Universal Scaling: Evidence from Village-level Societies

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Abstract

Emerging theory proposes that urban scaling phenomena emerge from individuals arranging themselves in space so as to balance the costs of movement with the benefits of the resulting interactions. The fact that the parameters and processes embedded in urban scaling models are not unique to modern systems leads to the hypothesis that these models actually capture universal properties of all human societies. If so, scaling phenomena should be observable throughout the archaeological record. In this chapter, we show that scaling phenomena observed in modern urban systems, and more recently observed for early civilizations, are also apparent in small scale societies containing settlements of no more than a few thousand people. Collectively, these findings suggest scaling is an essential ingredient of a general theory of human societies as complex systems.

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Figure 1 presents historical depictions of two US settlements that on the surface appear worlds apart. In the 1830's, New York was a bustling commercial hub of about 300,000 people that connected an emerging industrial economy to the world. During the same decade, Mih-tutta-hang-kusch, a Mandan village on the upper Missouri, was home to about 800 people who spent most of their time growing crops, hunting bison, and trading with fur trappers and nomads. So if 1830s New York represents modern urbanism, capitalism and industrialization, Mih-tutta-hang-kusch represents a traditional society that lacked all these things.

Industrialization and capitalism have indeed wrought remarkable changes in the material conditions of life for millions of people, and it is obvious that a much greater variety of activities, which produce many more goods and services, occur in modern cities than in traditional agricultural villages. These differences support intuitive notions that cities represent a distinctive type of settlement, that one can define their unique properties, and that there was a time when such settlements did not exist. From this perspective, questions like "how did cities come to be?" or "what drives urban development?" seem both appropriate and important.

Although we do not deny these intuitions, we make a different argument in this chapter. Specifically, we suggest that modern cities and agricultural villages are much more similar on a functional level than they appear on the surface. We argue that both kinds of settlement are expressions of the same fundamental process; namely, the concentration of social interactions in space and time, subject to a variety of constraints. If we are right, then there is a sense in which a modern city is merely a scaled-up agricultural village, and many of the properties that set New York apart from Mih-tutta-hang-kusch are simply emergent properties of scale. Thus,

urban scaling theory may not merely be about cities, but about humans as social organisms, and human societies as an especially interesting type of complex system. So even if there was a time before cities (M. E. Smith, et al. 2014), there may not have been a time before the social mixing process at the heart of cities (Jacobs 1969).

To make these points, we first review empirical patterns of urban scaling that have been documented in large measure by the contributors to this volume. Then we discuss emerging theory that seeks to explain these patterns and explain why it should apply to non-urban settlement systems as well. We then demonstrate that predictions of urban scaling theory are in fact borne out in data from two village agricultural societies from native North America. Finally, armed with these results, we consider the implications of a broader settlement scaling theory for our understanding of cities and for general understandings of human society.

Background

One of the most exciting recent developments in complex systems research is the discovery of widespread scaling phenomena in contemporary urban systems. These discoveries have been made possible by significant advances in data collection by a number of agencies and institutions, and by the ability to aggregate data collected at various scales into metropolitan statistical areas representing human settlements as functional units. Several basic findings have emerged from these studies. First, there are systematic economies of scale with respect to infrastructure and the use of space, such that more populous metropolitan areas on average encompass less land area and less infrastructure per capita (Bettencourt 2013). Second, there are systematic returns to scale with respect to a wide range of socio-economic outputs, such

that more populous metropolitan areas generally "produce" more per capita (GDP, patents,

R&D employment, but also crime and infectious disease) in comparison with less populous

areas (Bettencourt, Lobo, Helbing, et al. 2007; Bettencourt, Lobo and Strumsky 2007;

Bettencourt, et al. 2010). Third, individuals in more populous cities tend to have more social

connections than individuals in less populous cities (Schläpfer 2012). Finally, more populous

metropolitan areas possess a more extensive division of labor and greater degrees of

productive specialization on average (Bettencourt 2014; Bettencourt, et al. 2014).

Researchers have been aware of such regularities for some time (Batty 2008; Glaeser

and Gottlieb 2009; Glaeser and Sacerdote 1999; Nordbeck 1971; Samaniego and Moses 2009),

but what has not been appreciated until recently is that these relationships have typical

elasticities. So if the functional form of these relationships is $X = X_0 N^\beta$, the exponent β is

typically about 5/6 when X is a measure of infrastructure or the division of labor, and about 7/6

when X is a measure of aggregate interaction or socio-economic output. What is even more

exciting is that one can derive these typical exponents using simple models that capture the

average properties of human social networks embedded in space (Bettencourt 2013; Ortman,

et al. 2014). The basic ideas embedded in these models are: 1) human settlements are first and

foremost concentrations of human interaction; 2) given a set of energetic constraints imposed

by technology and institutions, people arrange themselves in space and create infrastructural

networks so as to balance the costs of moving around with the benefits of the resulting

interactions; and 3) socio-economic outputs are proportional to the total social interactions

that occur over a given period of time. The parameters of these models—the cost of moving

around, the average energetic benefit of social interaction, the typical distance traveled per

person and per unit time, a number of people, and a settled area—are very general and are not tailored to the specific technologies and social institutions of the modern world. Yet they succeed remarkably well in predicting the average aggregate properties of settlements in modern urban systems.

So here is perhaps the most exciting possibility—if in fact these models explain observed scaling patterns in modern cities, and the parameters of these models are characteristics of any social network embedded in space, then any human settlement system should exhibit the same relative scaling properties as modern cities regardless of time, culture or level of socio-economic development. In other words, although urban scaling theory seeks to explain empirical regularities in modern urban systems, the theory itself may capture basic and universal properties of human societies throughout history. Anthropologists have been aware of relationships between community population size and social complexity for some time (Carneiro 1967, 2000; Chick 1997; Feinman 2011; Naroll 1956), so the idea of systematic relationships between population, the built environment, social interaction, productivity, and the division of labor is not surprising. But what is surprising is the notion that mathematical relationships among these properties might have specific, predictable values.

Ortman and others (2014; 2015) have previously shown that several predictions of urban scaling theory are borne out by archaeological settlement data from the Pre-Hispanic Basin of Mexico. This is an important proof of concept but data from this early civilization are not ideal for testing the hypothesis of universal scaling because Pre-Hispanic Central Mexico shares a number of properties with modern systems, including cities, class stratification, markets and productive specialization. Here, we suggest that even stronger data for testing the

hypothesis of universal scaling derive from "Neolithic" societies, which lacked many attributes of modern urban systems and whose economies were organized around a domestic mode of production (Sahlins 1972). We examine data from two such societies in this chapter.

Scaling in Archaeology: Empirical Issues

The idea of using archaeological data in scaling research seems straightforward, but it is important to emphasize that data suitable for scaling analysis must meet certain criteria and archaeological data often do not meet them. Thus, an important preliminary of this study is a discussion of the data requirements for archaeological scaling analysis. We discuss these briefly below in the hope of stimulating additional research in this area.

The first and most important requirement for scaling analysis is a suitable proxy for settlement population than can be applied consistently across a range of settlement sizes. In addition, population must be estimated in such a way that the population densities of settlements can vary. Thus, a common method of estimating population, which involves measuring site areas and multiplying by a constant population density (Johnson 1987; Wright 2001), will not yield suitable data. Probably the most reliable population proxy is the number of houses in settlements, but the use of house counts is complicated when individual house occupations were much shorter than settlement occupation, or it is difficult to identify individual houses from surface archaeological remains. For example, in many archaeological sites habitation areas are definable but individual houses are not due to the sharing of walls or insubstantial construction.

The second requirement is that settlement areas should be estimated consistently. Unfortunately, methods for defining site boundaries often vary in cases where settlement area has not been perceived as an important quantity, and this leads to significant variation in the data for small settlements. For example, a typical method of estimating the areas encompassed by small settlements is to measure the length and width of the archaeological remains and compute the area of an ellipse defined by these dimensions. This method is compatible with current scaling models (see Ortman, et al. 2014), but the level of precision of the underlying measurements is most often determined intuitively on a case-by-case basis. To some extent this is a practical response to the variety of taphonomic processes that affect the archaeological record (Schiffer 1972, 1987). But since archaeological data typically accumulate through the collective efforts of many researchers, and a variety of factors make it impossible to go back and re-measure some sites using a single standard, site area datasets are often a hodge-podge of data collected in a variety of ways.

Third, the data need to come from settlements that encompass the entire range of settlement populations. Such data have not often been collected. In studies of early civilizations, for example, methods are often tailored to practical problems related to recording the largest settlements, and as a result many small settlements are either overlooked or measured at the same level of coarseness as the largest settlements (Parsons 1971; Sanders, et al. 1979). The latter case can be problematic because the parameters of scaling relations are typically estimated through ordinary least-squares regression of log-transformed data. Since the raw measurements are converted to logarithms as part of the analysis, relatively imprecise data for the largest settlements make little difference in the results, but similarly-imprecise

data for the smallest settlements can make a big difference. Imprecise measurement of small settlements leads to blocky or "fat" lower tails of archaeological data distributions in log-log scatterplots (see figure 3, below) and can also skew scaling parameter estimates. Precision is not critical when one is working with modern cities because aggregate measures for these settlements vary over many orders of magnitude. In agricultural villages, in contrast, measures typically vary over three orders of magnitude at best. As a result scaling analysis is less robust with respect to errors or imprecision in measurement. The best way to counteract this problem is to analyze data measured at a level of precision appropriate for the smallest settlements and to work with large samples of such settlements in the hope of canceling out random errors in measurement.

Due to empirical issues discussed above, appropriate data for scaling analysis either do not exist or are not available in the archaeological record of many past societies. And in other cases data may exist but the proxies used for population or socio-economic outputs are calculated in such a way (e.g. area x a constant population density) that they define away potential scaling relationships. Fortunately, the archaeological record of some past societies does preserve the raw material for appropriate measures, and some of these records have been investigated in such a way that it is possible to estimate population, settled area, and socio-economic output for the full range of settlement sizes at a reasonable level of precision and in ways that allow the population densities of settlements to vary. Here, we work with data from two such societies.

Materials and Methods

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The analysis that follows utilizes archaeological settlement data from two native North American societies. Both were "Neolithic" or village-level societies with an economy focused on maize agriculture, with little division of labor above the household level, and informal political integration above the village level. Both created settlements that had clear boundaries, were inhabited for relatively short periods, and contained houses that are easy to see on the modern ground surface. In addition, both societies have been studied intensively over many decades, resulting in large amounts of relatively high-quality data.

The first society we consider is the ancestral Pueblo society of the Central Mesa Verde region in southwest Colorado. The building blocks of settlements in this society were highly standardized household residences that leave robust archaeological expressions (Figure 2). These households are defined by a central, circular pit structure, an associated, small surface room-block, and a trash midden located to the south or downslope of the pit structure. These unit pueblo households were the basal units of production and reproduction (Bradley 1993; Cater and Chenault 1988; Kuckelman 2000; Lightfoot 1994; Lipe 1989; Ortman 1998; Varien 1999) in this society. Most settlements were single-family farmsteads, but villages containing more than 100 houses also occur.

We focus on the period between 1060 and 1280 CE for several reasons. First, settlements were constructed of sandstone masonry during this period. These stone masonry buildings were much more substantial than earlier constructions of earth and wood, they were inhabited for longer periods, and they were rarely razed and built over (Cameron 1988; Lightfoot 1994; Varien and Ortman 2005). Although the sizes of these settlements changed over time, in most cases it is reasonable to assume that the entire architectural footprint of a village

was inhabited at some point. Second, the stone-lined pit structures of this period are identifiable today as fairly deep and well-marked depressions. As a result, accurate house counts and house area measurements can be made through visual inspection of the modern ground surface. Third, these stone settlements are typically surrounded by relatively dense artifact scatters that are easy to see and measure. So it is straightforward to measure the area encompassed by stone masonry and to obtain at least a minimal site area, although there is inter-observer variation in the definition of settlement boundaries based on artifact densities that is generally more pronounced for smaller settlements than for larger villages.

Finally, this period in Central Mesa Verde society has been studied intensively over many decades, most recently by the Village Ecodynamics Project (Kohler, et al. 2012; Kohler, et al. 2007; Kohler and Varien 2012). As a result, teams of researchers have put considerable effort into compiling data from cultural resource databases and the extensive local literature to reconstruct the population histories of individual settlements (Ortman, et al. 2007) and the larger region (Varien, et al. 2007). Recently, we have augmented existing site area, pit structure count and room-block area estimates for all recorded settlements in this area by digitizing the best available map of every settlement containing eight or more houses. The resulting measurements have been incorporated into a settlement pattern reconstruction for the VEP II Colorado study area (Schwindt, et al. n.d.). We utilize the settlement database from this project, incorporating information from all settlements associated with three or more houses, settled area estimates, and total room-block area estimates. We chose a cut-off of three houses because this seemed to be the smallest possible settlement in which the spacing of houses might capture the balance of costs and benefits associated with interaction between houses.

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The data for settlements associated with 3-7 houses represents a compilation of data from many sources in which significant inter-observer variation exists. However, the data for all settlements associated with eight or more houses have been made consistently, either through analysis of plan maps or new field work (Glowacki 2012; Glowacki and Ortman 2012).

The second society we consider is the ancestral Mandan and Hidatsa society of the Middle Missouri region, primarily in North Dakota. Here, we focus on the period between 1300 and 1885 CE which corresponds to the entire duration of the agricultural village tradition of the Middle Missouri region. The building blocks of villages in this society were earth lodges—partly subterranean timber-framed or post-and-beam structures with packed-earth walls (Figure 3). These lodges also leave clear rings and depressions on the modern ground surface, as well as subsurface traces that can be picked up through a variety of geophysical survey techniques (Mitchell 2008). Continuity with ethnographic descriptions of Mandan and Hidatsa people demonstrate that earth lodges were domestic residences (Bowers 1950, 1965). Thus, for many settlements the total number of lodges, and thus households, are known. Lodge sizes vary somewhat, and due to the long history of excavation and remote sensing the floor areas of individual houses are available for many villages.

Settlements were constructed on terraces above and outside the Missouri river floodplain and were often defined by ditches or other fortifications. These are often visible on the modern ground surface today or are identifiable through remote sensing (Kvamme and Ahler 2007). As a result it is relatively straightforward to define village boundaries and to count the houses within them. Settlements range from a few to more than 100 earth lodges. The occupation spans of these villages vary, and some were re-built and re-occupied multiple times.

Fortunately, when this occurred houses were often rebuilt on the foundations of old ones (Fenn 2014), and it is often possible to distinguish distinct occupations (Kvamme and Ahler 2007). Recent studies of the economies of these communities show an emphasis on domestic production, with evidence of part-time specialization and increasing household productivity during periods of larger community sizes (Mitchell 2012).

The archaeology of the Middle Missouri region is not as well-known or as intensively-studied as that of the Central Mesa Verde region, but due to long-term effort by a small group of dedicated researchers and a large volume of salvage archaeology related to reservoir construction the local literature contains an abundance of useful data for these settlements. A recent synthesis and evaluation of this information by Mitchell (2012) has provided a suitable dataset for scaling analysis. We have augmented and slightly-revised Mitchell's dataset, as noted in the appendix. Although the dataset is small, it is of very high quality and contains data collected using consistent methods, often involving excavation and geophysical survey data.

Expectations

The basic models with which we work are developed in Bettencourt (2013) and Ortman and others (2014; 2015), and readers who wish to study the assumptions and derivation of these models are encouraged to read these sources. Here, we discuss expectations for Central Mesa Verde and Middle Missouri settlement data that emerge from these models.

The settlements of both societies were relatively small, and only the very largest villages from the Central Mesa Verde contain evidence of formalized paths that facilitated within-settlement movement. In addition, the areas of most settlements in both regions are defined as

elliptical circumscribing areas on the basis of artifact scatters or boundary features (walls,

banks, ditches). Thus, one would expect the amorphous settlement model (see Ortman, et al.

2014) to apply to settlements from both societies. In addition, the best population proxy in

both cases is the number of houses, and thus households, in a settlement. So if population is

measured in terms of households, one would expect the average relationship between house

count H and settlement area A to be $A = aH^\alpha$, with $\alpha \approx 2/3$ and a reflecting the area taken

up by an individual household in the smallest settlements.

In addition, scaling theory hypothesizes that the productivity of an economic unit is

proportional to the number of interactions that unit has with others on a regular basis. Thus,

households in larger settlements should be more productive on average. Household

productivity should in turn be reflected in the total roofed space in which household members

lived and in which household production was stored and consumed. Evidence from Middle

Missouri villages suggests that changes in average lodge size over time do in fact reflect

changes in productivity rather than changes in average household composition (Mitchell 2012),

and studies of house area distributions from a variety of societies suggest that they provide a

useful proxy for household income (Abul-Megd 2002; Blanton 1994; Bodley 2003; Hirth 1993;

Maschner and Bentley 2003; Morris 2004). Thus, one would expect average house area to

increase with settlement house count according to $y = y_0 H^\delta$, with $1/6 \leq \delta \leq 1/3$ and y_0

reflecting the average area of a house in the smallest settlements. In turn, one would expect

the total productivity, or the total area encompassed by houses in a settlement, to vary with

house count according to $Y = Y_0 H^{1+\delta}$, where Y_0 reflects the total house area in the smallest

settlements.

Finally, given that per capita productivity $y = G\,H/A$ and $G = \hat{g}a_0 l$ (where l is the typical distance traveled by an individual per unit time, a_0 is the distance at which physical interaction occurs, and $\hat{g}$ is the average benefit conferred by each interaction), G should be independent of house count. G can be estimated for individual settlements as $G_i = y_i A_i/H_i$, and although one would expect it to vary across settlements for a variety of reasons, theory suggests this variation should be unstructured relative to settlement population. Thus, the exponent of the average scaling relation between G and H should be approximately zero, and the correlation between these two variables should also be approximately zero.

The expected range of δ requires further comment. Under the amorphous settlement model, it is assumed that houses are sufficiently dispersed and unorganized that interaction between households is accomplished through travel along straight paths such that the distance L needed to traverse the settlement is simply its transverse dimension, $L = A^{1/2}$. These conditions lead to an expected exponent of $\alpha = 2/3$ for the relationship between population and settled area, and thus a per capita productivity of $y = G\,H/A = G\,H/aH^{2/3} \propto H^{1/3}$. However, even in amorphous villages movement becomes constrained by the distribution of houses, and one would expect this constraint to increase as the size and density of the village increases. Under these conditions, paths across the settlement become progressively less straight and thus longer than the transverse dimension. Thus, in compact villages one would expect the morphology of typical paths to approach that found in "networked" cities organized around transportation infrastructure, in which $\alpha = 5/6$ and thus $y = G\,H/A = G\,H/aH^{5/6} \propto H^{1/6}$. Thus, one would expect the value of δ to range between 1/6 and 1/3, even if the value of α remains close to 2/3, in these data.

To evaluate these expectations, we estimate a, α, y_0, Y_0 and δ through ordinary least-squares regression of log-transformed data and we provide a measure of G_i for individual settlements by multiplying the house area per person (or mean house area) by the settled area, and then dividing by the house count.

Results

The results of our analyses, presented in Table 1, show that the expectations described above are met for the most part. In both societies, $\alpha \approx 2/3$ and $1/3 \geq \delta \geq 1/6$. Also, G is clearly independent of H for the Middle Missouri data. The one area where the data may not be consistent with expectations is that G appears to be somewhat negatively-correlated with H in the Central Mesa Verde data. However, the R^2 value of this relationship is quite small and the confidence interval for the exponent very nearly incorporates zero, so we believe this specific result is due to issues with the site area estimates discussed earlier. So overall, our results indicate that both the economies of scale with respect to settled area, and increasing returns to scale with respect to house area, are apparent in the settlement data from these two societies. Further, the elasticities of these economies and returns are consistent with models that also predict the elasticities observed in modern urban systems. These results provide supportive evidence for the hypothesis of universal scaling and suggest the elasticities observed in agricultural villages derive from the same fundamental social networking processes that lead to scaling patterns in modern urban systems.

It is also quite remarkable that the prefactors of average scaling relations are so similar for these two societies: the average area taken up by a household in the smallest settlements

was .21 hectares in the Central Mesa Verde and .24 hectares in the Middle Missouri, and the average house area in the smallest settlements was approximately 56 square meters, or about 600 square feet, in both societies. These similar values are remarkable given the variation in collection methods behind these data. In the Central Mesa Verde, for example, settled area was most often defined by the extent of the surrounding artifact scatter, whereas in the Middle Missouri it was most often defined by fortifications or house distributions combined with terrace edges. Likewise, in the Central Mesa Verde only the total house area across all households was recorded using surface evidence, whereas in the Middle Missouri mean house areas were estimated from excavated houses in various sites. Yet, Figure 4 shows that, if one multiplies these mean house areas by the number of houses for the Middle Missouri data and then plots the results on the same axes as the Central Mesa Verde data for total house area, the scaling relationship is essentially identical.

The similarity of scaling parameters in these two societies is also surprising in light of the many differences between them. For example, in the Central Mesa Verde walking was the only means of traveling between settlements; but Middle Missouri people used bull boats or canoes to transport goods and people along the river, dogs and travois to transport goods over land, and horses to move both goods and people after 1700 CE. Also, the baseline productivity of agricultural land varied substantially in the two societies. Studies of agricultural yields suggest traditional Mandan fields produced at least 1,200 kg/ha on average (Mitchell 2012), whereas Central Mesa Verde fields only produced 250-400 kg/ha (Varien, et al. 2007). One would expect these dramatic differences in between-settlement transport technologies and agricultural productivity to have enabled higher regional population densities in the Middle Missouri, but

these differences had little effect on settlement densities or the baseline productivity of households. The insensitivity of our analyses to between-settlement transportation technology and agricultural productivity are both consistent with scaling theory because these factors are not incorporated in current models. However, within-settlement transport costs are involved, and in both societies the only way of moving people and goods within settlements was on foot. So if one could compare these results with data from societies in which intra-settlement transport was aided by beasts of burden or wheeled vehicles we would expect the prefactor of the population-area relationship to be somewhat higher than observed here.

It is also important to note that, although average scaling relations show remarkable consistency across societies and through time, the societies examined here were not static. In the Middle Missouri, for example, the data in the appendix suggest the mean population size of settlements increase from about 50 households in the 1300-1600 CE period to about 70 households in the 1600-1885 period; and mean house areas also increased from around 110 square meters to 130 square meters over this same period. What these results do suggest, however, is that the increases in household productivity suggested by trends in mean house area, storage pit count and density, and the intensity of craft production (Mitchell 2012) all derive from changes in the scale of community organization as opposed to technological progress. This result mirrors that found in other studies of archaeological data from the pre-industrial world (Ortman, et al. 2015) and suggests socio-economic development prior to the industrial revolution has been driven largely by factors that promote increases in the scale of strongly-interacting social networks. This is a fascinating prospect for future research.

We also note that the exponent δ, which relates household productivity to settlement population, is closer to 1/6 than to 1/3. This is not surprising given the density of houses in villages from both societies. This would have required people to take more circuitous paths to interact with village-mates, and thus a scaling of interaction with area that is closer to that observed in networked settlements.

It is important to emphasize one area where scaling analysis may reveal differences between the Middle Missouri and Central Mesa Verde systems. Although there is no clear relationship between G and H in either society, the value of G_0 is somewhat higher for the Middle Missouri system. Since according to theory $G = \hat{g} a_0 l$, and both l and a_0 are defined by human biology and are thus effectively constant, the larger mean value of G for the Middle Missouri implies that the average energetic benefit of each social interaction, $\hat{g}$, was greater in that society. Why this should have been the case is an interesting question. One possibility is that the Middle Missouri floodplain was more productive than the Mesa Verde loess, so the higher value of G in the Middle Missouri may reflect the fact that there were more calories available for exchange in that society. Another possibility is that the social institutions of Middle Missouri society lubricated the flow of goods and services to a greater extent than those of Central Mesa Verde society. Ethno-historic literature indicates that the Middle Missouri was a well-known trade center and that the Mandan and Hidatsa people inhabiting this region were skilled trade negotiators (Fenn 2014). In addition, native societies throughout the Great Plains utilized a set of ceremonies known as the calumet to forge trade partnerships that greatly-facilitated inter-tribal exchange (Blakeslee 1975, 1981). In contrast, very little evidence of external trade or of inter-tribal ceremonies has been found in Central Mesa Verde sites (Lipe

1992, 2002). If these differences in between-group interaction were mirrored at the settlement level, social interaction may also have been more productive on average in the Middle Missouri than in the Central Mesa Verde.

Finally, it is important to emphasize that, although most previous studies of urban scaling have used individuals as the units of population, this study shows that the same results are obtained when households are used as the population unit. This is good news for archaeologists because in many societies it is far easier to count houses than to determine the number of residents of each house and their kinship relationships. But this may also seem surprising given that household composition varies across households in individual settlements (Wilk 1984), within societies (Wilk and Netting 1984) and across societies (Blanton 1994). There must have been similar variation in the households considered here, but this seems to have little effect on overall scaling relations. We can think of several factors that may underlie the insensitivity of scaling analysis to household composition. First, in "Neolithic" societies households are productive units and the division of labor is both strong within households and replicated between them (Sahlins 1972). Thus, even if each individual in a household has interactions with others in their community, these interactions are generally complementary rather than overlapping in purpose. Second, social relations within households are typically characterized by generalized reciprocity and economic decisions are generally made to benefit the household overall. Settlement scaling theory describes the dynamics of balanced reciprocity, and this realm is more characteristic of overall relations between households than to relations between each individual, even in modern societies. So there is a sense in which entire households are appropriate socioeconomic units in scaling analysis. Indeed, it may be

that households are the most appropriate unit of mass for settlement scaling theory, and that

total population is merely a good proxy that is proportional to household count in most

settings. Finally, in agricultural villages the primary impediment to movement and interaction is

created by the distribution of houses and households, not people per se. Thus, one would

expect the connectivity and intensity of interaction between people from different households

to be influenced primarily by the arrangement of houses themselves.

Implications

Modern cities are remarkable places with pronounced divisions of labor, intensive

interaction across specializations, and massive flows of people and material on dense

infrastructure networks. In comparison, agricultural villages appear to be very simple places

where the division of labor was limited above the household level, interaction was structured

primarily by kinship, and the built environment was relatively unorganized. Such comparisons

lead many researchers to view a city as a different kind of thing than an agricultural village.

From this perspective, the appearance of cities in history represents a dramatic innovation, and

the remarkable economies and returns to scale noted in contemporary cities are seen as a

product of urbanization—a process that does not occur in traditional agricultural villages.

The results presented here cast doubt upon this view and suggest one should instead

view cities as lying on a continuum with all forms of human settlement in all times and places.

Indeed, the results presented here are consistent with the idea that the productivity and

division of labor that characterize modern urban systems are simply properties of human social

networks that expand exponentially with scale. This leads to the appearance of qualitatively

different processes in modern cities when in fact these are just quantitative differences in expressions of the same processes. Since the properties of social networks are nonlinear, they lead to exponential changes in the use of space, productivity, knowledge expansion and the division of labor as the nodes in a social network grow—but the processes that generate these changes appear to have been part of human societies all along. Thus, from a scaling perspective, cities are simply bigger villages where the division of labor, levels of productivity, and rates of change are more pronounced due to the opportunities created by scale itself. For example, in Middle Missouri society, the archaeological record suggests a trend toward part-time specialization that correlates with agglomeration (Mitchell 2012), but given the small scale of these settlements the effects were sufficiently modest that they affected household task mixes more than economic specialization of the kind we are familiar with from modern cities (also see Bettencourt 2014).

Our results, which demonstrate that scaling patterns observed in modern urban systems are equally apparent in small-scale farming societies, suggest settlement scaling theory captures universal aspects of human societies as social networks, at a scale where their effects are well-behaved and even partly-predictable. Social scientists have made many generalizations about human social behavior, but very few of these have been formalized in ways that yield specific and novel predictions that are borne out by new data, and which produce results which make sense in light of contextual details. Settlement scaling theory conceptualizes human social behavior at a coarse-grained level where properties and dynamics become relatively well-behaved, but they are still interesting and not obvious. That the social sciences might be able to build theory following this physical-science style of reasoning is a striking thought. There are

many areas of social science that may never be amenable to this approach—but given the accomplishments of the physical sciences it seems important for social scientists to take advantage of those domains where a physical-science type of reasoning is productive. Scaling theory appears to be one such domain.

Finally, our results suggest something important about the potential of the archaeological record for expanding knowledge of human society. The archaeological record will always be partial, distorted and chaotic when viewed in detail. Nevertheless, the archaeological record captures information on the full sweep of human experience and can provide insights into the fundamental nature of human societies that cannot be obtained through any other data source. Given that dominant signals overpower noisy data at large spatial and chronological scales, and that human behavior appears more regular at such scales anyway, it seems to us that archaeological evidence has a significant role to play in building a general theory of human societies as complex systems. The archaeological record has undeniable power due to the fact that it preserves traces of human behavior in utterly different kinds of societies than the ones we live in, and we can know that the people who created this record were not aware of the theories we bring to interpreting it. Thus, finding that specific predictions of urban scaling theory are borne out by data from ancient societies organized at a variety of scales has theoretical significance far in excess of the data. In addition, archaeological data do more than provide novel tests of existing scaling theory—they also expand the theory by clarifying the underlying concepts, as this study has done by noting the role of households, the effects of agglomeration for interaction intensity in the absence of infrastructure, and the identification of institutional factors that may have impacted the average productivity of social

interaction. For these reasons we suspect continued use of archaeological data in scaling

research will prove critical for a deeper understanding of human societies as complex systems.

Figure 1. Above, Rue De New-York En 1840, by Hippolyte Sebron; below, Bird's eye View of the Mandan Village, 1800 Miles above Saint Louis: 1838, by George Catlin (Source: Wikipedia).
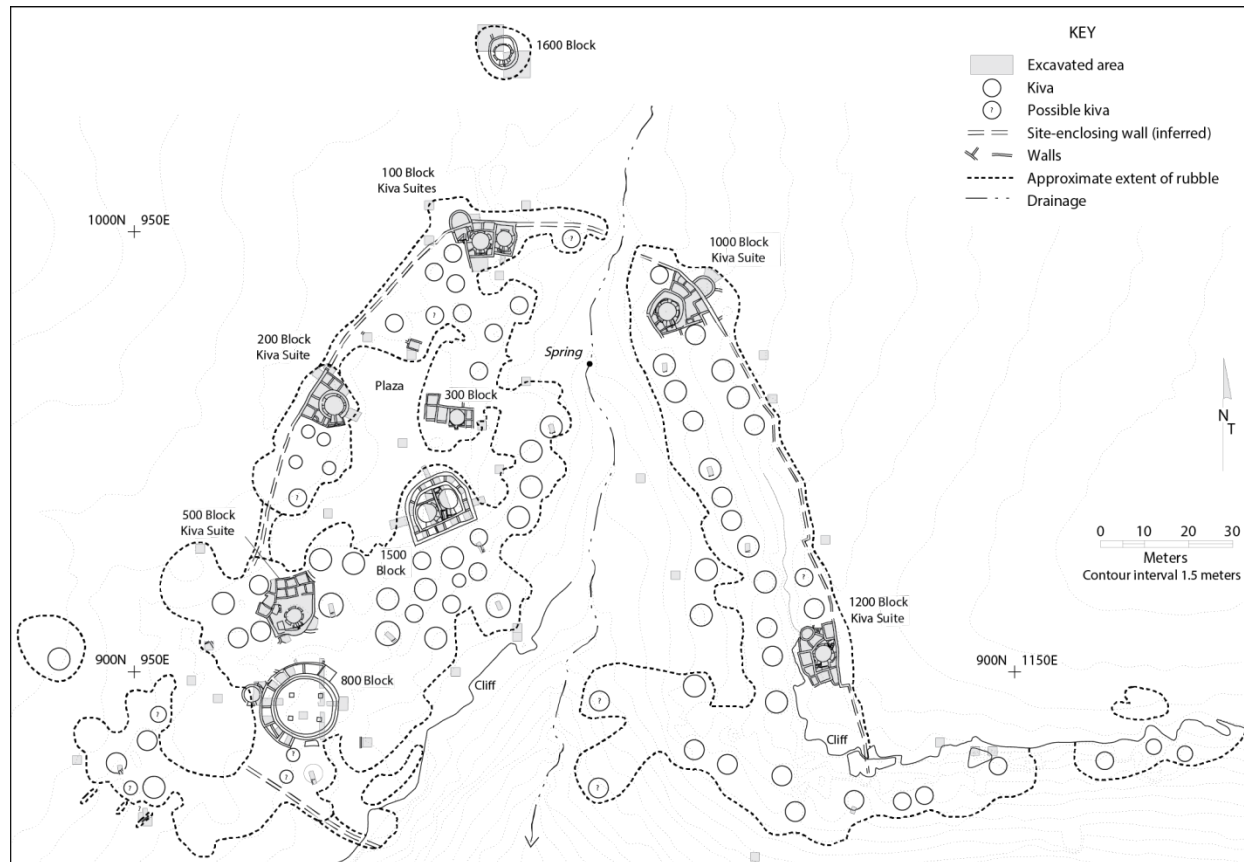
Figure 2. Sand Canyon Pueblo, a 13th century CE Central Mesa Verde village, illustrating surface stone rubble areas, pit structure (kiva) depressions, and a sample of excavated houses.

32BL9
Larson Village

Interpreted Plan Map

Plaza

Mound

B — Basin

H — House

H — House (?)

Ditch

Figure 3. Larson Village, a Middle Missouri village, illustrating surface features. The houses within the inner-most fortification date from the 18th century; the entire settlement was inhabited during the 16th century; portions have eroded into the Missouri river floodplain.

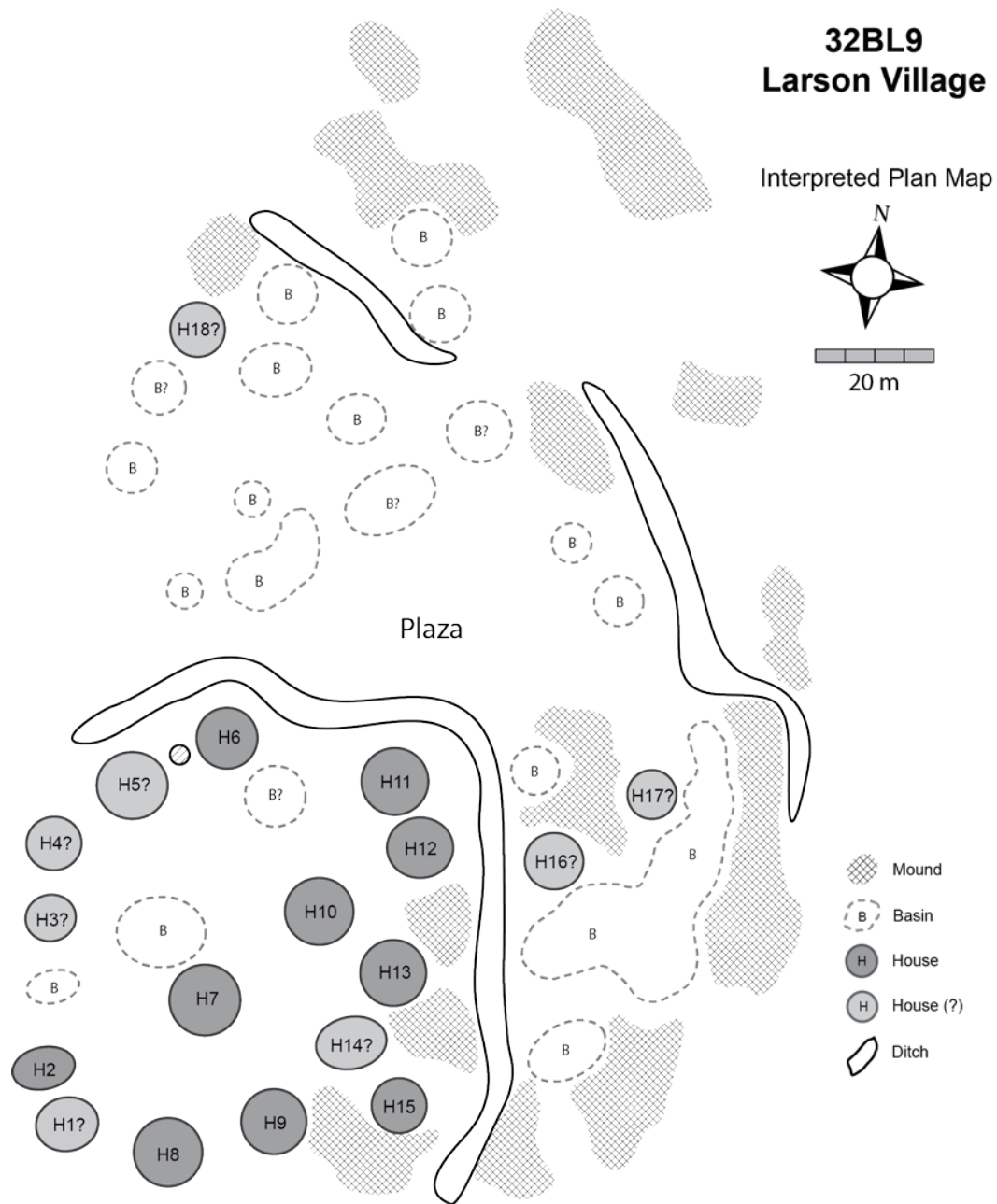Figure 4. Relationship between village population and total productivity. For the Central Mesa Verde system, *Y*=total roofed area; for the Middle Missouri system, *Y*=*mH*, where *m*=mean area of excavated houses and *H*=total house count. The nearly identical relationship in the two datasets implies that changes in average household productivity through time were due to changes in community scale as opposed to agricultural production or technology.

$Y = 56.607N^{1.1938}$
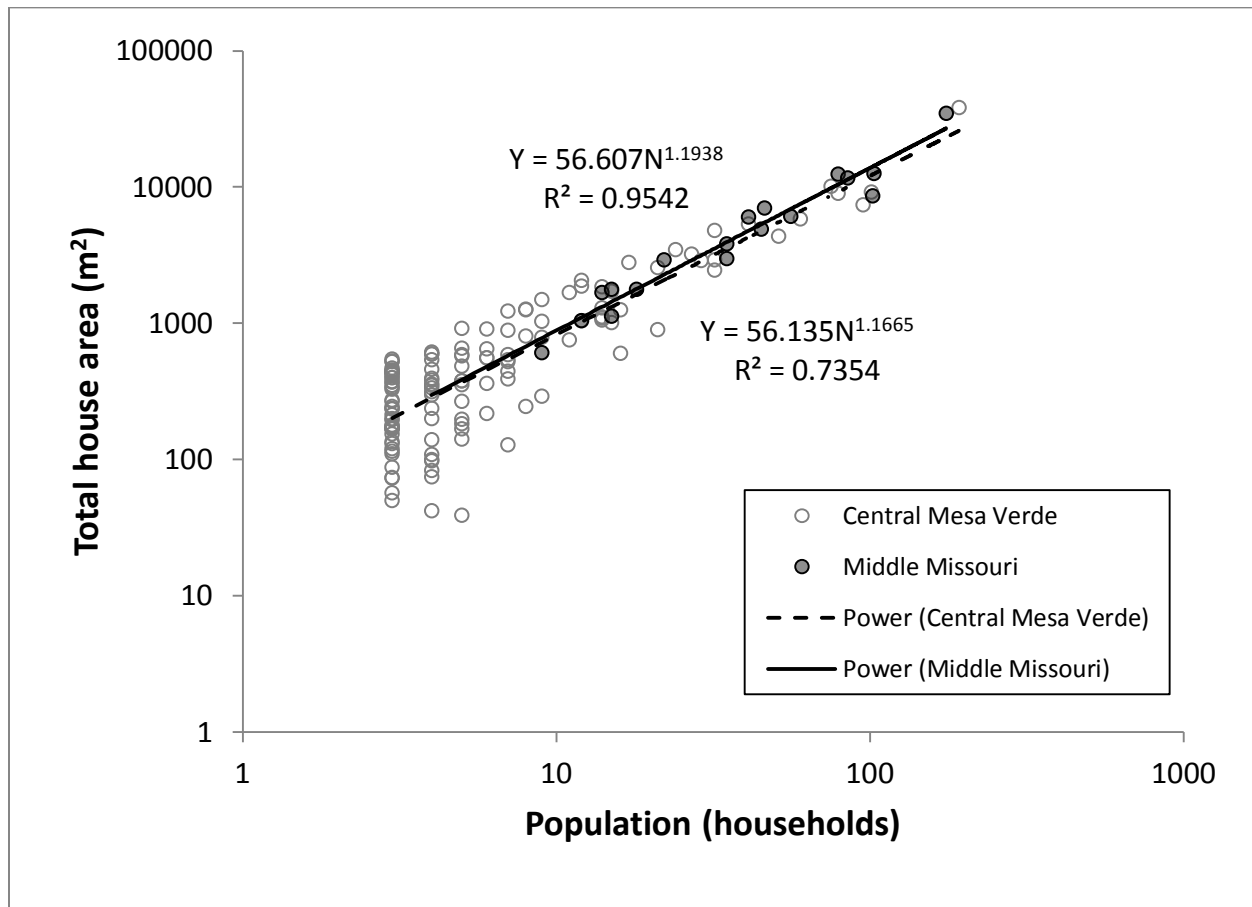$R^2 = 0.9542$

$Y = 56.135N^{1.1665}$
$R^2 = 0.7354$

Legend:
- ○ Central Mesa Verde
- ● Middle Missouri
- – – Power (Central Mesa Verde)
- —— Power (Middle Missouri)

Axis labels: Total house area (m²) (vertical), Population (households) (horizontal)

Table 1. Scaling results.

System[a]	Dependent variable[b]	Sample size	Exponent (C.I.)	Prefactor (C.I.)	R^2	Signif.
Central Mesa Verde (1060-1280 CE)	Settled Area A (ha)	278	α=.662 (.513-.812)	a=.213 (.160-.285)	.216	.000
Middle Missouri (1200-1886 CE)	Settled Area A (ha)	38	α=.670 (.518-.823)	a=.238 (.133-.424)	.688	.000
Central Mesa Verde (1060-1280 CE)	Total house area Y (m^2)	130	$1+\delta$=1.167 (1.044-1.289)	Y_0=56.14 (43.58-72.31)	.735	.000
Middle Missouri (1200-1886 CE)	Mean house area y (m^2)	18	δ=.194 (.055-.332)	y_0=56.61 (34.01-94.21)	.355	.009
Central Mesa Verde (1060-1280 CE)[c]	G	121	γ=-.248 (-.470- -.026)	G_0=10.96 (6.86-17.52)	.040	.029
Middle Missouri (1200-1886 CE)[c]	G	18	γ=-.105 (-.453-.242)	G_0=13.78 (3.84-49.45)	.025	.530

Notes:
a) Population ranges are: Central Mesa Verde, 3-192 houses; Middle Missouri, 4-175 houses.
b) In all cases, the independent variable is population (house count).
c) G_i for each settlement is estimated by $G_i = y_i A_i / H_i$, where y_i is the mean house area, A_i is the settled area, and H_i is the house count.

Appendix. Middle Missouri Settlement Data.[a]

Site	Dates (CE)	Complete[b]	Area (ha)	Total Houses	Exc. Houses	Mean house area (m^2)	Ditch[c]	Plaza[d]
Jake White Bull	1200-1300	N	1.6	11			Y	
Ketchen	1200-1300	Y	1.4	12	2	87.5	N	Y
Paul Brave	1200-1300	Y	1.5	14	3	120.4	N	N
Clark's Creek	1200-1300	Y	2	14			N	Y
McKensey	1200-1300	Y	0.8	18[e]	1	98.5	N	Y
Vanderbilt	1200-1300	Y	3.5	22			N	Y
Bendish	1200-1300	Y	6.2	45	2	109.2	N	Y
Tony Glas	1200-1300	Y	5.2	46	2	152.8	Y	Y
Havens	1200-1300	Y	5.9	56	4	109.6	N	N
Thomas Riggs	1200-1400	Y	3.4	22	6	132.4	Y	Y
Cross Ranch	1300-1400	N	1.3	9	2	68.1	N	
Helb	1300-1400	N	1.3	15	2	75.6	Y	
Durkin	1300-1400	Y	2.1	15	3	118.9	N	Y
South Cannonball	1300-1400	Y	6.5	35	6	109.6	N	Y
Shermer	1300-1400	Y	3.8	79[f]	4	158	Y	Y
Mandan Lake	1400-1500	Y	3.5	97				
Bagnell (Late)	1400-1500	Y	3.9	97			Y	
Huff	1400-1500	Y	4.4	103	10	122.8	Y	Y
Molstad[g]	1400-1550	N	0.5	4			Y	N
Larson	1500-1550	Y	5.1	115[h]			Y	Y
Double Ditch	1500-1550	Y	8.9	160[i]			Y	Y
Smith Farm	1500-1600	Y	1.8	27			Y	
Lower Sanger	1500-1600	Y	1.6	34			Y	
Hensler	1500-1600	Y	4	125				
Larson	1700-1785	N	0.6	12[h]			Y	Y
Double Ditch	1700-1785	Y	1.7	33			Y	Y
Lower Hidatsa	1700-1785	Y	4[j]	57			N	N
Slant Village[i]	1700-1785	Y	3.4	85			Y	Y
Boley	1700-1785	N	4.5[i]	102[i]	1	84.4	Y	
Motsiff[i]	1700-1785	Y	6.5	142			Y	Y
Amahami	1785-1830	N	1.3	21			Y	Y
Rock	1785-1830	N	1.3	35	13	85.2	Y	Y
Greenshield	1785-1830	Y	1.5	40			Y	Y
Sakakawea	1785-1830	N	2.2	41	1	147.3	Y	Y
Big Hidatsa	1785-1830	Y	4.7	86			Y	N
Star Village	1830-1886	Y	5.8	85	5	137.2	Y	Y
Fort Clark[k]	1830-1886	Y	7.2	86			Y	Y
Like-a-Fishhook	1830-1886	Y	11.9	175[l]	14	198.8	Y	Y

Notes:

a) All data are from Mitchell (2012) unless otherwise noted.

b) "N" indicates that an unknown portion of the village has eroded away.

c) "Y" indicates the presence of fortification ditches and banks surrounding all or a portion of the settlement.

d) "Y" indicates the presence of a plaza within the site area.

e) Data from Caldwell (1966).

f) Estimate from Sperry (1968).

g) Data from Mitchell (2007).

h) "Definite houses" from remote sensing study (Mitchell 2008).

i) Data from Swenson (2007).

j) Corrected based on: http://www.nps.gov/knri/historyculture/awatixa-xie-village.htm

k) Also known as Mih-tutta-hang-kusch.

l) Data from Smith (1972).

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