2022, Figs. 5–7, pp10-12). The interior of the valley is therefore unlikely to have exerted substantial circumscribing pressure on society formation, given the available settlement pattern and environmental evidence. While other factors may have influenced the formation of societies in the Valley of Oaxaca (Nicholas and Feinman, 2022), formally testing the potential impact of the environmental (and resource) conditions through the use of an agent-based model is an important step to quantify their relative importance and identify the lines of evidence that would be necessary to either confirm or refute the effect of circumscription in this area.

In previous work (Williams and Mesoudi, 2024), we examined the logical consistency of the circumscription theory using agent-based

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models in abstract geographical and social conditions. We used a measure of settlement hierarchy to approximate social complexity following the assumption that increasing population size combined with increasing differentiation between settlements of the same polity (in size and proportion of non-residential buildings) implies greater societal organisation and internal hierarchy (Spencer and Redmond, 2004; Drennan and Peterson, 2006; Crema, 2014). Measuring settlement hierarchy allows us to compare the model output with the settlement data in the archaeological record more directly. We also followed the classifications of Perret and Currie (2023) such that environmental and resource circumscription are combined into a single measure of geographical circumscription due to overlap in how the conditions are described and their effect on population movement. We simulated the impact of social and geographical factors that are described implicitly and explicitly in Carneiro's circumscription theory on the rate of settlement hierarchy formation. We found 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. Limiting population movement to create socially circumscribing conditions had the greatest overall impact on increasing the rate of hierarchy formation and this effect was amplified when resource availability caused rapid population growth. Geographically circumscribing conditions that caused the initial population to cluster in the same stretch of land allowed for a higher rate of hierarchy formation compared to conditions that were too circumscribed, causing settlements to be isolated.

Our parameter exploration of the range of circumscribing conditions in an abstract environment enable us to formulate specific predictions for real-world scenarios. The Valley of Oaxaca is an ideal case to test Carneiro's circumscription theory, given our previous results, with highly circumscribing mountains surrounding a continuous valley of habitable land that could support a growing population.

In this paper, we explore whether the geographical conditions of the Valley of Oaxaca could have contributed to the formation of social complexity. We parameterise our agent-based model using archaeological and environmental data from the years before and during the formation of the territorially expansive Zapotec society. We also use the model to explore the potential impact of parameters for which we do not have secure archaeological data, and thereby fully assess the range of conditions required to fulfil the predictions of the circumscription theory in the Valley of Oaxaca.

The Valley of Oaxaca in southern highland Mexico presents an ideal area to test the circumscription theory for three reasons: (1) there is evidence for early and primary social complexity formation, prior to other equally or more complex societies (Spencer and Redmond, 2001, 2003, 2004; Redmond and Spencer, 2008, 2012; Spencer, 2010); (2) there is substantial archaeological evidence documenting the changes in social complexity over 3000 years from the first occupation of the valley (Flannery and Marcus, 1983, 2005; Marcus and Flannery, 1996; Kowalewski, et al., 1989a, 1989b; Balkansky, 1998; Feinman, et al., 1985); and (3) the valley itself is highly environmentally circumscribed, with mountains on all sides (Carneiro, 1970, 2012a).

Multiple signs of increasing social complexity began to appear in the Valley of Oaxaca between the start of the Tierras Largas phase (1400 BCE) and the end of the Monte Albán II phase (200 CE) (Marcus and Flannery, 1996; Spencer and Redmond, 2003). We use two main lines of evidence to determine whether social complexity is increasing in this area. Firstly, we assess population increase in the region over time, as indicated by the size and number of settlements (Kowalewski, et al., 1989a, 1989b), while acknowledging the limitations of inferring social complexity from estimated population size and survey data (O'Brien and Lewarch, 1992). Secondly, we include 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) (Spencer and Redmond, 2004). This information is summarised by the levels of settlement hierarchy present in the valley within each phase (Table 1).

During the first three phases of settlement change (Tierras Largas, San José, and Guadalupe, 1400 – 700 BCE), there was very little size difference between most settlements. Only San José Mogote in the northern Etla subvalley remained consistently larger in size with a higher proportion of non-residential buildings (Flannery and Marcus, 2005). The size and number of settlements increased over this time into the Rosario phase (700 – 500 BCE) when three distinct societies began to emerge in the three subvalleys, with an increase in size and proportion of non-residential buildings in settlements in addition to the main settlement San José Mogote (Spencer and Redmond, 2004; Kowalewski, et al., 1989a, 1989b; Drennan and Peterson, 2006). The highest levels of settlement hierarchy appear over the Monte Albán phases (500 BCE – 200 CE). Monte Albán became the main central settlement of the unified valley with four distinct levels of settlement hierarchy in the Monte Albán II phase (100 BCE – 200 CE) (Spencer and Redmond, 2003, 2004; Kowalewski, et al., 1989a, 1989b; Flannery and Marcus, 1983; Marcus and Flannery, 1996; Sherman et al., 2010).

2. Methods

The model is written in Netlogo (version 6.0.1; Wilensky, 1999) and is described in full following the ODD protocol in the Supplementary Materials 1. The abstract agent-based model that this paper builds on is described in Williams and Mesoudi (2024). Full documentation of the model code and R scripts are available on GitHub (https://github.com/ajw246/Oaxaca_ABM).

2.1. Verbal outline of the model

The model is intended to simulate the behaviour of people living in the Valley of Oaxaca between 1400 BCE and 200 CE at the settlement level. The model agents are villages that can initiate conflict with one another. The likelihood of winning a conflict is proportional to the relative sizes of the attacking and defending polities. A defeated polity may either attempt to escape or remain in place and become subordinate to the winning polity. The likelihood of escaping is proportional to the potential resource gain from moving away as opposed to remaining in place and paying a cost of subordination. Defeated polities that become subordinate to the attacking polity retain their internal structure between villages and are ranked directly below the head village of the attacking polity. The greater the potential resources available in unoccupied surrounding patches, the more likely villages are to both move to a new location if defeated in conflict and found a new, autonomous, village. The distribution of resources across the model environment corresponds to the environment of the Valley of Oaxaca and remains consistent between and within model experiments. One time step of the model is the equivalent of 10 years of archaeological time and the model ends after 160 time steps (1600 years) have elapsed.

Table 1
The levels of settlement hierarchy in the Valley of Oaxaca from the Tierras Largas to the Monte Albán II phase (see SM 2 for further archaeological background).

Phase	Dates	Levels of settlement hierarchy
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

2.2. Parameter space

2.2.1. 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 (Nicholas, 1989). Kirkby (1973) and Nicholas (1989) have classified environmental zones within the valley by the potential maize yield of the different areas at the time of survey (see Fig. 1). We follow the classifications of Kirkby (1973), Nicholas (1989), and Nicholas and Feinman (2022) to classify the broadly different zones of potential agricultural yield within the Valley of Oaxaca (SM Table 2, SM 1.1.5.1). Class I land is the most fertile with the most consistent ground water supply, where Kirkby (1973) estimates a potential yield of over 2 metric tons of maize per hectare. Class I patches are therefore given the maximum number of resources (*land-resources* = 100). The resources of the remaining land types are set at a lower estimate of the potential maize yield in proportion to the resources of Class I. Class II land is high quality but more dependent on rainfall for high yield (estimated 1.21 – 2 tons of maize per hectare by Kirkby, 1973) (*land-resources* = 60). Class III land is dependent on rainfall for yield and is divided into Class IIIa and Class IIIb by how much of the land consists of rocky outcrops (Nicholas, 1989): Class IIIa is assigned *land-resources* = 20; Class IIIb is assigned *land-resources* = 10. The uncultivable mountain zone is estimated to yield 0 – 0.2 tons per hectare (Kirkby, 1973) (*land-resources* = 0). Additional experiments with the *land-resources* of the mountain patches set to 10 are discussed in SM 3.1.2. Further refinement of potential yield is possible within each sub-valley with estimated past rainfall, labour, agricultural techniques, and maize cob size (Nicholas and Feinman, 2022; Benz and Long, 2000; Flannery, et al., 1967;

Table 2
Parameter settings for Experiment 1 and 2. For further detail on chosen parameter settings, see SM Table 2 and SM 1.1.5.

Purpose	Parameter	Experiment 1	Experiment 2
Social circumscription	*initial.villages*	21	
	probability.grow	0.1	
	probability.death	0.01	
	village.range	1, 10, 50	1, 10
Environmental & resource circumscription	*land-resources*	0 – 100, divided into 5 zones: – **Class I** = 100 *land-resources* – **Class II** = 60 *land-resources* – **Class IIIa** = 20 *land-resources* – **Class IIIb** = 10 *land-resources* – **Mountain** = 0 *land-resources*	
Polity conditions	*tribute*	0.1	
	probability.fragment	0.01	
	probability.attack	0.1, 1	0.1, 1
	Initial village location	Archaeological site location	– Archaeological site location – Randomly on Class I & II land – Randomly on Class I, II, and IIIa land
General setup	*step*	160 steps	200 steps
	Iterations	100	50

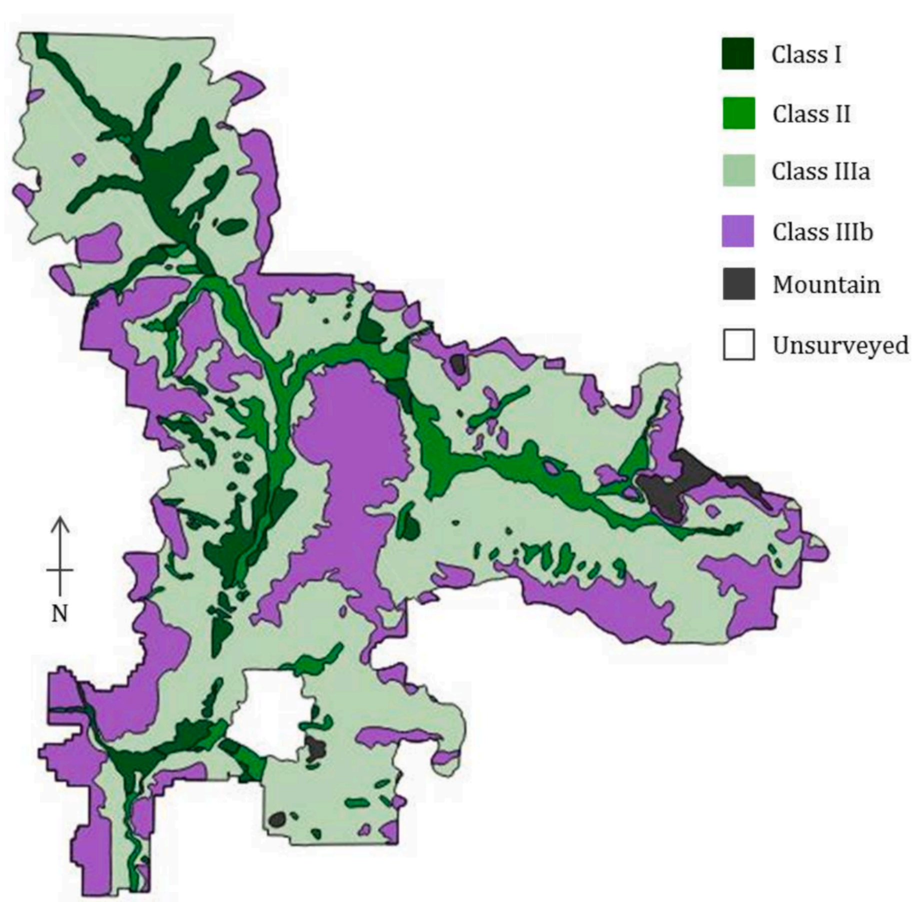

Fig. 1. Map showing the different land types in the Valley of Oaxaca, adapted from Nicholas (1989, Fig. 14.3, p461).

Flannery and Marcus, 1976; Mangelsdorf, et al.1964; Neely, et al., 1990), but have been excluded here to simplify our model and capture the overall effect of the geography of the Valley of Oaxaca.

2.2.2. Population growth

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 can vary greatly depending on assumed population density (Blanton, et al., 1979; Marcus and Flannery, 1996; O'Brien and Lewarch, 1992). To avoid confusion in population estimates, we only use the number of settlements present during each phase and not their estimated area or population size to measure overall population trends over time (SM Fig. 1). The number of settlements increased from 21 in the Tierras Largas phase (1400–1150 BCE) to 500– 750 in the final two phases considered here (Monte Albán Late I and II, 300 BCE – 200 CE). The number and initial location of settlements is based on settlement survey data from Kowalewski, et al. (1989a, Fig. 3.1, p56).

2.2.3. Timescale

The length of time represented by each time step in the model was calculated based on the rate of population growth expected given resource availability within the valley. In this model, each time step is roughly the equivalent of ten years during which the probability of creating a new village is 0.1 (SM Fig. 2, SM 1.1.5.3). Each model run begins with 21 villages, representing the initial number of settlements identified as present during the Tierras Largas phase (Kowalewski, et al., 1989a). The final population size after 1600 years (or 160 time steps) has elapsed will roughly correspond with the archaeological population size of 500 – 750 settlements in the final two phases.

2.2.4. Warfare

Warfare is present in all phases discussed here (Spencer and Redmond, 2003, 2004; Flannery and Marcus, 1983; Marcus and Flannery, 1996; Kowalewski, et al., 1989a, 1989b; Flannery and Marcus, 2003; SM 2.2). 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 the model with the archaeological data, we therefore assume that conflict did occur during all phases but vary the frequency at which conflict may have occurred to allow for different scenarios (Table 2). Each polity has an opportunity to initiate conflict with a neighbouring polity within range in each time step (SM Table 2). The rate of conflict can be adjusted by varying the probability that a polity will enter into conflict with an identified neighbour. Conflict will not occur if polities are too isolated to be 'visible' to one another and the smaller the number of polities the smaller the number of possible conflict events within each time step. Conversely, the greater the population size the greater the actual frequency of conflict, as villages are more likely to be within range of one another and the possible number of polities increases. By varying the parameter for the likelihood of initiating conflict, we therefore set upper and lower bounds to the number of conflict events that may occur, while allowing for more realistic interactions between polities driven by proximity to emerge.

2.2.5. Movement distance

How far people were willing to relocate to establish new villages can be estimated by the distribution of settlements across the Valley of Oaxaca. Settlement patterns suggest that most settlements cluster within 0.5–2 km distance from one another, but also founded new settlements across the whole valley (Kowalewski, et al., 1989, Figs. 3.1, p56 and 7.2, p163).

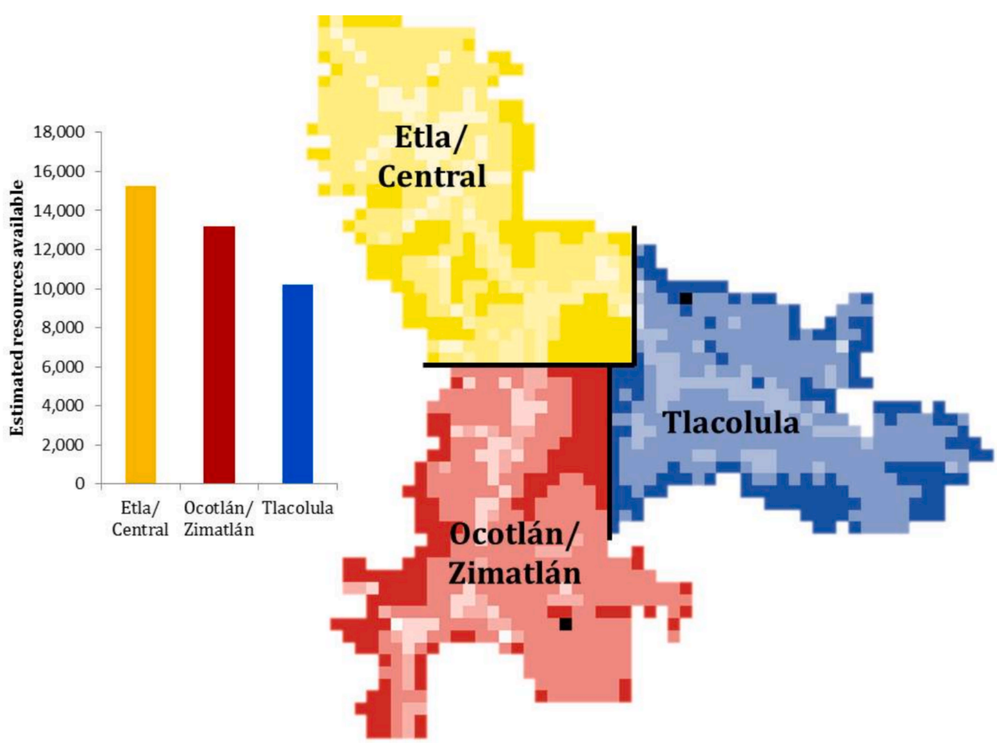

Fig. 2. The three different subvalleys of the Valley of Oaxaca delineated in the model environment. The divisions are based on the valley sub-divisions in Spencer and Redmond (2003, p57), but adjusted here to allow for an almost equivalent number of patches in each valley area. The map is adapted from Nicholas (1989, Fig. 14.3, p461). The highest number of available resources are in the Etla/ 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 in Fig. 1). 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.

Based on the settlement patterns, we believe it likely that people tended to prefer to remain relatively close together. As this assumption is based on relatively little information, we vary the parameter for the range of village movement between upper and lower bounds. When scaled to the Valley of Oaxaca, one patch in our model equates to roughly 1.2 km in distance. This means that a village range of 1, 10, and 50 patches in radius from the village's location is roughly equivalent to 1.2 km, 11.4 km, and 57.2 km across the valley respectively (SM Table 2). Patches with more resources will be selected by preference with a probability determined by the relative difference in *land-resources* between all patches within the village range, but only patches that are unoccupied can be selected (SM 1.1.4). The surveyed valley is around 70 km wide at the widest point. The parameter range therefore allows for both close clustering and the possibility of moving much further afield across almost the whole valley to form new settlements, as suggested by the settlement pattern distribution.

2.3. Model experiments

2.3.1. Experiment 1: The mountainous range surrounding the Valley of Oaxaca

In the verbal formulation of the circumscription hypothesis, Carneiro (1970, 2012a) suggests that the conditions of geographical circumscription seen in the Valley of Oaxaca could have limited population movement and thereby intensified pressure from warfare to accelerate the formation of social complexity. Our previous investigation of the logical consistency of the circumscription theory in an abstract ABM environment (Williams and Mesoudi, 2024) supports the theory insofar as there are sufficient resources to allow for population growth within any hemmed-in geographic areas. Given that the Valley of Oaxaca forms one relatively continuous, confined area and there is cultivatable land across the valley, we predict that the geographical conditions of the valley will cause the formation of hierarchy.

In our first experiment we investigate the role of geographical circumscription on the formation of social complexity. The simulated villages are located in known archaeological site locations within the valley at the start of each model run. Villages are allowed to grow in population size and engage in conflict with the frequency determined by the parameters shown in Table 2. We vary parameters for the frequency of warfare and range of village movement between plausible upper and lower bounds based on archaeological inference (Table 2, SM 1.1.5) and the large potential effects of these parameters in previous work (Williams and Mesoudi, 2024; Williams, 2019).

If the role of environmental circumscription is supported, the mountain range surrounding the valley should result in comparable levels of settlement hierarchy over the 1600 year time period. Following from Williams and Mesoudi (2024), we record the average level of settlement hierarchy across all villages in the model at each time step, summarised between model iterations by the inter-quartile range. This provides an overall trend in hierarchy formation that can be compared with the levels of settlement hierarchy seen in the archaeological record. Experiment 1 is run for 160 time steps to correspond with 1600 years of archaeological time and repeated for 100 iterations (Table 2).

2.3.2. Experiment 2: Subvalley geographical differences within the Valley of Oaxaca

The earliest differentiation of settlement hierarchy in the archaeological record of the Valley of Oaxaca occurs in the Etla subvalley with the presence of San José Mogote (Flannery and Marcus, 2005), and later the location of the centre of the Zapotec polity at Monte Albán (Spencer and Redmond, 2004; Kowalewski, et al., 1989a, 1989b). Although Carneiro (2012a) suggests that resource concentration was unlikely to have had a circumscribing effect within the Valley of Oaxaca, we assess whether the higher concentration of cultivatable land in the northern Etla subvalley (Fig. 2) could have contributed to the earlier formation of social complexity when compared with the other subvalleys.

In the second experiment we assess the effect of the different geographical conditions within each of the subvalleys by comparing the levels of settlement hierarchy that emerge between the three sub-valleys of the Valley of Oaxaca. The division of the valley into three subvalleys is based on the regions suggested by Spencer and Redmond (2003) and adjusted here to divide the valley area almost equally (Fig. 2). The roughly equal number of patches between subvalleys ensures that no subvalley has a greater opportunity for resource acquisition or population growth through a higher number of patches than the other subvalleys. We estimate the total potential resources of each subvalley as the sum of the potential resources of each patch (Fig. 2). The average level of settlement hierarchy is compared between subvalleys and not directly with the archaeological record. Experiment 2 is run for 200 time steps and repeated for 50 iterations (Table 2).

We vary the parameter values for the frequency of warfare and range of village movement (Table 2). Results for the 11.4 km range of movement are shown in SM 3.2. We decided not to include the widest extent of village movement (57.2 km) because this would negate any effect of separating the subvalleys. Three separate tests are included here to control for settlement starting location:

1. Each village is placed in a position roughly equivalent to the locations of settlements in the Tierras Largas phase (Kowalewski, et al., 1989a, Fig. 3.1, p56). This experiment is the most direct comparison with the archaeological record. However, this also means that most villages are located in the northern Etla valley and may therefore bias the comparison between subvalleys.
2. Each village is located at random on any patch of either Class I or Class II land. In this test, we assume that people would prefer to occupy the most fertile land where possible, but do not control the specific starting location of each village. However, the starting location bias towards the northern Etla valley persists as this valley contains the highest number of Class I and Class II patches.
3. Villages are located at random on any Class I, Class II, or Class IIIa land. The archaeological starting locations of settlements suggest that people did live on all these land types during the Tierras Largas phase (Kowalewski, et al., 1989a, Fig. 3.1, p56). 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.

3. Results

3.1. Experiment 1: The effect of geographical circumscription on the formation of social complexity in the Valley of Oaxaca

The results in Fig. 3 show that hierarchy forms in our simulations within a timeframe comparable to the archaeological record of the Valley of Oaxaca. 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 rate 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), the median level of settlement hierarchy between polities is between the upper and lower archaeological estimates for the first 1300 years, showing a good fit between the model and archaeological data. However, from the Monte Albán Late I phase (300 BCE – 100 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), there is the potential for much higher levels of hierarchy in the model. With a higher rate of conflict, the median level of hierarchy in the model is consistently higher than expected from the archaeological record. The exception is in the first 300 years when the range of village movement is small (1.2 km) and the median hierarchy is within the

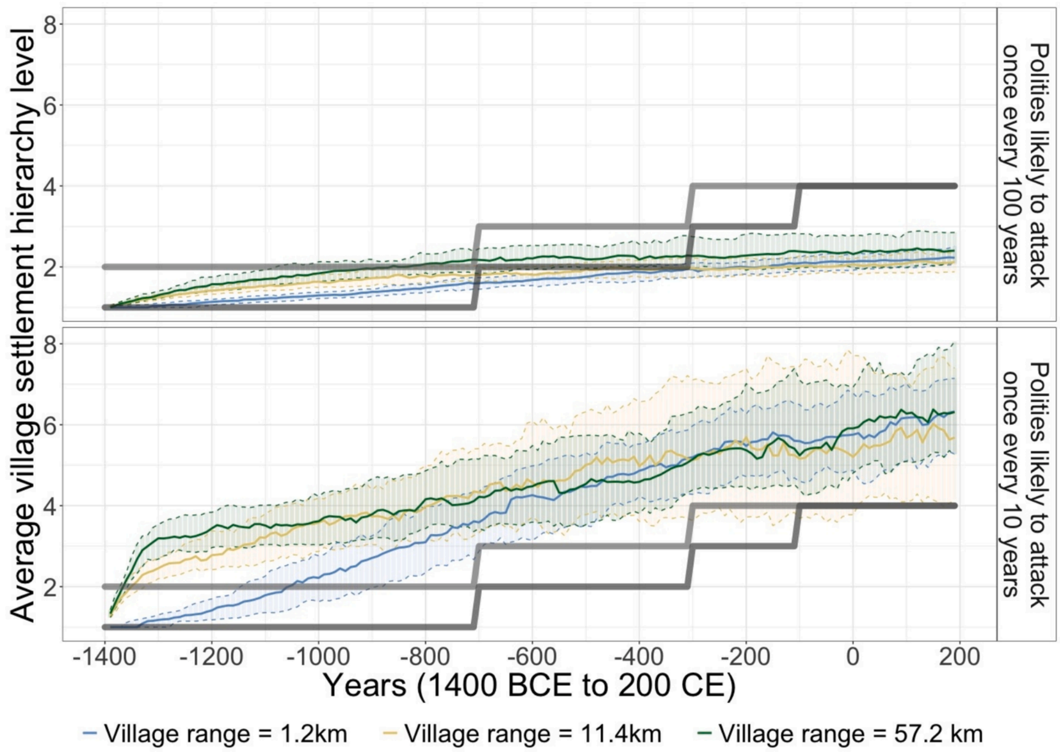

Fig. 3. Graphs comparing the average hierarchy among all villages at each time step with archaeological upper and lower estimates for the levels of settlement hierarchy in polities in the Valley of Oaxaca for each phase (light grey and dark grey represent upper and lower estimates of the levels of settlement hierarchy respectively, see Table 1). The results from repeat model runs are summarised by the interquartile range with the median shown as a continuous line.

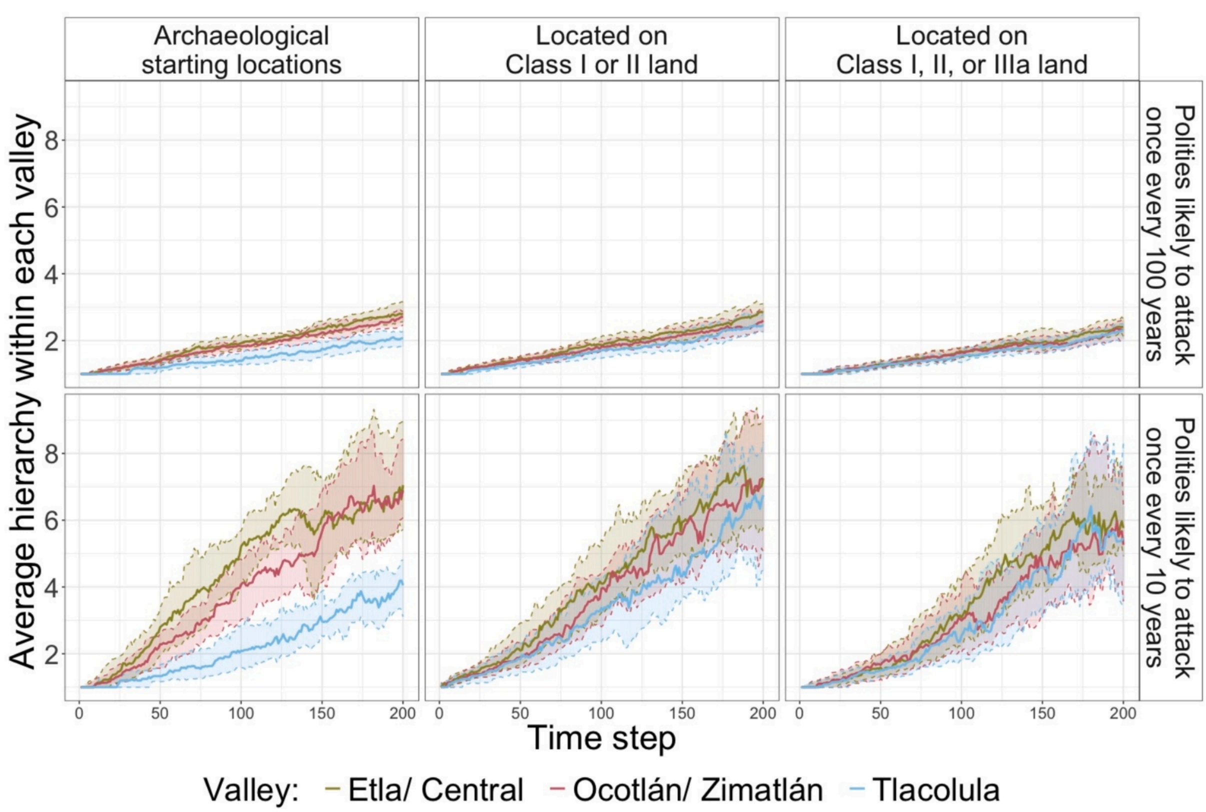

Fig. 4. The average level of hierarchy among villages in the Etla/ Central (yellow), Ocotlán/ Zimatlán (red), and Tlacolula (blue) subvalleys of the Valley of Oaxaca. Parameters varied are the starting location of the 21 villages (archaeological location, randomly on Class I or II land, or randomly on Class I, II, or IIIa land) and the rate of conflict (once every 10 or 100 years). The range of village movement is 1 patch (1.2 km). The results from 50 repeat model runs are summarised by the interquartile range with the median shown as a continuous line. The range of village movement parameter is varied in SM Fig. 9.

archaeological estimate.

The rate of hierarchy formation is lowest when the range of village movement is small (1.2 km), with little overlap in hierarchy levels with the wider ranges of movement (11.4 km and 57.2 km) for the first 500 years of the model runs. The difference is most pronounced when the frequency of warfare and range of movement are high and hierarchy levels increase rapidly within the first 100 years. There is a convergence in hierarchy levels between the different ranges of village movement around halfway through the model runs (~600 BCE). There is a greater overlap with the archaeological estimates for settlement hierarchy until the end of the Monte Albán Early I phase (300 BCE) across all ranges of village movement if the frequency of warfare is low. When warfare is more frequent, the overlap only occurs for the first 400 years when the range of movement is small.

3.2. Experiment 2: The effect of circumscription within the subvalleys of the Valley of Oaxaca

The results in Fig. 4 show some differentiation in hierarchy formation between the subvalleys if villages are initially located in archaeologically determined places, but very little difference if villages are more randomly spread on Class I, II, and/or IIIa land. The difference between subvalleys is clearer if the frequency of warfare is high (once every 10 years per polity). Increasing the range of village movement to 11.4 km diminishes the difference between subvalleys even further, with complete overlap between valleys in all cases (SM Fig. 9).

4. Discussion

The Valley of Oaxaca has often been described as an archetypical case study of the effect of geographical circumscription on the initial formation of social complexity (Carneiro, 1970, 2012a). Building on our previous exploration of the logical consistency of Carneiro's circumscription theory (Williams and Mesoudi, 2024), we based our agent-based model on real-world archaeological and environmental data from the Valley of Oaxaca to formally test the circumscription theory in a real-world situation. Our results suggest that the valley conditions as a whole could have contributed to the formation of social complexity, if we assume each polity may attempt to initiate conflict with another polity every 10 and 100 years. However, the geographical conditions between the subvalleys of the Valley of Oaxaca are unlikely to explain the earlier formation of social complexity in the Etla/Central area.

In our first experiment, we used environmental zones of estimated maize yield to inform the model environment, placed villages in archaeologically equivalent locations at the start of each model run, and based all possible other parameter settings on archaeological and environmental data to situate our circumscription ABM in conditions resembling the real world. The two parameters that we could not set based on existing data were varied between plausible upper and lower bounds.

We found that roughly equivalent levels of settlement hierarchy formed over the corresponding archaeological time period, but that the match between model results and archaeological estimates depend on the frequency of warfare and distance of movement (Fig. 3). A high rate of warfare where each polity attempts to initiate conflict every decade caused overall higher levels of settlement hierarchy than predicted from the archaeological record, while the lower rate of warfare (every century) limited hierarchy formation to around 2 levels. The upper ceiling of settlement hierarchy with fewer incidences of conflict does not correspond with the critical increase in settlement hierarchy in the archaeological record from the Rosario to the Monte Albán Early I phases (700 – 300 BCE), where 3-tiered societies formed in the subvalleys before the unprecedented 4-tiered Zapotec society formed across the valley in Monte Albán Late I to II phases (300 BCE to 200 CE) (Table 1, Spencer and Redmond, 2003, 2004; Kowalewski, et al., 1989a, 1989b; Marcus and Flannery, 1996; Drennan and Peterson, 2006). A more variable frequency of warfare could reconcile this difference, with lower levels in the earlier phases increasing in frequency in the later phases to a greater extent than expected from an increasing population size. Alternatively, allowing the agricultural potential of the environment to increase with technological developments, such as the Hieve el Agua irrigation system (Neely, et al., 1990), or maize yield (Benz and Long, 2000) could increase the rate of hierarchy formation by increasing social circumscription, as suggested in the original circumscription theory. We observed a similar pattern in our previous abstract model, albeit by varying static environmental parameters (Williams and Mesoudi, 2024). To further verify the circumscription theory, we could both extend the model to include dynamic relationships between the population and the environment, and target archaeological research on the rate of warfare across the phases of early social complexity formation with data from this or analogous regions.

Reducing the range of village movement across the valley reduces the level of settlement hierarchy formation, despite forming a larger population size (SM Fig. 4). When warfare levels are high, a smaller range of movement (1.2 km) reduces the rate of hierarchy formation to archaeological levels (1–2 tiers) for the first 400 years of the model runs. The settlement distribution across the valley suggests that people tended to prefer to remain close together within 0.5–2 km (Kowalewski, et al., 1989a) and may therefore imply that warfare was more frequent than once a century per polity to form the archaeological patterns of settlement hierarchy. However, the impervious mountain range border we have simulated here was passable and 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 the model. Additional model experiments allowing for much greater movement outside of the surveyed region of the Valley of Oaxaca suggests that increasing movement does not decrease hierarchy formation compared to an impermeable border (SM 3.1.2). Further work to improve the realism of the model may involve increasing the geographical area to include the movement of people and resources to and from regions outside of the Valley of Oaxaca. In addition, increasing the dynamism of the range of movement by allowing villages to 'see' and move much further afield but with a preference for interactions closer to their current location could be accounted for.

The model presented here does not explicitly test the continuation of social complexity evolution and maintenance beyond the formation of the Zapotec state with four levels of settlement hierarchy. The number of habitable patches in this model limits the population size to 1454 (see SM Fig. 3), 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. We have chosen the parameters of this model to simplify reality in a way that would allow us to explore the potential impact of geographical circumscription in the Valley of Oaxaca as a primary case study in circumscription literature. Our model and this first experiment follow on from our previous findings (Williams and Mesoudi, 2024) to show that the level of geographical circumscription experienced by people in the Valley of Oaxaca could have contributed to the initial formation of social complexity, if our assumptions about the frequency of warfare and range of movement can be supported.

In our second experiment, we further explored the potential effect of geographical circumscription by comparing hierarchy formation in the different conditions of the three subvalleys of the Valley of Oaxaca. The earliest large settlements formed in the Etla/ Central area of the valley (Drennan and Peterson, 2006) with the highest potential yield (Fig. 2) and therefore the highest potential for population growth and competition over resources.

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 located during the Tierras Largas phase. However, not every settlement location may be directly related to the ease of cultivation (Nicholas, 1989). If villages are distributed more evenly across the valley on Class I, II, and/or IIIa land, the difference in hierarchy formation diminishes, even though the rate of population growth is higher in areas richer in resources (SM Figs. 10 and 11). The much lower level of hierarchy formation in the Tlacolula subvalley is likely due to a higher village extinction rate in this valley if the archaeological starting locations are used because far fewer settlements are found in this valley. The difference between the Tlacolula subvalley in population size and hierarchy formation noticeably disappears if villages are more equally distributed between the subvalleys. Moreover, increasing the range of village movement to 11.4 km removes any clear differentiation in hierarchy formation between the subvalleys (SM Fig. 9). This experiment does not support the prediction of the effect of geographical circumscription within the Valley of Oaxaca. Instead, the archaeological pattern of social complexity formation in the Etla subvalley is more likely to be due to settlement location choices made by people at the start of the Tierras Largas phase. However, this model is based on the assumption that human behaviour was primarily informed by subsistence needs, whereas other inedible resources (such as access to raw materials or defensible locations) may have caused other clustering effects that could have amplified social complexity formation.

5. Conclusions

Here we adapted our previous agent-based model of Carneiro's circumscription theory (Williams and Mesoudi, 2024) to test the impact of geographical circumscription on social complexity formation in the Valley of Oaxaca (Carneiro, 1970, 2012a). The patterns of settlement hierarchy formation in the model corresponded with those seen in the archaeological record, dependent on conditions of relatively frequent warfare and a preferred small settlement relocation distance across the valley. However, geographical differences between the subvalleys of the Valley of Oaxaca were not sufficient to explain the earlier formation of social complexity in the subvalley with the highest potential yield within the circumscription theory framework. Targeted archaeological research to refine our estimates of warfare frequency at the time would confirm whether the circumscribing conditions of the Valley of Oaxaca gave rise to social complexity.

CRediT authorship contribution statement

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

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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/Oaxaca_ABM).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105147.

Data availability

Model code and data from model outputs are available on GitHub. Archaeological data are published and referenced in the manuscript.

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