

CHAPTER 14

THE APPLICATION OF AN ENTROPY MAXIMIZING MODEL TO THE RISE OF URBANISM

Supplementary data: <http://discovery.ucl.ac.uk/1355838/>

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INTRODUCTION

This chapter introduces a spatial interaction model for investigating the development of pre-industrial urbanism and regional settlement patterns in southern Mesopotamia. The chapter uses sites from the Late Uruk period as examples of how the geographic setting and attractiveness of sites for trade and settlement, whether because of social, religious, or environmental reasons, could have influenced urban growth or decline. Southern Mesopotamia serves as a natural setting for the study of early pre-industrial urban change, in part because debates and discussions have focused on this region particularly during the Uruk period (Adams 1981; Pollock 2001; Algaze 2008) when some of the first cities arose. While theories such as Complexity Theory (Adams 2001) have been increasingly used to discuss how urbanism developed in southern Mesopotamia, relatively few attempts have advanced quantitative techniques that could provide an explanation of relevant processes that propelled urban transformations.

Spatial entropy maximising models (Harris & Wilson 1978; Wilson 2012; Dearden & Wilson 2012), or spatial interaction models, have the potential to provide explanations that address settlement expansion or contraction under given geographic settings. Such models are particularly attractive because specific causal factors (e.g., avulsion, ideology, population pressures, etc.) for urban change are difficult to isolate or quantify from the archaeological record. However, such transformative vectors' effects can be represented or applied within general models, such as entropy models, for understanding how they affect urban growth. This chapter explores the utility of such modeling and provides the potential insights that might be gained even when there is little data available. The goal is to present a simple simulation model that explores how the spatial setting and factors that affect the flow of goods and people can influence urban transformations and settlement layouts. The chapter utilizes the pattern of Late Uruk sites (LC 5: ca. 3400-3000 BC) first surveyed and compiled by Adams & Nissen (1972) and Adams (1981) in southern Mesopotamia. While using empirical survey data, the chapter also uses hypothetical data to explore how sites that initially seem to be equal in size and population may quickly become differentiated and grow or diminish in size as a result of feedback. While one cannot recreate what exactly contributed to urban transformations in the Uruk period, the model applied demonstrates a formal approach that suggests explanations for evolutionary processes that affect settlement within a geographic setting.

The paper begins by introducing background information on the case study and discussions on early urbanism and relevant theoretical perspectives. The modeling approach applied is then presented in order to demonstrate how the concepts discussed and the associated background information can be applied in quantitative form. After this, the modeling results, including variations from the initial scenario, are provided. These results explore different factors that may have catalyzed or diminished urban population growth. The significance of the simulations to the understanding of the development of early urbanism in southern Mesopotamia is then discussed. Finally conclusions are provided with regard to the methodology and its potential for general ancient settlement system research.

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

BACKGROUND TO THE CASE STUDY

The data applied for this case study derive from surveys conducted by Adams and Nissen (1972) and Adams (1981) in southern Mesopotamia between the Tigris and Euphrates south of Hillah and to the region just south of Samawah (Fig. 14.1). While the modeling uses sites that date to the Late Uruk period, which corresponds to a period when the city of Uruk and other settlements in southern Mesopotamia had become established as major centers (Algaze 2008), the intent here is to demonstrate how major sites could arise while also affecting the surrounding settlement layout. Some sites, such as Mashkan-Shapir, which although not known as Late Uruk centers, did have a minor Late Uruk presence. In such cases, even this is considered sufficient for a site to be included in the modeling exercise. The key focus here, however, is to look at known urban areas and see if such locations can potentially lead to the development of large sites and what might cause this process, including site importance, geographic advantages, or other factors. Therefore, the goal is not to thoroughly present each site and explain why it may have been settled or reached a given size or population in the Late Uruk; rather, the goal is to show how processes associated with urban transformations could have developed. Although some site size estimates from archaeological surveys can be problematic, the results, in general, demonstrate that in the Late Uruk period relatively few sites appear to have reached a large size, whereas the vast majority were very small. Certainly by the Late Uruk many aspects of southern Mesopotamian urbanism, such as large temple complexes, monumental architecture, and political institutions, were well established, indicating a level of social complexity not witnessed during the Ubaid and other prehistoric periods (Algaze 2005). Although it is very likely that by the Early and Middle Uruk such urban characteristics were already established (Wright 2006), sites from the Late Uruk are chosen as the working examples because it is clear that this period represents a mature stage of early urbanism; the site of Uruk, for example, may have reached a size of approximately 250 ha by this period (Chapter 3; Finkbeiner 1991).

Not only has there been considerable scholarly interest in the Uruk period, contemporary archaeological theory has also tended to focus on the economic and environmental circumstances that made southern Mesopotamia attractive for settlement and urban growth in the fourth millennium BC (Hole 1994; Algaze 2005). This was a period when the regional climate was probably wetter and provided relatively ample water supplies (Aqrawi 2001). The marshes and hinterlands must have provided ideal food sources for early centers to develop (Pournelle 2003). Such circumstances provided the potential for southern Mesopotamia to develop an urban society at an early date. Nevertheless, such information does not fully explain how the process of urbanism, with its associated feedbacks and interactions between different social and environmental components, along with interactions between sites and geographic advantages, developed over decades or hundreds of years.

Theories of Urban Growth

Algaze (2008) has summarized the economic and environmental reasons that underlie the early development of southern Mesopotamian urban growth. Economic advantages include the development of low-cost transport via canals and boats, increased trade activity, and geographic location. Together, these not only helped centers to initially develop, but also enabled positive feedbacks to form that reinforced the advantages gained with likely results in towns growing even further. The effects of positive feedback systems on urbanization have certainly been noted in the context of modern trade and the global economy. In such cases larger or more significant centers took advantage of their economic and social position and grew to unprecedented scales, whereas other regions diminished in economic strength due to processes of negative feedback (Krugman 1995). Feedback systems essentially create new economic and social opportunities that enable major cities and regions to grow to a greater extent. These then have secondary effects that result in reducing or increasing population and economic growth in the surrounding settlements and regions (Jacobs 2000). The system of growth and decline may then stabilize until new events disrupt a given state, once again changing patterns of settlement growth and decline. Similar reasons have been given for processes that underlie the development of states and empires, urban development, and changing social or political complexity in various periods and parts of the world. For example, Braudel (1995), Fox (1971), and Desrochers (2001) all incorporated geography, environment, and transport as factors that shaped social developments which, in turn, transformed major urban centers so that they

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

possessed significant advantages relative to other regions. While such factors probably played a major role in urban growth, ideology and social institutions that concurrently developed in association with settlements also affected social norms, which, in turn reinforced the status of major centers (Collins 2000). Ideology and institutions can, therefore, contribute to positive feedback which enable settlements to expand further, while conversely, this can diminish the population and economic potential of other settlements. Early preindustrial societies are likely to have experienced low rates of natural population growth (McNeil 2000), whereas 'pull' factors, such as trade, economic incentive, or ideology, are more likely to have increased population and size of settlements (Persson 2010).

Cronon (1991) demonstrates a specific example of feedback and associated growth in his presentation on the reasons behind the rapid growth of Chicago in the nineteenth century. Despite Chicago's initially marginal setting, the geography of Chicago, with its access to large inland lakes and rivers and its central location within the burgeoning railroad networks of the nineteenth century, soon provided the city with significant advantages over other urban areas. These early advantages eventually contributed to the development of industries and economic innovations, which, in turn, attracted many more people to the city. Thus, while the city grew naturally from population growth, the vast majority of Chicago's early population growth is attributed to the pull and attractiveness that the city had for many migrants and goods. As the city grew, the surrounding geography and smaller urban centers developed in relation to the larger city of Chicago, so that some areas benefited while others lost prominence in relation to Chicago.

Such examples of Chicago's rapid growth, and reasons as to why pre-industrial cities grew or diminished in population, lend themselves well to Complexity Theory, which incorporates concepts of feedback interactions as well as the role that socio-environmental systems play in influencing societal transformations and urban development (Adams 2001; Batty 2005; Bentley & Maschner 2008). Complexity Theory essentially provides an analytical framework that allows factors such as urban settings, the environment, and cultural practices, to be seen as interacting in a non-linear manner. However, some factors have more relevance in contributing to transformations, and it is these interactions that develop feedbacks that enable a settlement to grow, decline, or stabilise, sometimes at a very rapid rate.

Discussions of the economic, geographic, and ecological factors contributing to urban growth are well articulated in the field of urban geography. Huff (1963) had conceptualized these factors in work describing trade and urban areas in the modern day. Later, more formal, quantitative methods were developed in order to analyze spatial relationships, population, markets, and the significance of centers in attracting urban consumers and encouraging population growth (Wilson 1967; Wilson 1970). This type of modeling has been used to describe how cities develop in a variety of different settings and circumstances, both in the present (Birkin & Heppenstall 2011) and past (Wilson 2012). Given the advancements in quantitative methods that explain spatially bounded urban transformations affected by different social and environmental vectors, one can begin to apply approaches such as Complexity Theory in a quantitative form to demonstrate and explain urban transformations such as those evident by the Late Uruk period in southern Mesopotamia.

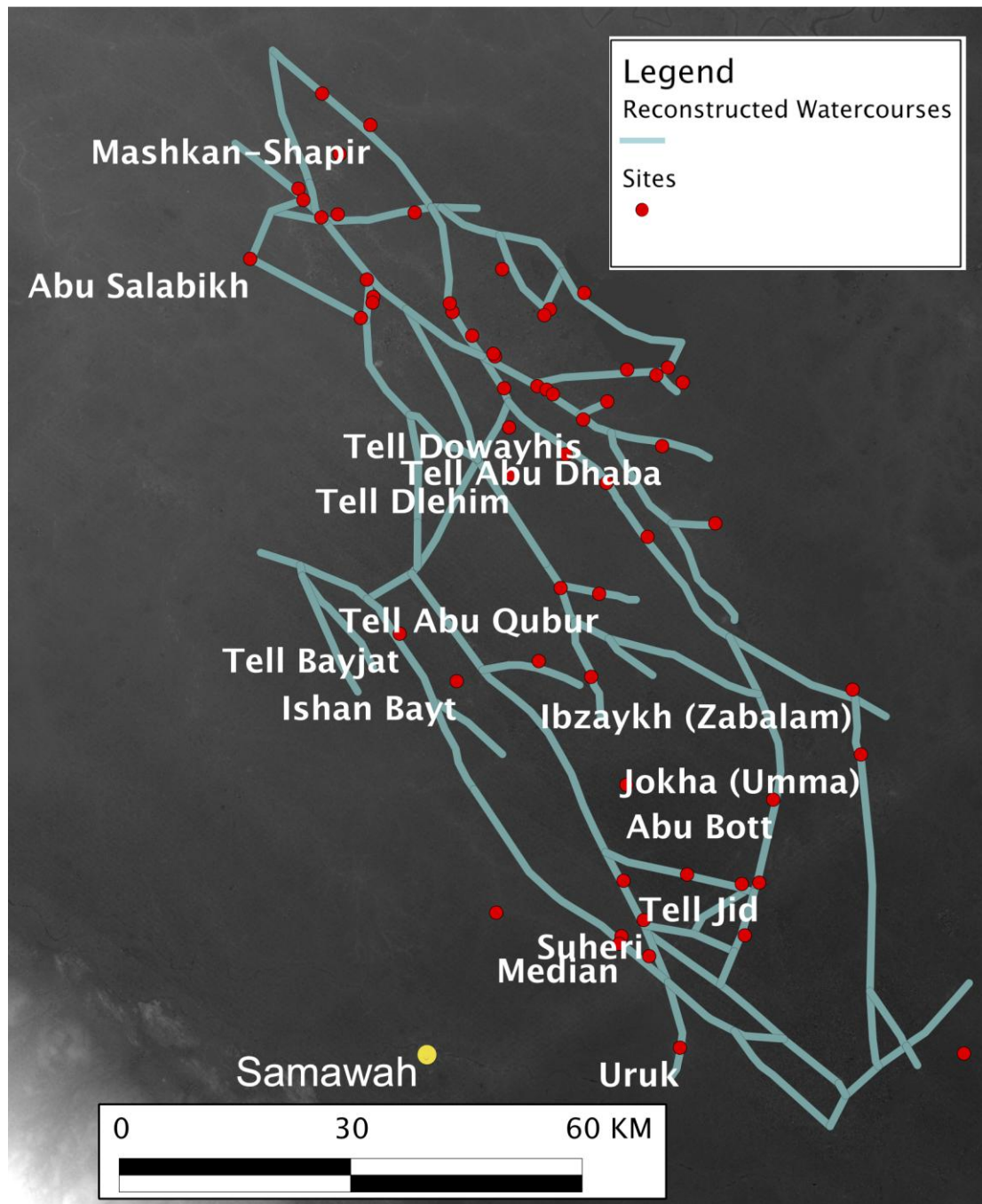


Fig. 14.1 Late Uruk sites investigated in southern Iraq (site shapefiles provided by Carrie Hritz) superimposed over ancient watercourses reconstructed from ASTER (2012) elevation data.

MODELING APPROACH

Among the most widely used urban economic or population growth models have been entropy maximisation models. These have been used to describe, not only urban growth within regional contexts, but also smaller scale settings such as the locations of individual stores and areas within cities that have experienced different economic fluctuations (Heppenstall *et al.* 2006; Birkin *et al.* 2010; Birkin & Heppenstall 2011). These models have traditionally taken the form of Lotka-Volterra equations, which have been used to model such dynamics as predator-prey relationships. Specifically in the case of urban and spatial modeling, these have been applied in the form of Boltzmann-Lotka-Volterra equations (Wilson 2008). Such models have been traditionally employed to account for uncertainty in given systems. In this case, uncertainty represents unknown reasons, including

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

social or ecological factors, as to why certain settlements developed large populations. Recently, these models have incorporated bottom-up perspectives, specifically via the application of agent-based modeling (Dearden & Wilson 2012). Nevertheless, the underlying entropy model has continued to be an effective tool for articulating changing urban landscapes as well as factors that explain the growth or decline of cities and markets.

For the purposes of this paper, a spatial entropy model, such as that advanced by Wilson (1967; 1970) and Harris & Wilson (1978), is very useful for applying to pre-industrial urban contexts where rapid population growth is less likely to have been driven by natural population growth. In other words, to understand how pre-industrial cities grew one needs to understand non-biological growth that created opportunities for some centers to thrive whereas others grew at only marginal rates or even declined. Because this is the pattern apparently noticed for the Late Uruk period (Adams 1981), where few centers exceeded twenty hectares and a vast majority of sites were likely to be very small (on the order of one hectare or less), the model presented is used to describe this process in quantitative form. The first step as the model begins is stated as:

$$S_{ij} = e_i P_i W_j^{\alpha_j q_j} \exp(-\beta d_{ij}) \quad (1)$$

Here:

S is flow (or expenditure) for settlement i in relation to another settlement j ; flow represents movement of population or goods to a settlement;

e_i is a scalar used for settlement i ;

P is the population of site i ;

W is the size of settlement j , in this case the variable is a relative and notional value that allows a settlement's population to increase or decrease more greatly;

α represents the 'attractiveness' of site j 's location and size, which can include social, religious, or environmental factors which make specific settlements more attractive than they otherwise would be;

q represents external contacts or interactions, namely those outside the modeling region, such as trade or political favor that make j more or less attractive,

β represents the ease of travel between sites, with decreasing β representing fewer restrictions to travel and greater β represents more hindrances to travel; like α , this variable could represent a variety of factors that contribute to easier or more difficult travel, including political, economic, or transport-related reasons; and d is distance.

For outputs of S_{ij} , a base-10 logarithm is adopted to scale the value. In this model, shortest path distance (d) between towns is determined by an A* algorithm (Hart 1968) that uses distance based on watercourses connecting sites (see Fig. 14.1). In other words, in the simulation, people and goods from within sites access the nearest watercourse to them and move to sites using the shortest distance along any watercourse. This simulates the effect of river-based traffic as a major factor in shaping urban growth in southern Mesopotamia, and it also calculates the distance using relative topographic changes in the region. This topography, which represents the levees of channels and rivers, is based on ASTER elevation data (ASTER 2012).

Other ways of determining d include the use of a probabilistic framework for route selection or social factors (e.g., political or territorial divisions) that constrain route selection between cities. For the type of study presented here, flow is used to determine the flow of goods (i.e., 'capital') and/or people through migration to different settlements. The focus in this paper will be mostly on migration as determined by flow. In the next step of the model, overall flow for a given site j is then determined:

$$D_j = \sum_i S_{ij} \quad (2)$$

where the summation of S is D (overall flow); in this case all cities are considered to be residential zones with some exchange or market functions. The next step determines the size of an urban area based on overall flow calculated:

$$W'_j = W_j + \varepsilon(D_j - kW_j) \quad (3)$$

where W' is the next increment of site size (i.e., in the next time iteration) based on ε that controls the pace of change, overall flow (D), a constant (k), a notional value representing the cost of operating a city of a given size, and the current city size (W). This step simply looks at benefits of flow to a settlement and how these either negatively or positively influence urban growth. While k is difficult to determine for ancient urban areas, it is possible to measure the growth of cities and urban locations relative to each other. Absolute growth is not the main focus; rather, because the results measure sites against each other, a relative scale is used to determine where urban growth is more pronounced in relation to other sites. This allows us to account for k without necessarily requiring the specific knowledge of this variable. Therefore, k is a constant for all sites and simulation scenarios. In the model applied, the next step is then to determine the population and under what circumstances population is drawn towards a settlement as a function of its size. In other words, the next step applies population migration or flux to settlements in the model based on the following function:

$$P'_j = \left\| W_j * \sum_j P_j / \sum_j W_j \right\| \quad (4)$$

This takes the nearest integer of the result in order to modify P . Essentially, this proportionally adjusts j 's population based on size as calculated in (3). Although it might be difficult to determine the exact population for settlements, in a manner similar to W , P provides a notional value that indicates where population is likely to cluster. For the simulated cases, population is stationary (i.e., no natural growth) and people are assumed to migrate based on which city is growing in size. Given that W and P are used hypothetically to enable comparisons between sites, raw outputs are not intended to replicate empirical values.

MODELING RESULTS

Based on the above model, four scenarios are represented in the following results. The scenario data used and discussed for the simulations can be found at: <http://discovery.ucl.ac.uk/1355838/>. Whereas sites sampled in the modeling date to the Late Uruk period, the model uses demonstrative values to test how trends in urban transformations may develop. This has the goal of determining how a situation like that of the Late Uruk, where only a small number of urban centers thrive, is possible even if initially populations and site sizes are the same. Results are then able to provide insights into how centers emerge, stabilize, or decline, assuming that such dynamics occur without biological population change and within a specific spatial setting. Given these assumptions, the first example provides a baseline case where all values are equal for all locations; this tests the role of geography and transport in shaping urban growth. In the sub-scenarios for this case, α (attractiveness) and β (ease of travel) are the same for all sites, but are varied in each sub-scenario. The next scenario tests variations on α for specific sites, together with changes to β , which demonstrate how differential values representing each settlement's importance can be used to create urban layouts similar to those of the Late Uruk. The third case investigates the role of foreign trade and contacts in affecting urban change. Finally, a scenario is applied which investigates how shifts in urban importance and the flow of goods can influence the resilience of populations in surrounding settlements.

Scenario 1: Baseline Scenario

For this case, the intent is to identify which sites may have geographic and transport advantages that allow them to potentially emerge as relatively larger sites and to what extent site attractiveness (α) and willingness to travel and move goods (β) affect migration of people to settlements. As α increases, attractiveness to any given site is considered to increase, whereas the increase of β indicates there is less willingness or greater hindrance to travel far to sites. Initial values used for this scenario are listed in Table 14.1, specifically for Scenario 1a, with sub-scenarios b-i varying α and β . Therefore, in all sub-scenarios site size and population are equal at the beginning

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

of the simulations. The scenario is run until the population and size results are considered stable or the simulation ends, resulting in runs being 120 axis ticks long.

Figure 14.2 shows the end result of this scenario; the outputs indicate the point locations and the populations of the settlements relative to each other. When comparing sub-scenarios, it is evident that Figure 14.2c has the greatest variation in site point values, which indicates that there is greater population variation for settlements. In contrast, Figure 14.2g has the least variation, indicating that population is more evenly distributed. While α increases (i.e., Fig. 14.2d-i), resulting in the increase of the size variable (W), proportionally, the population of settlements does not increase because all sites are increasing in size together. In other words, when α alone increases for all sites, no settlement becomes pre-eminent over other sites, thus creating a relatively even distribution of population. On the other hand, β has a greater effect in the differentiation of population (Fig. 14.2b-c, e-f, h-i), so that more distant sites become less attractive as β increases. Figure 14.3 shows population differences in three of the sub-scenarios modeled, showing that low α and greater β result in populations becoming more differentiated. In essence, equally high α values do not allow any particular settlement to increase dramatically in population, whereas changes to β have a more pronounced effect on population differences.

This results in Figure 14.2c exhibiting the greatest differentiation in population because the more northern sites in the model region have more nearby settlements, and therefore draw on greater access to flow of nearby sites. This results in the northern sites (e.g., Sites 1129, 1069, and Tell Dlehim) increasing their populations relative to surrounding sites. The results imply that areas to the north of Uruk and in the region of Nippur are more likely to attract a greater portion of people if all others factors are equal. Another pattern to note is that Uruk is among the smallest sites in all the results, reflecting that it does not attract as much flow of goods and people despite its spatial location and accessibility along watercourses.

Table 14.1 Initial values used in Scenario 1a.

Population (P)	Size (W)	Scalar (e)	Attractiveness (α)	Travel (β)	ε	Size Cost (k)	External (q)
1000	20	1	1	0.2	0.05	1	1

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

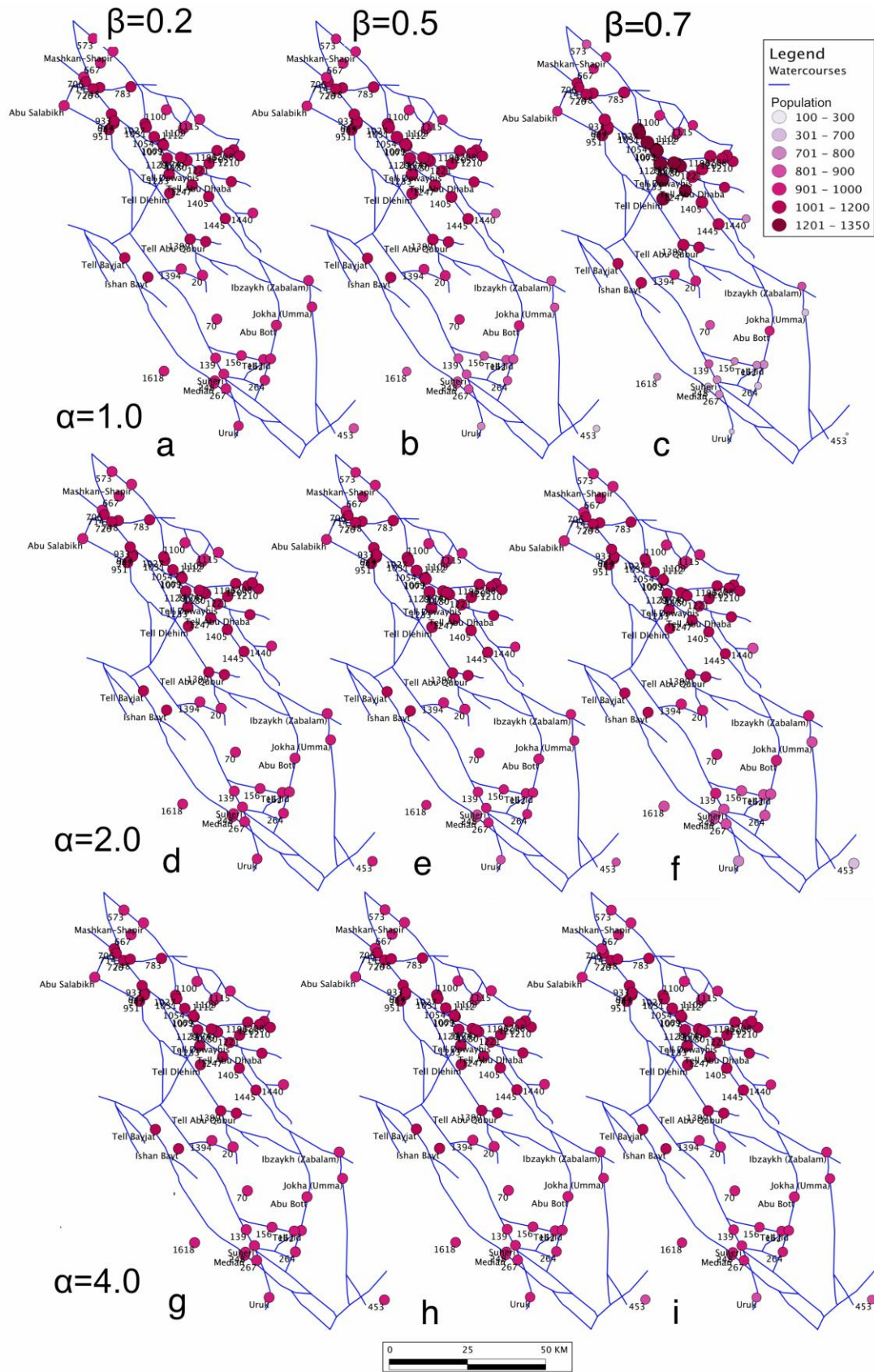


Fig. 14.2 Final simulation results from the baseline scenario (a-i) showing variations of α and β and their effects. Settlement population (P) variations are displayed using shades of grey and point size.

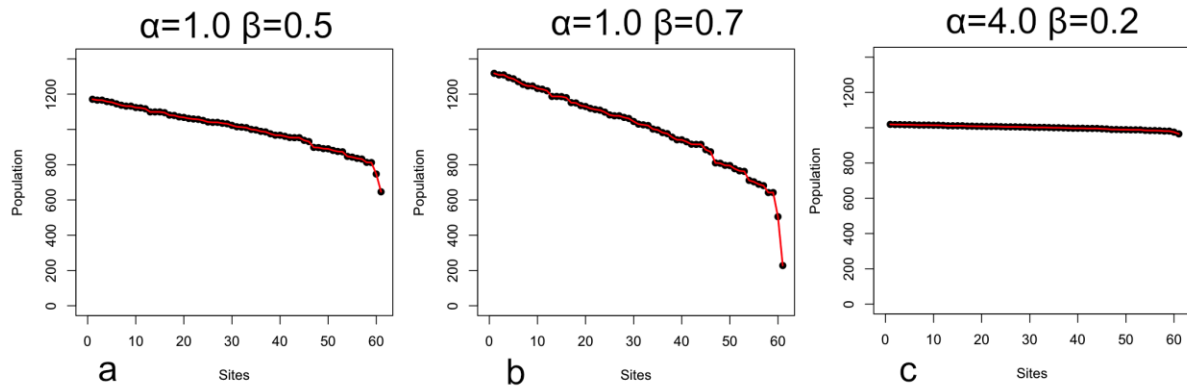


Fig. 14.3 End population results for three of the nine sub-scenarios modeled in Scenario 1 (b, c, & g respectively from Fig. 14.2).

Scenario 2: Variation of Site Attractiveness and Willingness to Travel

The previous scenario simply examined for geographic and transport advantages within the region being modeled. However, it is known that Uruk, a relatively southern site, became the largest site during the Late Uruk period. In Scenario 2, we investigate reasons as to how this may have developed specifically based on regional interactions. This scenario conducts a ‘parameter sweep’,¹ and addresses (North & Macal 2007), specifically for α , for each site, and β as a global variable, with all other values remaining the same as in Scenario 1; these settings can be found in the data hyperlink provided. The intent is to find α and β settings that produce resultant city sizes that at least qualitatively resemble those perceived for the Late Uruk (Adams 1981). Two sub-scenarios (a & b) in Scenario 2 are used to illustrate contrasting results. As before, the outcome of the simulation focuses on population variation (Fig. 14.4), with point size derived by dividing a settlement’s population by the median population value for the modeled region. The scenario has been run until the results appear relatively stable (120 ticks in Scenario 2a) or when sites completely lose their population (78 ticks in Scenario 2b).

Figure 14.4a shows the population outputs for Scenario 2a, whereby Uruk, Umma, Tell Dlehim, and Abu Salabikh are the largest sites. Uruk has now become nearly 62 times larger in population than the median site in Scenario 2a, while Tell Dlehim (~12 times larger), Umma (~12), and Abu Salabikh (~6) have become the next largest sites. On the other hand, the majority of sites are near 1.0 or lower and appear in Figure 14.4 as very small sites or not at all. For Scenario 2b, β has been changed from 0.2 to 0.44; this increase was chosen, rather than even higher values, because higher β causes the simulation to end very quickly, as sites reach 0 size and population. In Figure 14.4b (i.e., Scenario 2b), the results are even more dramatic than in Scenario 2a, as Uruk increases to ~81 times the population of the median site. The next largest sites remain roughly the same as before except that their sizes are now ~15, ~15, and ~7 times the median population value respectively. These have not increased as much as Uruk but nonetheless they represent an increase from Scenario 2a. As for the smaller sites, they have become even smaller than in Scenario 2b. This demonstrates the effect of β once again, whereby travel to the larger α sites is maintained, but increasing β provides less reason and greater impedance to travel or maintain relative flow to sites with a lower value of α . This results not only in greater relative cumulative flow to the larger centers, but also in sites near those with larger α values and farther away from other sites, to decrease in population more dramatically. The settlement populations for the two sub-scenarios are indicated in Figure 14.5a&b.

Overall, the median population values for the region are 388 and 329, which represent a decrease of 15%, for Scenarios 2a&b respectively; standard deviation are 3155 and 3479, indicating a greater variation in settlement size in Scenario 2b. This result indicates that a larger percentage of the population is concentrated in fewer,

¹ Namely tests on different variable settings,

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

larger centers in Scenario 2b. In contrast, in Scenario 2a smaller settlements are better able to maintain their population. Figure 14.5c&d illustrate this result and show the flow, in this case used to represent migration and movement for two contrasting sites, as well as what happens to larger and smaller settlements. W , (settlement size), is always increasing or stabilizing, although not at the same rate, throughout Scenario 2a (Fig. 14.5c&d), resulting in slight growth or a stabilizing population for Site 453. However, this is not the case in Scenario 2b. In this Scenario, Site 453 (Fig. 14.5d) has a negative population flow and eventually reaches zero, whereas Abu Salabikh maintains a slightly higher size. This indicates how a decreased incentive for travel to smaller sites contributes to the raw size of a site with population reaching 0 for Site 453 at the end of the simulation run. In the case of Site 453, located near Uruk, a greater portion of its population is pulled to Uruk, whereas at the same time few sites near Site 453 are able to contribute flow, and therefore population, to the site. As a result, there is a disproportionate decline in population for any settlement that is more distant from other sites and at the same time is affected by a nearby, larger site's economic and demographic attraction.

To emphasize the contrast in the sub-scenarios, Figure 14.6 shows aggregate flow (S_{ij}) between sites for sub-scenarios a & b. As indicated in (1), flow relates to how sites receive goods and people from surrounding towns, ultimately affecting site size (W) and population (P). In other words, flow measures how much pull a site may have on the surrounding settlements, with flow helping to determine how large a site will become. In Figure 14.6, which examines the largest and smallest two sites in sub-scenarios a & b (Uruk and Site 453 respectively), the results indicate the underlying dynamics that affect differences in the sub-scenarios. In Figure 14.6, Uruk always receives a larger share of the flow between the two towns. However, there is a distinction between Scenario 2a&b. Whereas there is positive flow in Scenario 2a for both Uruk and Site 453 (Fig. 14.6a), in Scenario 2b, Site 453 (Fig. 14.6b) experiences mostly negative flow. This negative flow causes the outcome seen in Figure 14.5d, in which size and ultimately population decrease toward 0. On the other hand, the results in Figures 14.4b and 14.5b show that Uruk increases in size in Scenario 2b. However, Figure 14.6b makes it clear that flow is not actually increasing but is sharply decreasing the flow at smaller sites such as Site 453. This enables Uruk to be relatively larger in Scenario 2b. The relative percentage flow to Uruk, therefore, increases due to decreases in flow at the smaller sites. Overall, what makes Uruk large is that it has a greater α than other settlements, which makes it more attractive for settlement relative to other sites, and a greater β for all sites makes it increasingly more difficult to travel to sites with lower α . This gives sites with greater α a better advantage for increased growth. Scenario 2b simply emphasizes this phenomenon even more.

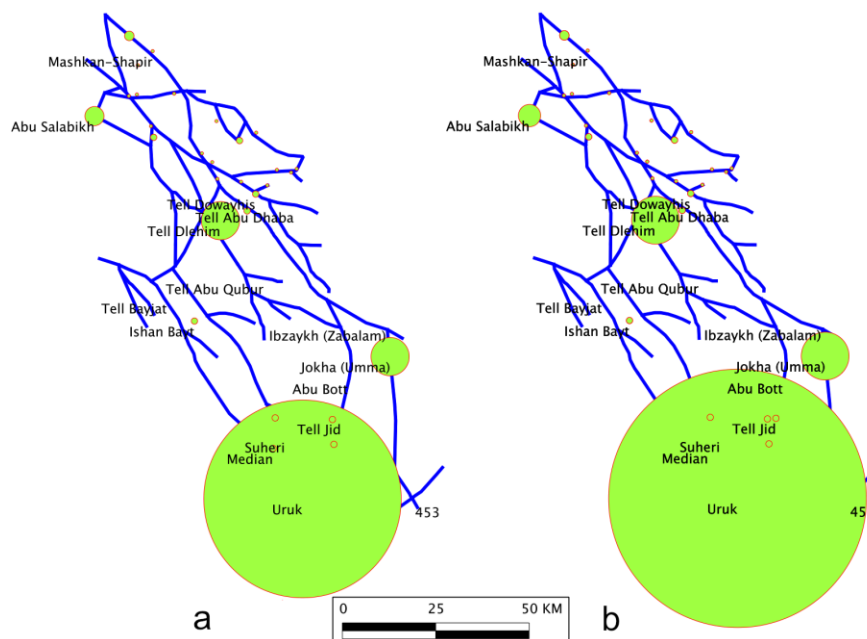


Fig. 14. 4 Final output results from Scenario 2a&b investigating α variations for sites and changes to β . Settlement size indicates proportional population calculated by dividing each settlement's population by the median population.

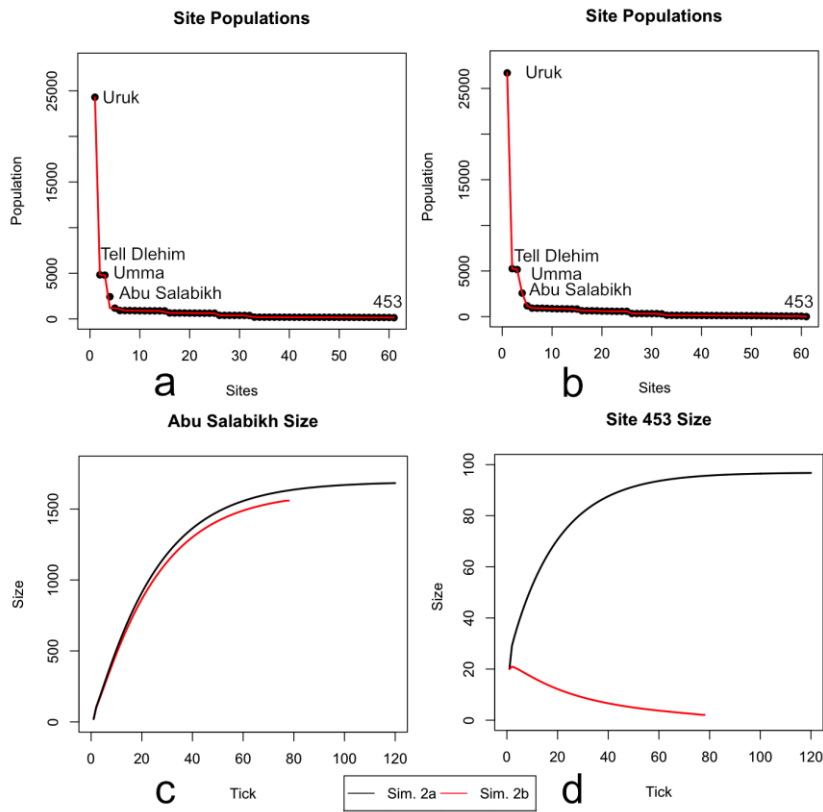


Fig. 14.5 Population for Scenario 2a&b (a & b respectively) at the end of simulations and the evolution of the size variable (W) in two of Scenario 2's sites (c & d). In the case of c & d, simulation 2b is the lower curve.

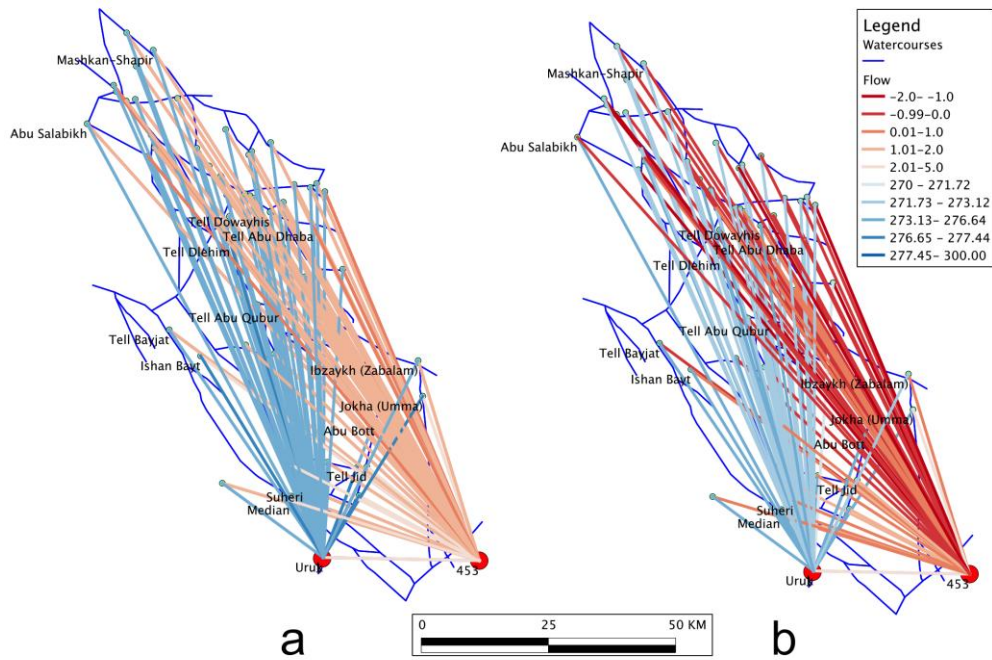


Fig. 14.6 Aggregate flow (S_{ij}) for Uruk and Site 453 at the end of Scenarios 2a&b (a & b respectively).

Scenario 3: The Role of External Contacts

The previous results have ignored the role that settlements or regions outside the model area may have played on the development of settlements in southern Mesopotamia. Scenario 3 is similar to the previous cases in that site size hierarchies are comparable to those reconstructed for the Late Uruk period; however, here the role of external contacts (q) is also considered. For this scenario, hypothetical cases are used to demonstrate the concept of exogenous or external contacts that sites could have that may influence their growth. In this case, q represents trade or interactions that increase or decrease the importance of a site based on links outside the modeled region. The variable captures exogenous settlements and regions that affect how a settlement within the region might evolve. Therefore, exogenous areas could either negatively or positively affect flow and ultimately population change.

As before, the parameter settings used are in the data link provided. In Scenario 3, two sub-scenarios (a & b) are modeled. The difference between these sub-scenarios is that Scenario 3a applies β at the level of 0.2, while in Scenario 3b β is 0.65, for similar reasons as stated for Scenario 2b. Scenario 3a is run to 120 ticks, whereas Scenario 3b is 78 ticks. Figure 14.7 shows the relative populations based on point size using the same type of output as discussed previously. Similar to Scenario 2, results indicate varying degrees to which the population of a settlement changes as β is changed. In Scenario 3a (Fig. 14.7a), Uruk reaches a population ~64 times (24,792 individuals) the size of the median population, whereas for Scenario 3b (Fig. 14.7b) it is ~92 (29,236). The reasons for this discrepancy in size are the same as for Scenario 2; the key focus here, however, is how q (i.e. external links) influence the results. In both Scenarios 3a&b, q is set to 7 for both Uruk and Mashkan-Shapir, which is here used hypothetically as an example for external benefits received rather than implying that empirically the site was ever large in the Late Uruk period. Alpha is 10 for Uruk, whereas it is 1 for Mashkan-Shapir as well as for the majority of the other sites. The results show how a settlement such as Uruk could have made up for its diminished local importance by increasing its relevance outside of the southern alluvium. For example, the well-known Late Uruk trade colonies could be an example of how external linkages (q) affect the model results such as those shown in Figure 14.7 (Stein 1999). In addition, in both Figure 14.7a&b the results demonstrate how a site such as Mashkan-Shapir could become a relatively large town despite the few attributes that make it more attractive locally (i.e., a relatively low α value). In Figure 14.7, Mashkan-Shapir's population is closer to those sites with greater α values such as Umma and Tell Dlehim.

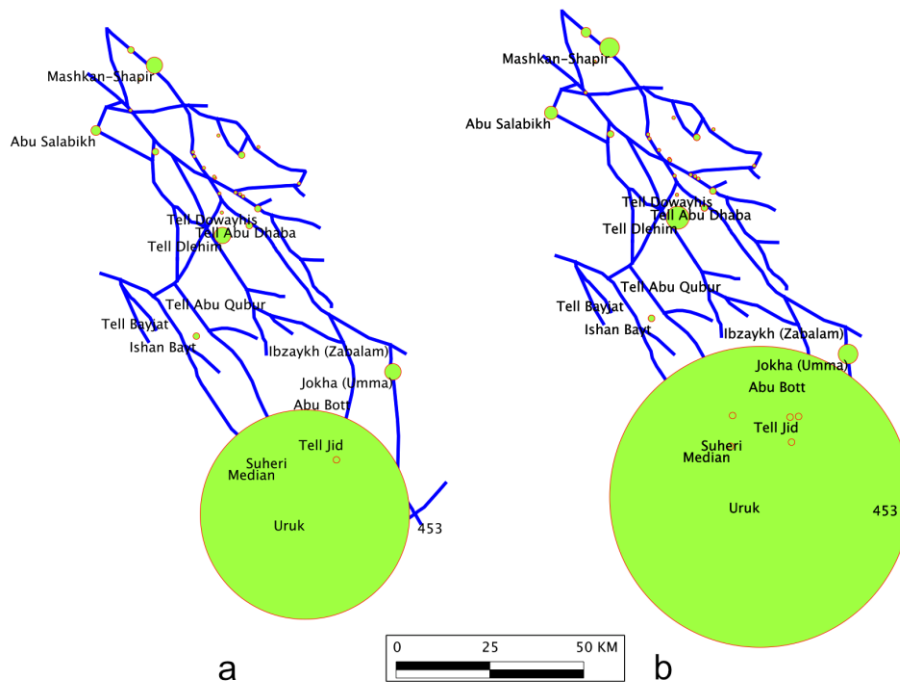


Fig. 14.7 Settlement population for sites indicated by relative size of settlements in Scenario 3a&b (a & b respectively).

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

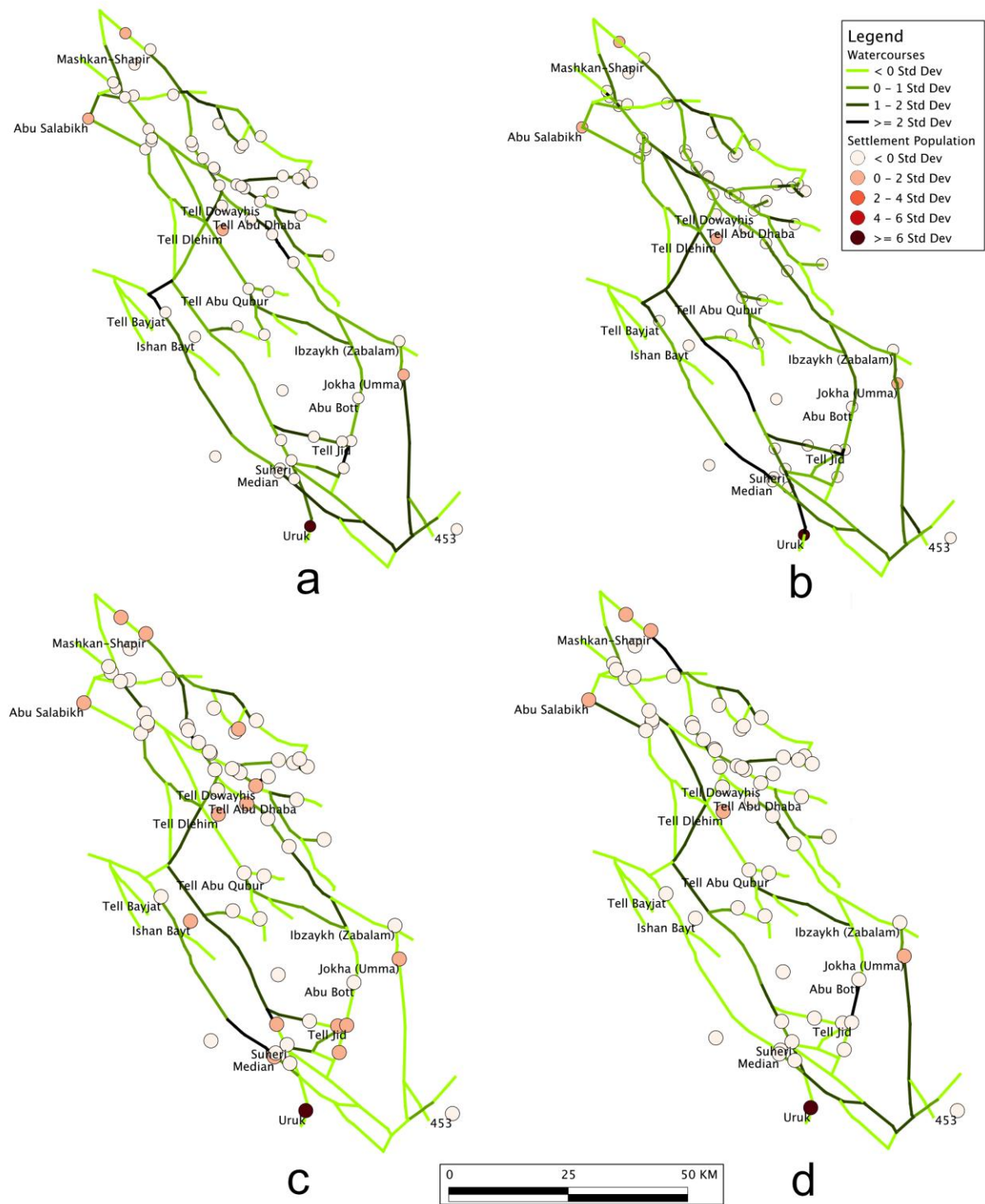


Fig. 14.8 Watercourses travelled based on proportional division of settlement flow (S_{ij}) between sites in Scenarios 2a&b (a & b) and 3a&b (c & d).

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

Another relevant outcome of this scenario, and largely ignored in the discussion so far, is the role of the transport infrastructure. One output that can be monitored is which routes people use to migrate or to bring goods to settlements. There are many ways of dividing up route usage according to flow outputs (i.e., S_{ij}). For simplicity, the approach taken here adopts the least-cost path and applies the route in relation to the flow. This simply means that the shortest path taken between two sites (i.e., a watercourse linking the two sites) assigns 100% of the flow between the sites to the specific path. This indicates a potential path that could be taken in the flow calculation. Figure 14.8a&b show route usage for the last scenario, Scenario 2a&b, respectively. This output is contrasted with Figure 14.8c&d that shows Scenario 3a&b respectively. Not surprisingly, those routes in closest proximity to other settlements, that is in the northern parts of the alluvium, and those that lead to Uruk and other larger centres, are the most used in Figure 14.8a&b. Population and flow here are expressed as standard deviations to highlight the large differences between population and flow to sites. As the larger centers gain a greater percentage of the flow, routes connecting these larger towns become more heavily used (Fig. 14.8b), which follows conceptually the point made in Figure 14.6. In Scenario 3b (Fig. 14.8d), the results show how as β is increased, population (expressed by standard deviation), accumulates in fewer centers than in Scenario 3a (Fig. 14.8c). This then concentrates flow along watercourse routes that connect the fewer relatively large centers. Sites such as Uruk, Mashkan-Shapir, Umma, and Abu Salabikh, for example, all have nearby watercourses that are more heavily travelled, while in Scenario 3a there is more dispersion of flow to other settlements. The watercourses between Umma and Uruk, for instance, are more heavily used in Scenario 3b than in Scenario 3a. In short, Figure 14.8 demonstrates the effect of constraining relative travel (that is increasing β), upon those routes that have access to the towns with larger values of α and q , with the result that these towns take an increased percentage of overall flow.

Scenario 4: Measuring Resilience

In previous scenarios, the results provide estimates of the Late Uruk settlement patterns and site size hierarchy. These include factors such as site geography, transport, trade, and external contacts that are relevant to the development of urbanism during that period. Scenario 4 conducts simulations to determine how significant transformations, such as changes of α during a simulation, might suggest which settlements could be more resilient, and thus maintain a greater population, under conditions of changing α (Adams 1978). Such changes are intended to replicate political, social, or environmental factors that may make some regions more or less attractive than others. As with the previous case, this scenario applies hypothetical cases, with this measuring relative site resistance to changes to α . Therefore, changes to a site's attractiveness or importance, expressed as α , measures how population is better able to be relatively preserved even after a site loses its importance. Resilience of sites expressed through changes to α could, therefore, suggest areas of settlement that might be better able to withstand more dramatic change in the local socio-environmental setting.

In this scenario, Abu Salabikh has initial values of $\alpha=5$ and $q=2$, whereas all other settlements have both values set to 1.0. This, as expected, makes Abu Salabikh the dominant settlement at the beginning of the scenario. However, after every 20 ticks, starting at tick 10, $\alpha=5$ and $q=2$ are applied to a random set of settlements chosen. For example, in Figure 14.9, by tick 60 several settlements are randomly chosen to become more dominant, specifically Tell Jid, Site 1115, Site 1445, and others indicated by darker colors. However, by tick 70 this has shifted once again as new sites have been chosen. The key point in this situation is how some sites are able to retain a higher level of population than other sites, despite having α and q values equal to most other sites. The results at tick 80 show that Site 1445 maintains a greater population than most surrounding settlements, even while other former high α and q sites (e.g., Site 1115 or 573 in tick 60) have already become more like some of the other lower α and q settlements. This shows that sites that lose their importance or external contacts (which in this case are such sites as 1115 and 573 from tick 60), could rapidly lose their population by tick 80. However, not all sites lose their population as rapidly and some sites, in this case Site 1445, are able to retain a greater portion of their previous population. By tick 100, Site 1445 and Tell Dlehim attain high α and q values, with these sites also chosen randomly, while other sites are set to 1.0 for these parameters. At this time, the former higher α and q value sites (i.e., those from tick 80 including Sites 951 and 139) have a similar population to other surrounding settlements. At tick 120, Site 1445, once again, and Tell Dlehim, are able to retain

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

relatively greater populations, similar to that shown in tick 80, although they had lost their higher α and q values.

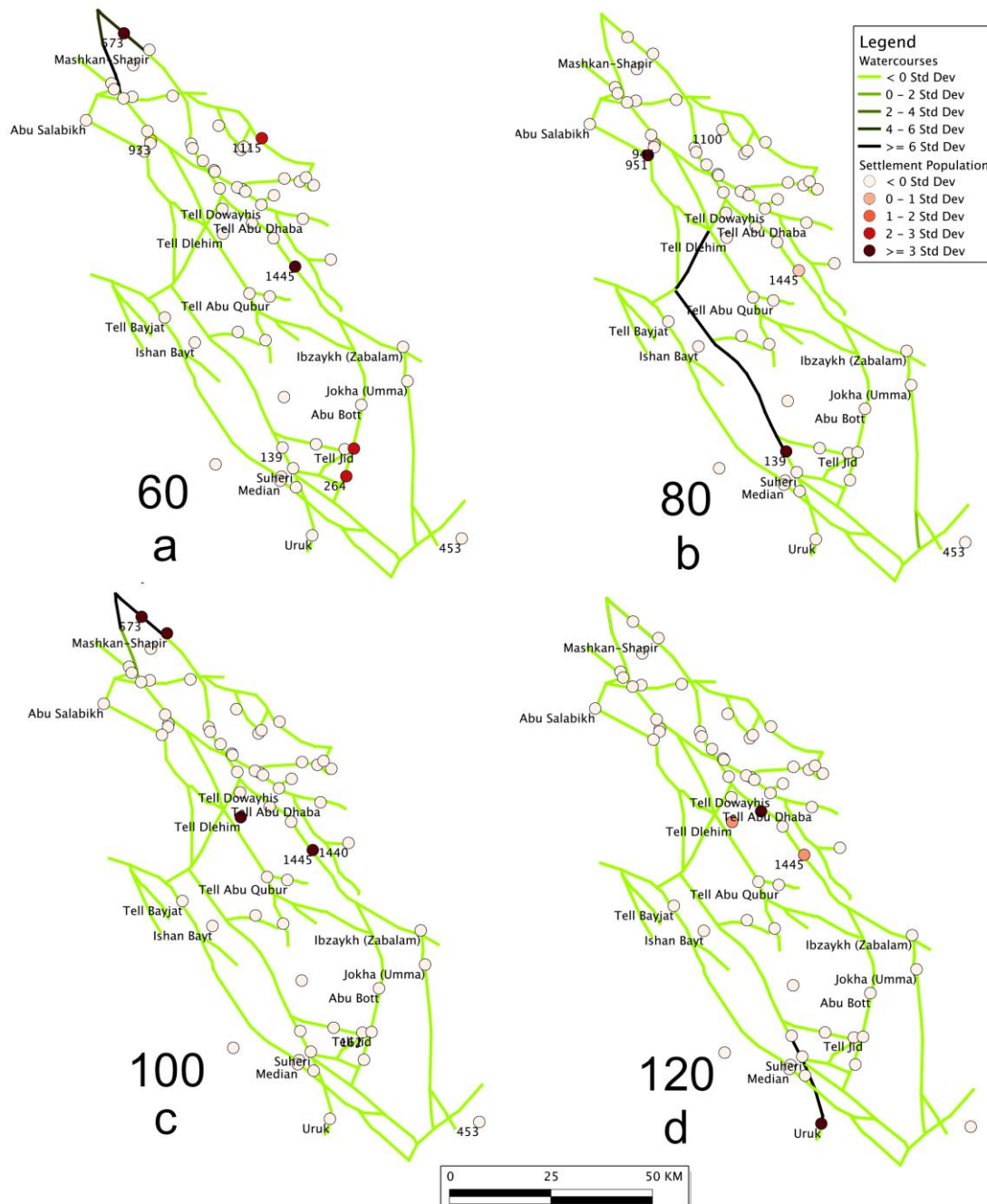


Fig. 14.9 Watercourses travelled and population (in standard deviation) in Scenario 4 with tick counts indicated above the figure letters.

The significance of these results is that they demonstrate that transport links and geography are capable of maintaining resilience to decreases in α and q . In other words, relatively higher overall flow is maintained in some sites that formerly had greater α and q values because their connectivity to other sites enabled them to maintain a greater population than many sites with similar α and q values. Population resilience is, therefore, demonstrated by those sites that have greater overall links and access to nearby sites. Access to a large number of settlements enables sites to have easier access to some share of trade and population flow. Such relative

robustness suggests how sites could maintain some level of population even after their importance had decreased. Figure 14.10 illustrates this point for Abu Salabikh and Tell Dlehim, by showing how Tell Dlehim is more robust, with greater flow values after both sites had lost their greater α and q values (by tick 110). Greater transport connectivity and advantages to access to other sites can help to maintain some site population after a site loses importance.

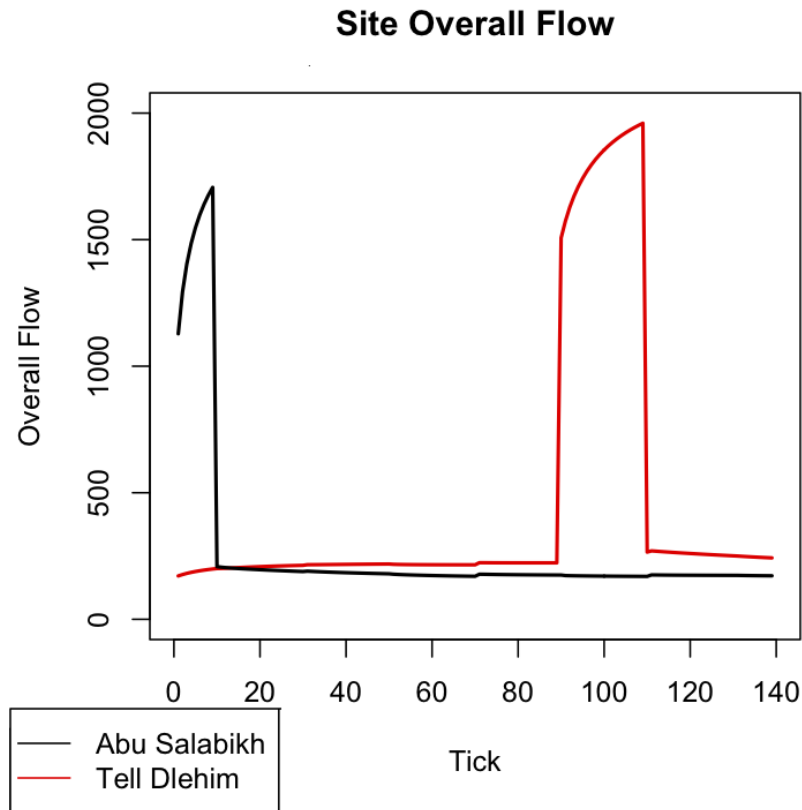


Fig. 14.10 Overall flow (D_j) of Abu Salabikh (left-hand curve) and Tell Dlehim (right-hand curve) in Scenario 4. In this case, Tell Dlehim is able to maintain relatively higher overall flow than Abu Salabikh after both sites have lost their greater α and q values. The sharp increases in overall flow indicate when these sites have greater α and q values, while sharp decreases indicate when these values are equal to most other sites.

DISCUSSION

Scholars have debated how growth and population shifts can affect urban systems for a variety of periods and under very different circumstances (Chandler 1987; Turchin 2003). For early urban Mesopotamia, debates have focused around the themes of economic, trade, environmental, and transport developments that enabled some centers to become much larger than surrounding settlements (Algaze 2008). While models such as those presented above cannot determine with certainty what outputs match past events, entropy models do provide a relatively simple way of showing heuristically how observed phenomenon may have developed. Each scenario demonstrates a hypothetical case that displays how different factors might affect urban transformations. While it is difficult to know if specific circumstances such as river avulsion, soil salinization, ideology, or political power may have propelled cities such as Uruk into a position of rapid growth, the methods presented here demonstrate that if such factors are evident, it is therefore possible to explain how such factors influence settlement and population change. As an example, in the model we apply α as a variable, which represents the importance of any city. However, this variable does not indicate what specifically made a site relatively important. Similarly, β attempts to represent the abilities or desires of a population as well goods capable of being mobilized, but it does not address the reasons that cause greater or diminished levels of mobility at specific locations. This signifies

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

that in the absence of specific social or ecological reasons as to why settlements grow or decline, spatial entropy models can determine how different levels of importance, incentives for mobility, and other variables may affect settlement interactions and transformations. Such modeling enables one to determine how relative variations of key variables enable outcomes to emerge which can then be compared to empirical survey results. By assigning a degree of importance to the settlement at Uruk and restricting overall transport, for instance, leads to Uruk becoming a very large site. This could indicate which factors made Uruk more favorable for settlement, while social or environmental conditions may have restricted greater movement to other settlements.

Scenario 1, shows how the advantages of geography and access to watercourses give some sites initial benefits over others. This is evident in the northern parts of the southern Mesopotamian plain where settlements grew larger because of their proximity to other settlements and access to different watercourses. The results show how diminished incentive for distant travel, that is increased β , results in a greater differentiation of site population, as more people and flow of goods concentrate in the most accessible sites. On the other hand, increased α increases the overall flows to settlements, but those settlements do not become more distinguished in terms of relative population from other sites.

Whereas Scenario 1 demonstrates which regions may have had initial advantages, namely the northern parts of the alluvial plain, Scenario 2 attempts to understand how internal interactions between sites could propel a settlement such as Uruk to become very large relative to other sites, particularly when settlement importance increases. In addition, Scenario 2a shows that settlement remains stable when trade flow and population are maintained, even for the smaller sites. On the other hand, Scenario 2b indicates how flows of feedback, which replicate trade and the movement of people, enable sites to grow and diminish at more extreme scales. In Scenario 2, a greater value of α enables Uruk to attract more flow and increase its size, so that overall population increased nearly 24-27 times the initial population of 1000. In addition, increasing β creates a negative effect on smaller sites, as people and goods are less inclined to move to lower α sites with the result that overall flow even becomes negative. This indicates that as attractiveness and mobility decrease and the sites with smaller α values are less able to attract goods and people, population became concentrated at fewer settlements, resulting in the majority of settlements becoming very small or even being abandoned. This phenomenon, where growth concentrates in few centers, has been proposed for early Mesopotamian cities by Falconer and Savage (1995). This pattern of the rich getting richer (see Chapters 11 & 15), so to speak, is most clearly demonstrated for small sites near a major settlement such as Uruk. In this case, Site 453's population became subsumed within the larger center because this site had fewer nearby connections that were capable of attracting migration and economic flow to maintain its population. In other words, for sites with a low value of α , the existence of few connections to other sites and its proximity to a high α site leads to decreasing flow and population as the incentive for travel decreases (i.e., β increases). This benefits the growth of the larger sites as flow concentrates in these areas.

Scenario 3 largely replicates the results of Scenario 2, but this scenario suggests how settlements could depend on external contacts and links to compensate for shortfalls in α . This demonstrates that settlements with powerful ties to trade networks and external contacts could become relatively large. This implies how trading colonies of the Uruk period (Stein 1999) could have shaped settlement growth. Whereas settlements may have become transformed as α , q , and β are varied, it is also evident that these variables affect transport as the greater value of α/q increases flow to sites and the greater β directs more transport to routes leading to the larger settlements. This has the effect of making some transport routes more significant than others, such as those on the western half of the alluvial plain (Fig. 14.8b), and changing the options for trade, migration, and routes for how people and goods move.

The final scenario, Scenario 4, demonstrates how resilience could enable some sites to persist at relatively higher population levels even after their attractiveness for trade and migration has declined. This demonstrates how geography and transport can increase resilience by increasing access to beneficial links. In this case, sites with greater nearby settlement interactions are better positioned to retain a greater portion of their population even after such sites lose their importance.

AN ENTROPY MAXIMIZING MODEL & THE RISE OF URBANISM

The models and simulations demonstrate how the survey results of Adams and Nissen (1972) and Adams (1981) can be understood from the context of populations and settlement dynamics. Without any major change in natural population growth, the populations of settlements can dramatically shift as sites gain or lose advantages or have greater or lesser access to transport arteries (McNeil 2000). These exploratory outputs enable the Late Uruk phenomenon to be succinctly expressed quantitatively in terms of a suite of relevant processes. Whereas the results from the surveys and simulations may not be comprehensive, they can be applied together to show how geography, transport, attractiveness of sites, both locally and external to the region, as well as the flow of goods and people could shape the urbanisation process in southern Mesopotamia.

CONCLUSION

The model outputs demonstrate how feedbacks of growth and population change can be analyzed for a range of settlement contexts and for a variety of settings using different types of scenario settings. These include scenarios that demonstrate the flow of goods and economic factors that represent a core-periphery dynamic in which some areas prospered while others did not (e.g., Fujita & Krugman 1995). This reflects the work of scholars such as Adams (2001) and Algaze (2008) who have identified complexity and complex system dynamics as explanations for urban transformations in certain periods. According to these approaches, the presence of cultural, economic, and environmental interactions, as well as associated feedbacks, are likely to have operated. The model presented here offers a useful technique to explain fairly complex processes without having extensive empirical data specific for any given period. In other words, the few variables employed represent generalizing phenomena which make it possible to test the implications of a site becoming, for example, more attractive. In summary, simple entropy models offer a way to generalize theories such as Complexity Theory and present them in a quantitative form within a specific spatio-temporal setting. Such modeling contributes to the discussion of, for example, the Late Uruk expansion because it makes it possible to apply very different parameters to determine how different vectors may have affected changes in urban systems even in conditions of considerable uncertainty. Archaeological surveys frequently provide a limited spatio-temporal perspective, because the data can never be complete. The methods applied here, therefore, enable scholars to account for missing empirical data and to explore and generalize socio-environmental effects on settlement dynamics, such as changes in a settlement's political importance or transport restrictions between cities. At the same time it is possible to assess the modeling outputs to see how well they match archaeological data. In summary, a spatial entropy model makes it possible to draw conclusions about past urban transformations and provide succinct explanations for at least some empirical observations.

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Supplementary data: <http://discovery.ucl.ac.uk/1355838/>