Urban Scaling and the Growth of Rome

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Introduction

In a recent critique on the correlation between urbanization and economic development in the Roman world, it was stressed that 'we need a theory of (ancient) urbanization and of the nature of the processes that supported the development of urban centers before we can attempt to delineate and quantify the parameters of this development, let alone begin to discuss the implications of this for the economy' (Morley 2011: 153). Yet this is no easy task, as urban planners, economists, geographers, sociologists, and land use analysts still struggle to quantitatively and qualitatively understand the growth and sustainability of modern cities and urban systems. That said, progressive work in the field of urban scaling has finally allowed for a more scientific approach to the evolution of cities by identifying a set of basic principles by which all urban systems abide (Bettencourt *et al*. 2007). Developed by researchers at the Santa Fe Institute (SFI), urban scaling is used 'to predict the average social, spatial, and infrastructural properties of cities as a set of scaling relations that apply to all urban systems' (Bettencourt 2013b). While confirmed scaling relationships have been observed in thousands of modern cities worldwide (Bettencourt *et al*. 2007), only preliminary studies have been conducted for the ancient world, and solely in a Mesoamerican context (see Ortman *et al*. 2015). As the theoretical framework of urban scaling is designed to better examine and interpret the (often elusive) empirical and theoretical processes behind urbanization and demographic and economic growth, it has the potential to be extremely useful for Roman contexts, as will be discussed. This paper will begin by outlining some of the fundamentals of urban scaling, how it can be used to assess and quantify growth, and how scaling relationships have been observed in ancient contexts to date. This will then be followed by a more theoretical discussion in which I will use the tenets of urban scaling theory to explore the demographic and economic growth of Rome from the mid-Republic to the early Augustan period (*c*. 225 – 2 B.C.), and provide two competing scenarios for the overall growth (and decline) of the City.

Urban Scaling: How it Works

The emergence, development, and comparability of cities have long intrigued scholars from various disciplines, likely because urban centers often serve as proxies for cultural, economic, and demographic growth and change. Cities may be seen as 'sites in which the history of larger systems – states, societies, modes of production, world economies – is partially, but crucially, worked out' (Morley 2011: 153). However, despite the importance of cities throughout history, until very recently they have remained relatively poorly understood, especially concerning their predictability and sustainability. Today, over half the world population lives in cities, and as the global population continues to grow at a super-exponential rate (Bettencourt *et al*. 2007: 7301; unhabitat.org), the need for a 'science of cities' and clear plans for sustainable urban development have never been more pressing. These challenging aspects of urban growth have prompted a group of researchers affiliated with the Santa Fe Institute to devise a unified, predictive theory of urbanization based primarily on a quantitative understanding of cities, highlighting crucial scaling relationships within these complex systems (i.e. scaling laws).

Scaling itself has frequently been used as a tool to tease out underlying relationships across a broad spectrum of science and technology, especially in biology (Bettencourt *et al*. 2007: 7302). A well-known example of a biological scaling relationship exists between an organism's metabolic rate (B) and its body mass (M), which is shown as $B \propto M^{3/4}$ (Schmidt-Nielsen 1984; West *et al*. 1999). This means that as the body size (M) of an organism doubles, its metabolic rate (B) only increases by 75% (B scales with M to ¾) (Fig. 1). This relationship is true for all forms of biological life, and constitutes what is known as a power law (Hemmingsen 1960; Schmidt-Nielsen 1984: 60–62; West *et al*. 1999; Bettencourt *et al*. 2007: 7302). The discovery of a power-law is extremely significant as it can provide predictability in a complex system and be applied over a broad spectrum:

> 'The existence of such universal scaling laws implies … all mammals are, on the average, scaled manifestations of a single idealized mammal, whose properties are determined as a function of its size' (Bettencourt *et al*. 2007: 7302).

When plotted logarithmically, this specific power law relationship exhibits a sub-linear slope defined by 'decreasing returns to scale', e.g: $\beta = .75 < 1$. This means that for every one (1) hypothetical unit put in, you receive .75 in return. Despite the incredible variability of organisms, biology is dominated by sub-linear scaling, meaning the bigger organisms get, the less they need per capita, and the slower their pace of life becomes (Bettencourt *et al*. 2007: 7302).

The discovery of universal scaling laws in biology is significant for the study of cities as it begs the question whether urban (and/or social) systems feature similar scaling relationships. If so, this would suggest that every city is really just a scaled version of a single, 'idealized' city, and that all cities exhibit predictable commonalities. One of the primary research questions for the SFI team was then to determine if quantifiable scaling relationships, or power laws, existed within urban systems and, if so, to devise some kind of conceptual framework for the predictability of such systems. To clearly understand how population, infrastructure, and the economy interact within a city, a range of factors was explored (Table 1) and plotted against city size/population to determine scaling relationships (expressed as β in Table 1). While no universal power-law was uncovered, the results did confirm the existence of distinct scaling relationships and a 'taxonomic universality'. These were broken into three categories,

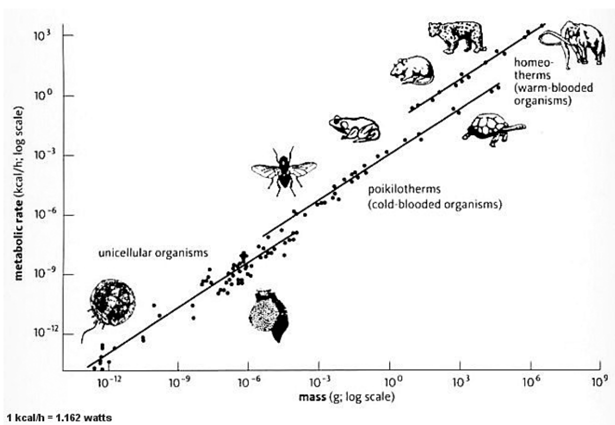

Figure 1: Super-linear scaling of biological organisms (Hemmingsen 1960).

Table 1: The three taxonomic categories of urban scaling, from top to bottom: β>1 (super-linear scaling); β=1 (linear scaling); β<1 (sub-linear scaling) (from Bettencourt, L., Lobo, J., Helbing, D. Kuhnert, C., and West, G. 2007. Growth, innovation, scaling, and the pace of life in cities. Proceedings of the National Academy of Sciences. 104 (17): 7303. © 2007 National Academy of Sciences, U.S.A.).

Y	*β*	95% CI	Adj-R^2	Observations	Country–year
New patents	1.27	[1.25,1.29]	0.72	331	U.S. 2001
Inventors	1.25	[1.22,1.27]	0.76	331	U.S. 2001
Private R&D employment	1.34	[1.29,1.39]	0.92	266	U.S. 2002
"Supercreative" employment	1.15	[1.11,1.18]	0.89	287	U.S. 2003
R&D establishments	1.19	[1.14,1.22]	0.77	287	U.S. 1997
R&D employment	1.26	[1.18,1.43]	0.93	295	China 2002
Total wages	1.12	[1.09,1.13]	0.96	361	U.S. 2002
Total bank deposits	1.08	[1.03,1.11]	0.91	267	U.S. 1996
GDP	1.15	[1.06,1.23]	0.96	295	China 2002
GDP	1.26	[1.09,1.46]	0.64	196	EU 1999–2003
GDP	1.13	[1.03,1.23]	0.94	37	Germany 2003
Total electrical consumption	1.07	[1.03,1.11]	0.88	392	Germany 2002
New AIDS cases	1.23	[1.18,1.29]	0.76	93	U.S. 2002–2003
Serious crimes	1.16	[1.11, 1.18]	0.89	287	U.S. 2003
Total housing	1.00	[0.99,1.01]	0.99	316	U.S. 1990
Total employment	1.01	[0.99,1.02]	0.98	331	U.S. 2001
Household electrical consumption	1.00	[0.94,1.06]	0.88	377	Germany 2002
Household electrical consumption	1.05	[0.89,1.22]	0.91	295	China 2002
Household water consumption	1.01	[0.89,1.11]	0.96	295	China 2002
Gasoline stations	0.77	[0.74,0.81]	0.93	318	U.S. 2001
Gasoline sales	0.79	[0.73,0.80]	0.94	318	U.S. 2001
Length of electrical cables	0.87	[0.82,0.92]	0.75	380	Germany 2002
Road surface	0.83	[0.74,0.92]	0.87	29	Germany 2002

Data sources are shown in *SI Text*. CI, confidence interval; Adj-R^2, adjusted R^2; GDP, gross domestic product.

namely: β<1 (sub-linear scaling, noted above); β=1 (linear scaling); and β>1 (super-linear scaling) (Table 1; Bettencourt *et al*. 2007: 7303).

Examining Table 1, we can see that sub-linear scaling relationships (β<1) are associated with city infrastructure, and as the population of a city doubles the necessary infrastructure increases by about 85% (Bettencourt and West 2010: 912). This is an example of an economy of scale, which parallels biological growth, whereby the bigger an organism (or in this case, city) gets, the less it needs due to its networks becoming more efficient rather than more extensive. Therefore, the physical growth of a city scales very much like the physical growth of an organism, i.e. sub-linearly. Linear scaling relationships (β=1) are then associated with the individual and individual needs, thus as the population of a city doubles the total number of houses and household consumption numbers will rise *pari passu* to accommodate. Finally, the super-linear scaling relationships (β>1) exhibited are the most intriguing, as they relate to socio-economic outputs and/or 'social currencies' that show no analogies in biology (Bettencourt *et al*. 2007: 7303). In fact, these super-linear scaling relationships indicate that as city population increases, proxies for socio-economic activity (when combined) scale at about β=1.15>1, meaning that the larger a city grows the more socially and economically productive it becomes (Bettencourt *et al*. 2007; Bettencourt and West 2010). Such sub-linear and super-linear scaling relationships reveal two distinct, often competing, aspects of urban growth, with one based on materials, infrastructure, and efficiency (sub-linear), and the other on social interactions, innovation, and wealth creation (super-linear) (see Bettencourt *et al*. 2007: 7303).

Understanding Growth and Collapse

Having discovered these 'taxonomic' scaling relationships within a variety of urban systems the SFI researchers then set out to determine how each impacted urban demographic growth. To accomplish this they used an equation that when solved created three separate growth scenarios depending on whether β was >1, <1, or =1 (Fig. 2). The first solution is solved using $\beta<1$ (sub-linear) and results in a sigmoidal (or logistic) growth curve when plotted logarithmically (Fig. 2a). This type of growth is bounded and mirrors that of biological organisms that grow to a certain point (maturity) and then maintain a 'steady state' before collapse (death). It is worth noting that this type of logistic equation was used in earlier models of population growth, most famously by Pierre-Francois Verhulst, who focused on the self-limiting nature of biological populations (see Verhulst 1838). The 'Verhulst equation' was based primarily on the writings of Thomas Malthus and examined the rate of reproduction in proportion to the existing population and available resources, thus predicting a bottleneck due to competition for resources (Malthusian restraints) and halting population growth upon reaching carrying capacity (K). This is a prime example of growth driven by economies of scale rather than wealth creation/innovation, and as predicted by the equations, any social or urban system driven by economies of scale (i.e. sub-linear growth/decreasing returns) is destined to cease growing, leading to stagnation and eventual decline (Bettencourt and West 2010).

While sub-linear scaling equations may have value for discussing demographic growth in antiquity (see below), the empirical evidence presented here shows that population growth exhibited in today's cities is unbounded and theoretically limitless (Bettencourt *et al*. 2007: 7306). Looking at Figure 2b, we can see that when the growth equation is solved using $\beta=1$, growth becomes exponential rather than sigmoidal, and when solving with $\beta>1$ growth becomes super-exponential (Fig. 2c), leading to 'infinite population in a finite amount of time' (Bettencourt *et al*. 2007: 7304). As the SFI researchers point out, this type of growth behavior can have dire consequences considering the planet's resources are ultimately limited, therefore making unlimited growth unsustainable (Bettencourt *et al*. 2007: 7304). In order to avoid collapse due to a lack of resources, continuous innovation and wealth creation that fuels super-linear growth (e.g. new technology, divisions of labor, inventions etc.) must be maintained in order to reset the growth cycle and postpone collapse (Fig. 3). However, as the population grows the time between cycles becomes progressively shorter, making it necessary to innovate at an increasingly faster rate. As both Bettencourt and West remark, this situation is akin to being on a continuously accelerating treadmill, where avoiding collapse becomes more difficult with every step.

The implications of this research are indeed substantial and far-reaching, however, there is not scope to delve into their ramifications for the future of contemporary cities here. Instead, at this juncture it is important to understand that the urbanization and urban growth processes we see today are largely dictated by super-linear scaling, and increasing returns at a socio-economic level in contrast to sub-linear scaling and decreasing returns at the infrastructural level. The discovery of such scaling relationships existing in contemporary cities then begs the question: did ancient cities exhibit similar scaling relationships? If so, why? And if not, why not? The answer to these questions could prove to be crucial for dealing with the future directions of

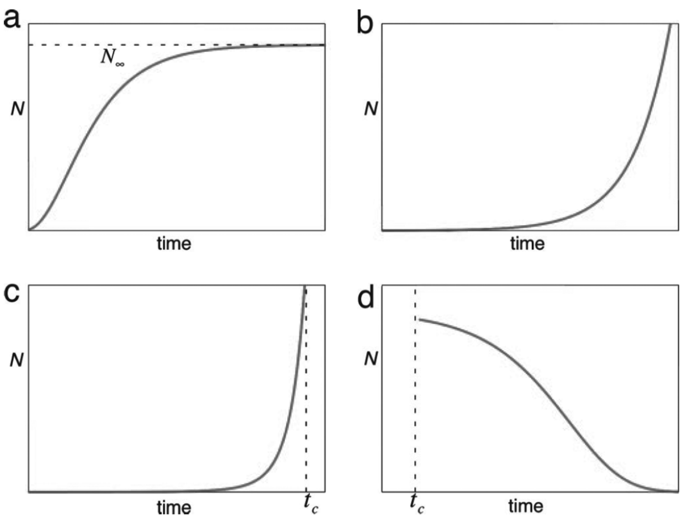

Figure 2: Image (a) illustrates growth driven by sub-linear scaling (β>1); image (b) illustrates growth driven by linear scaling (β=1); image (c) illustrates growth driven by super-linear scaling (β<1); image (d) illustrates collapse characterized by super-linear growth when resources are scarce (from Bettencourt, L., Lobo, J., Helbing, D. Kuhnert, C., and West, G. 2007. Growth, innovation, scaling, and the pace of life in cities. Proceedings of the National Academy of Sciences. 104 (17): 7305. © 2007 National Academy of Sciences, U.S.A.).

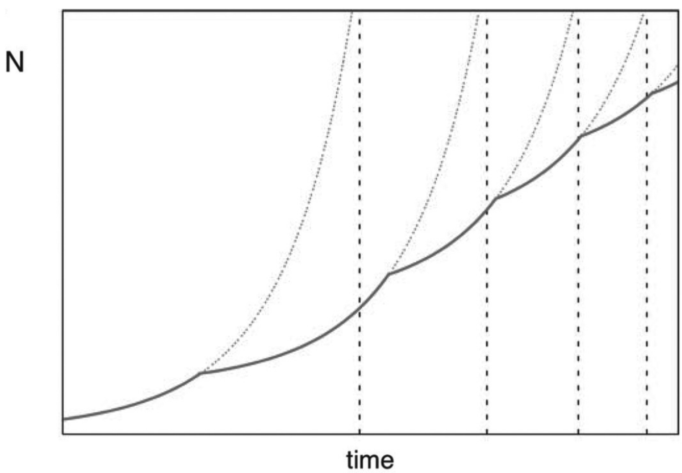

Figure 3: Successive cycles of super-linear innovation reset the singularity and postpone instability and subsequent collapse. Schematic representation: vertical dashed lines indicate the sequence of potential singularities (from Bettencourt, L., Lobo, J., Helbing, D. Kuhnert, C., and West, G. 2007. Growth, innovation, scaling, and the pace of life in cities. Proceedings of the National Academy of Sciences. 104 (17): 7305. © 2007 National Academy of Sciences, U.S.A.).

urban growth, as the study of past urban systems may provide more important clues concerning the predictability and sustainability of cities than the information available at present.

Scaling Relationships in an Ancient Context

As mentioned, only preliminary studies on scaling relationships in ancient societies have been conducted at this time; however, as an active area of ongoing research, SFI (in conjunction with Arizona State University) has hosted workshops focused specifically on urban scaling in pre-modern societies. While much of this research is still in its early phases, the results presented by Luis Bettencourt and Scott Ortman (Ortman *et al*. 2015) do show evidence for increasing returns expressed in the archaeological settlement data from the Pre-Hispanic Basin of Mexico (BOM). This groundbreaking work represents the first testing of urban scaling theory in a pre-modern context, and suggests that the processes leading to increasing returns to scale are not limited to modern contexts, but rather the result of more general phenomena underlying all human settlements regardless of space and time (Ortman *et al*. 2015).

The conclusions drawn by the SFI researchers are very intriguing, as they imply that similar scaling relationships may exist in ancient Roman urban systems as well. Yet before exploring those possibilities it is first necessary to examine how the BOM results were achieved, and to see if a similar methodology could be used in a Roman context. In brief, this study deals exclusively with settlement data collected during numerous regional survey campaigns prior to the modern construction of Mexico City (primarily from 1960–1980). The database contains over 4,000 sites ranging from the smallest hamlets to the largest urban centers (e.g. Tenochtitlan), dating from the Formative era to the Post-Classical (roughly 1500 B.C. – A.D. 1500). In order to check for increasing returns to scale, the researchers chose to use the construction speed of public architecture (m^3/year) and the area of house mounds as proxies to scale against settlement populations and populations of political units. Populations were based on settled areas of sites and estimated by mapping the site extent through artifact scatters (by period) from aerial photos; assigning each scatter a density class; and multiplying the extent of the scatters for each period by population densities derived from potsherd densities of various local settlement types in the sixteenth and twentieth century records (Ortman *et al*. 2015: 7).

When plotted logarithmically the results (Fig. 4) provide evidence for increasing returns to scale, indicating that the larger the settlement was, the more productive it was, as the speed of monument construction and the areas of house mounds all increased super-linearly in relation to population size. These results provide the first evidence for super-linear scaling and increasing returns in an ancient society, thus opening the door for further studies in other ancient contexts. However, it is important to note that the methodology used for the BOM data

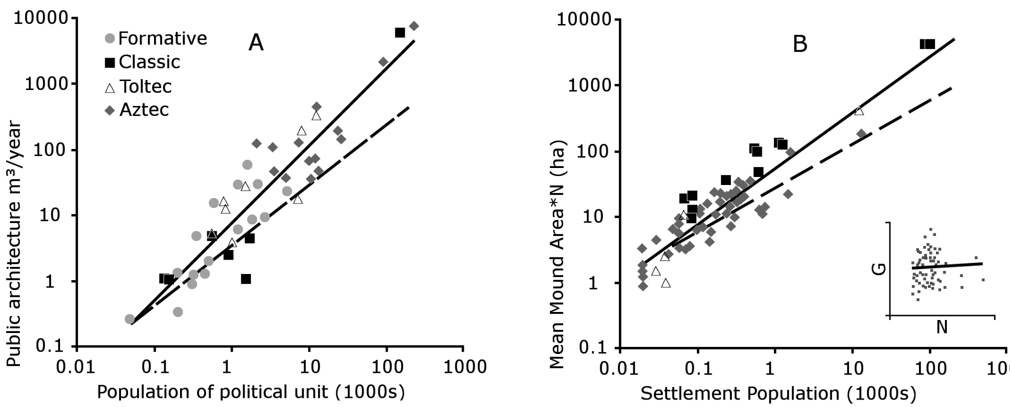

Figure 4: Super-linear scaling of socio-economic rates with population. A: political unit population vs. public monument construction rates. B: settlement population vs. total domestic mound area. Symbols denote time periods, solid lines show power law fits from OLS regression of the log-transformed data, and dashed lines represent proportionate (linear) scaling. Inset shows the independence of average G on N, where G = A/N(Mean Domestic Mound Area) (after Ortman* et al. *2015).*

would be problematic if directly applied in a Roman context. Firstly, the BOM settlement data is unique, as no such clear, comprehensive dataset exists for the Roman world. Secondly, it would be nearly impossible to determine the period of Roman sites from aerial photos (even without modern building), as many sites will feature chronologically mixed artifact assemblages in the surface scatter due to various post-depositional processes and disturbances. Thirdly, the political institutions, the speed of monument construction, the labor force behind it (not *corvée* labor; see Ortman *et al*. 2015: 4), and the materials used in the Roman world were vastly different from the situation observed in the BOM. Finally, the historical periods assigned to these societies by archaeologists and historians, and the level of written documentation pertaining to each vary greatly, further complicating the situation.

For example, to achieve the speed of monument construction in Classical Tenochtitlan (a settlement analogous to Rome) the BOM researchers divided the total volume of civic–ceremonial architecture (3,020,450 m^3) by the number of years in the Classical period (500) to get the m^3/year (6,041). Turning to Rome, if we take a structure like the Baths of Caracalla, and calculate the volume of the central block alone we get a figure of 805,723 m^3 (not including the pre-construction terracing and trenching which required the removal of 520,000 m^3 of dirt) (see Delaine 1997: Chap. 7). If we then label this construction as Imperial, a period of roughly 400 years, and divide, we get a rate of 2,014 m^3/year. However, we know from literary and epigraphic evidence that this structure was completed in a period of roughly seven years (Delaine 1997: 183), giving us an actual rate of construction closer to 115,103 m^3/year. This, of course, is a massive variation that would greatly alter any scaling relationships, and thus this (extreme) example serves well to illustrate some of the problems that could arise if a similar methodology were applied directly to Roman settlement data. While the results obtained from the BOM data remain valid in their own right as they take into account all ceremonial structures (none of which were documented in literary sources) rather than one well documented building; many public buildings in Rome were constructed rather rapidly with a large labor force whose work was either documented or can (sometimes) be deduced in one way or another (Delaine 1997; 2000). Therefore, in order to test for scaling relationships within Roman survey datasets, a new methodology accounting for the quantity and complexity of the data (both archaeological and epigraphic/literary) will need to be devised (an endeavor beyond the scope of this paper, but one the author is interested in pursuing).

Having identified super-linear scaling relationships in an ancient setting, it is next important to consider the scale at which these relationships are expressed. The BOM study incorporates and compares multiple settlements to test for increasing returns at a regional scale. While this approach is certainly viable, and probably preferable given that many Roman survey datasets are readily available for study and allow for anomalous data to often cancel out, the theoretical framework of urban scaling also has scope to explore scaling relationships within individual settlements, such as the city of Rome, as will be discussed in the following sections.

Urban Scaling Theory and the City of Rome: Implications for Growth

Over the years numerous attempts have been made to quantify and/or qualify the growth and productivity of Rome and the Roman economy using a variety of proxies (e.g. Silver 2007; Scheidel *et al*. 2007; Scheidel 2009; Wilson 2009a; Wilson 2009b; Bowman and Wilson 2009; Temin 2013; Kay 2014, among others). However, due to the paucity of empirical data available, debates continue over whether the Roman economy exhibited intensive or extensive growth (or both in different periods), and how demographic growth and change related to economic performance. Despite the complexity and quantity of the data, the theoretical implications of urban scaling can be helpful here given that we have some acceptable estimates of Rome's population growth from *c*. 225 B.C. – 2 B.C., a period when the city and territory of Rome saw substantial expansion. Based on work by Hopkins (1978) and Morley (1996), it is generally believed that Rome's urban population rose from about 200,000 (150,000 free) in 225 B.C. to around 1 million (650,000 free) during the reign of Augustus. As can be seen, the population of the City doubled *twice* in this period, exhibiting (temporary) exponential growth. According to urban scaling theory, anytime the population of a city doubles, a 15% rise in per capita socio-economic returns will accompany it (Bettencourt *et al*. 2007: 7303; Bettencourt and West 2010: 913). This fundamental relationship is a universal feature of all modern cities and constitutes a power law known as the '15% Rule' (i.e. β=1.15>1) (Bettencourt and West 2010: 913).

While only limited evidence exists for increasing returns to scale in ancient society we cannot assume *a priori* that the city of Rome followed universal scaling laws exhibited in modern cities today. However, given that super-linear scaling has been proven to exist in ancient contexts, it is certainly theoretically possible that the city of Rome featured similar scaling relationships in antiquity, especially given its size and primacy in the wider urban system. If the '15% Rule' did come into effect, it would imply that from *c*. 225 B.C. – 2 B.C. the city of Rome experienced a 230% increase in aggregate socio-economic quantities (e.g. GDP, income, occupations, house size, rents etc.) in relation to its contemporaneous population growth, with a 30% increase in per capita productivity. It is worth noting, however, that the '15% Rule' assumes transport cost and benefits of social interaction remained constant over the period in question (Bettencourt *et al*. 2007; Bettencourt 2013b; Ortman 2015 pers. comm.). Yet during the Republican period the Roman road system was growing rapidly (Quilici 1990: 12–17), with the purpose of bringing further removed regions into direct contact with the City (Laurence 1999: 23–26), thus increasing social interactions. Transport costs would have also gone down, as traveling by road was 33% faster than traveling off road, resulting in the compression of temporal space (Laurence 1999: 82). This coupled with the arrival of new transport technologies to Rome (and Italy) from places such as Greece, Gaul, Pannonia, and Britannia in the form of two and four wheeled animal drawn carts (Pisani Sartorio 1994: 49–61) would have further decreased transport costs, thereby increasing social interactions, and likely making the percentage of aggregate and per capita growth of socio-economic quantities even higher than the '15% Rule' would predict during the period in question.

If this type of intensive, per capita growth could be proven via the discovery of certain scaling relationships, the impact on how the broader Roman economy is understood and interpreted would be substantial. That said, some scholars are already beginning to see the Republican period as that of Rome's greatest growth and expansion (Bang 2009: 202), and extensive theoretical work by Phillip Kay in his recent book *Rome's Economic Revolution* (2014) concludes that the real per capita GDP of the Roman economy grew by 72% from 150–50 B.C., with an annual compound growth rate of 0.52%, further indicating this period as one of intensive growth (Kay 2014: 334). However, most of the data we have remain largely qualitative or stuck in a zone of theoretical conjecture. This is where urban scaling could prove to be very useful, since confirmed super-linear scaling relationships would add a degree of certainty to the situation. Yet the problem persists that no diachronic dataset (that the author is aware of) currently exists to scale against population growth in the Republican period. This, however, is currently an active area of research, and archaeological evidence, such as the number and size of fora, markets, tombs, entertainment spaces, and housing units, (grain) prices, aggregate public works construction, road widths, and fine-ware ceramic consumption, are some proxies that will/could be examined for scaling relationships in forthcoming works.

The Growth (and Decline) of Rome: Two Scenarios

In this section I will explore some of the theoretical implications concerning population and economic growth that the tenets of urban scaling theory hold, and how these may apply to ancient Rome. In urban scaling theory the population is seen as both the driver and the destroyer of urban systems. As the population grows, it pushes the system closer to its 'carrying capacity'; however, it is also responsible for the innovations and wealth creation that allow for continued growth, postponing Malthusian restraints and resetting the growth cycle (see Boserup 1965; Wood 1998; Bettencourt *et al*. 2007). In other words, without the innovations and technological advancements supplied by 'creatives' and entrepreneurs (who emerge with increasing population and profit potential) at an ever-increasing rate, decreasing returns will set in (more labor for less production) leading to stagnation and eventual decline (Bettencourt *et al*. 2007; also Scheidel 2007 for discussion). Today, most city populations are growing exponentially and this growth is sustained by continued innovation and wealth creation expressed by super-linear scaling relationships/increasing returns to scale (Bettencourt *et al*. 2007: 7303). Yet for ancient Mediterranean societies it is often posited that population growth was accompanied primarily by extensive economic growth based on economies of scale rather than increasing returns (see Scheidel 2007). Was this also valid for Rome in the last two centuries B.C. when the City was experiencing exponential population growth?

To provide some type of answer to this question it is first necessary to look at the full arc of Rome's population in antiquity (Fig. 5). As is evident, following the intense growth phase in the later Republican period, the city of Rome ceased growing after the reign of Augustus, holding steady at about 1 million inhabitants until the fourth century A.D. (aside from a dip due to the, so-called, Antonine Plague in the later second century A.D.), after which there was a steep decline (see Lo Cascio 1994). When plotted on a graph, Rome's population growth from Republic to Empire takes a distinctly sigmoidal shape, which could indicate logistic population growth (e.g. the Verhulst equation). However, logistic and exponential growth curves are essentially identical in their early stages (functionally and visually), but are generated by quite different processes and terminated by different problems. Thus, it is difficult to untangle which process was occurring in Rome during the Republican period by looking at a population graph alone. Therefore, the question remains: was the growth of Rome (and perhaps that of other ancient metropoleis) inherently logistic, and thus destined for collapse after reaching 'maturity' (i.e. the Malthusian model), or, was Rome experiencing exponential, super-linear growth in the Republic, but failed to maintain it?

To shed some light on the situation I will present below two competing hypothetical scenarios for the growth (and decline) of Rome using the premise and predictions of urban scaling theory, which may allow us to better model and interpret the available evidence and bring us closer to an answer. While this is not a novel approach, given that more recent and intensive studies of Rome's economic growth have often resulted in the rise of two competing growth scenarios (if with some variation, see Silver 2007; Scheidel 2009; Wilson 2009b; Temin 2013 for detailed discussions), I hope that the presentation of the following scenarios will add more substance to this nuanced debate.

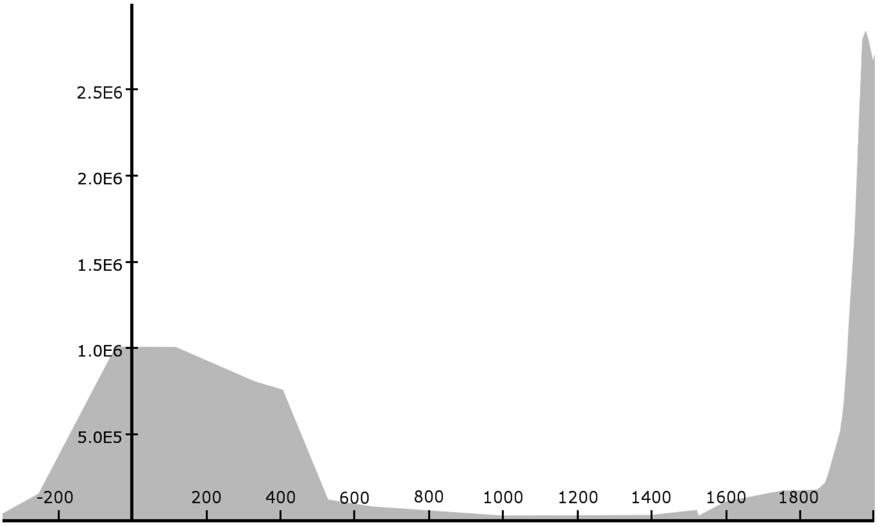

Figure 5: Population growth of Rome from 300 B.C. to present. Vertical line with population scale represents A.D. 1 (after Galbraith 2009).

Scenario 1

This scenario takes the classic position that Rome's population growth was inherently logistic (sigmoidal) and therefore bounded, following an equation similar to that set out by Verhulst (i.e. growth hindered by Malthusian restraints) (Fig. 2a). As discussed above, logistic growth is dictated by sub-linear scaling and driven by economies of scale rather than innovation and wealth creation. This scenario has long been popular with economic historians and ancient historians (see Silver 2007 for discussion) and follows the more traditional narrative that sees Rome's demographic and economic growth as 'one-off', extensive, and deeply rooted in agrarianism (e.g. Finley 1973; Jongman 1988; also Scheidel 2009 for a fuller treatment). As the tenets of the Malthusian scenario have already been discussed above (also: Temin 2012), it is instead worthwhile to explore some of the wider, more substantial implications of this model here, especially within the context of urban scaling theory.

First and foremost, if the Malthusian scenario were indeed correct it would imply that Rome (and likely other ancient cities) did not feature super-linear scaling relationships and that the processes behind the growth of ancient cities were fundamentally different than those today. While this is entirely plausible (and often taken as economic fact), it is worth noting the significance of this fundamental assumption for the wider study of past and present urban systems, as it implies that the super-linear scaling relationships observed in today's cities and in the BOM settlements did not exist in the ancient Mediterranean. Second, it would imply that Rome's political and legal institutions were largely statist from an early period (e.g. from 400 B.C.) and sought to control natural resources and the modes of production from the outset, thus limiting innovations concerning labor practices and technology necessary to postpone Malthusian restraints. Third, this scenario suggests that the economy (in Rome and in its greater empire) was almost solely agrarian, and that enterprises not directly linked to agriculture played a very minor role overall. This is, of course, a rather primitivist view and archaeological and literary evidence (ranging from banking and credit systems to mass production of fine wares, glass, building materials, and metals; extensive transportation and trade networks; integration and diversification of markets; services and entertainment; a substantial market for art and luxury goods; etc.) contradict some aspects of its implications; however, given the paucity of quantifiable evidence, and what can be reasonably deduced from such evidence, it remains a viable scenario.

Scenario 2

The second scenario sees Rome growing intensively with increasing returns (i.e. super-linearly) during the period in question, but hamstrung by a failure to innovate at an increasing rate due to changing political institutions and a rise in entropic elements such as disease, famine, and disorder – the dark side of the '15% Rule' (Bettencourt and West 2010). This endogenous shift – rather than exogenous, as is often postulated in scenarios concerning sustainable growth (e.g. Temin 2013) – occurs during the reigns of the Julio-Claudian emperors when the political system of the Republic was abandoned for a monarchic regime. This institutional overhaul brought with it a statist economic approach and bureaucratisation, which would have (inadvertently) hindered technological progress and economic growth over the *longue durée* (see Lal 1998 for details concerning statist economies and their outcomes). A brief case study on the demise of the *publicani* over the course of the Principate serves well to illustrate this.

The *publicani* (businessmen/private contractors) and the *societas publicanorum* were responsible for dealing with state contracts concerning public lands, resources, infrastructure, and tax collection (Harris 2007). As the *publicani* were essentially the primary entrepreneurs of the day, and their *societas* were the ancient equivalent of modern firms/companies competing for large government contracts (Harris 2007: 520; Malmendier 2010: 12), competition between the *societas publicanorum* greatly stimulated innovation concerning modes of resource extraction, building techniques, and revenue collection strategies – all opportunities that grew with Rome's colonial expansion. However, with the advent of the Principate an institutional shift from contracting to large-scale nationalization took place, all but eliminating the *publicani* from the economic system in favor of an imperial bureaucracy (Malmendier 2010: 13–14). Indeed, following reforms under Augustus, Tiberius '…removed from a great many cities and private individuals their old immunities and rights over mineral resources and revenue collection (*vectigalia*)' (Suetonius, *Tiberius*, 49). This effectively ended any competition among private contractors in the largest and most active economic sectors, as the emperor (and the imperial bureaucracy) now exclusively controlled and managed nearly all natural resources, public revenues, and public works.

The impact of this institutional shift is reflected in the relative lack of technological innovation (or importation) during the imperial period in comparison with that of the Republic. Despite the continued investment in public buildings, with no competition among private contractors, there was less motivation to invent or improve technologies, especially in the public sector. Furthermore, many of the inventions that became more refined and ubiquitous in later phases of the Empire were products of Greece, Egypt and the Near East, or Gaul that were imported or 'transferred' during Rome's most major phase of expansion between the third to first centuries B.C. – for example, water lifting/mills, cranes, compound pulleys, screw and bilge pumps, the chain drive, escapement, agricultural tools, transport vehicles, glass blowing etc. (see Pisani Sartorio 1994; Humphreys *et al*. 1998; Greene 2000; Cuomo 2007; Wilson 2009c). The primary facilitators and adopters of these transferred technologies were likely the *publicani*, who would have benefitted most through their large-scale employment. During the imperial period, we have very little evidence for the invention or uptake of *new* technologies, and the emperors themselves seemingly often stunted technological advancement in order to maintain the status quo (Suetonius, *Vespasian* 18.1; Pliny, *Nat. Hist.* 36.56.195); and machines like the aeolipile (a steam turbine developed by Hero of Alexandria in the first century A.D.) never became more than a temple wonder seen by a select few (Humphreys *et al*. 1998: 28; Bresson 2006 for wider discussion).

Again, quantifiable data are scarce, though some archaeological evidence does suggest a lack of sustained overall growth during the imperial period. Despite the many caveats associated with these data (see Wilson 2009a; Wilson 2009b), it is hard to argue that the current graphs for the number of discovered Mediterranean shipwrecks (Parker 1992; Wilson 2009a), and those dealing with pollution levels in the Greenland ice caps from ancient metal working (Hong *et al*. 1994) point to the sustained growth of both trade and production in the second to fourth centuries A.D. This seems to be corroborated by the data collected on villas around Rome, and especially in the Tiber valley (Fig. 6), indicating very few new constructions after the first century A.D., with many of those dated to that period attributable to the first half of the century, as is the case for the majority of villas in the '*suburbium*' (see Di Giuseppe 2004; De Franceschini 2005; Witcher 2009). While the empire did continue to grow physically during the imperial period, promoting extensive economic growth and new public works, Rome's intensive urban growth phase seems to have come to an end during the first century A.D., when population levels also settle for the City.

While the repercussions of these significant institutional changes may not have been immediately felt or known, they inadvertently brought about a statist economy that served to stifle commercial activity and innovation in the following periods (see Silver 2007: 237–241 for a similar opinion). This coupled with a 15% rise in entropic elements, accompanying the 15% rise in socioeconomic outputs (see Bettencourt and West 2010), and a lack of innovation to deal with such elements (e.g. disease, pollution, poor land/water management), were the primary factors that led to a shift from an economy and population seeing increasing returns and intensive growth to one based on extensive, logistic growth. Therefore, following the tenets of urban scaling theory, without innovations and/or major technological advancements, Rome could

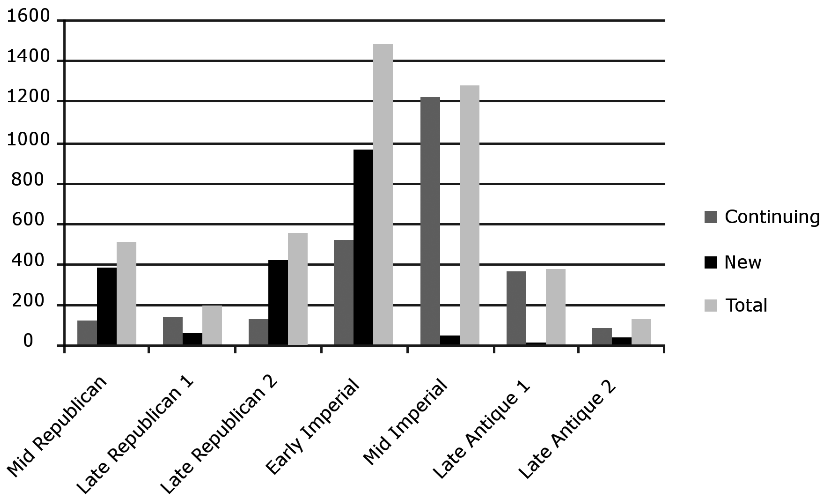

Figure 6: Graph showing construction and continuity of suburban villas north of Rome. NB: Lack of new villa constructions in mid-Imperial period (after Witcher 2009).

no longer reset growth cycles at a quick enough pace to postpone Malthusian restraints, thus leading to the slow and steady (but irreversible) collapse of the City. While Rome was certainly atypical for an ancient city given its size – as the largest growth pole in the Mediterranean any substantial issues it faced were likely radiated throughout the Empire. However, determining how much the City's economic and demographic well-being directly impacted the wider Roman urban system, and how and why its growth may have deviated from the average Roman city is still a task to pursue.

Conclusions

Since the present study is only in its preliminary stages, there are few conclusions to be drawn at this time, as without confirmed scaling relationships it remains difficult to determine if Rome experienced a super-linear growth phase. However, evidence from the BOM study suggests that the same processes that drive urbanization and economic growth today also existed in the ancient world. Thus, the theoretical parameters of scaling theory (e.g. the '15% Rule', super-linear growth driven and sustained by innovation, physical growth driven by economies of scale) provide scope to answer some long standing questions concerning the physical, demographic, and economic evolution of ancient Rome, despite the fact that empirical evidence cannot yet support this. It is my hope that the value and potential of urban scaling as both a theory and scientific framework for empirical testing have been adequately presented here, and that their further uptake in the field of Roman archaeology will lead to more thorough reassessments of the available data regarding scaling relationships at local, regional and supra-regional levels. Core, of course, will be the task of seeing how these ideas might be applied outside of Rome, to sites lacking such strong textual support. The challenge now is to find adequate socio-economic proxies that can be measured and used to determine scaling relationships in the Roman world. The nature and patchiness of the archaeological record make this a difficult task indeed, yet ongoing work by SFI researchers and collaborators (myself included) will hopefully produce some tangible results on this front and encourage the further use of scaling analysis in the archaeological discipline.

While the scenarios presented above provide no definitive answers concerning Rome's economic and demographic growth and decline, they do add another component to the overall discussion – one that looks internally rather than externally for a shift or 'shock' responsible for the failure to continue resetting the growth cycle and prolong super-linear growth, which, following the 15% Rule, seems to have been occurring during the Republican period. By bringing ancient Rome into the larger discourse on complexity in social systems and economics (www.santafe.edu/research/projects), and engaging with current studies in social sciences, urban morphology, and evolutionary anthropology, we may come closer to realizing a general theory of (ancient) urbanization that will not only benefit the wider discipline of archaeology, but also provide great return value for contemporary studies on urbanism. Such an interdisciplinary, comparative approach would also help break down long-standing barriers that exist between ancient and modern urban studies, history and archaeology, and traditional and progressive approaches that have so far hindered our ability to fully understand the inception, predictability, and consequences of urbanization processes. As we enter into a period of increasing uncertainty concerning the sustainability of our own contemporary complex urban social systems and practices, the need to predict and avoid disastrous outcomes has never been greater, and the further study of past urban systems can only enhance our ability to do so.

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