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Urbanisation and the division of labour in the Roman Empire

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ABSTRACT

One of the main hallmarks of human agglomeration is task specialization and an expanded division of labour and this relationship has been a long-standing topic of inquiry among archaeologists, anthropologists, sociologists, and economists. Recently, researchers investigating contemporary urban systems have proposed a novel explanation for this relationship grounded in a view of human settlements as fundamentally social, informational, and infrastructural networks embedded in physical space. This construal does not incorporate the particular socio-economic conditions and market economies of the modern world, and this leads to the question of whether the relationships between population size and productive diversity observed in contemporary systems also characterized pre-modern and even ancient systems. Here, we present a general model for the relationship between the population size and functional diversity of individual settlements within a settlement system in which functional (or skills) diversity is interpreted as an indicator of the division of labour. Using a novel dataset on occupational associations in ancient Roman cities, we develop an index of urban functional diversity to analyse the relationship between population size and skills diversity. Our empirical results are consistent with theoretical expectations and with patterns of professional diversity in contemporary cities. These results add further support to the view that urban systems throughout history have emerged through a common set of generative social processes.

Key Words: Settlement scaling theory, Complex systems, Roman Empire, Division of labour, Economic development, Archaeology
Introduction

Over the last decade, researchers investigating contemporary urban systems have developed an integrated approach to the study of human settlements, “settlement scaling theory”, which is grounded in the properties of human networks embedded in physical space [1-4]. The fundamental process at the core of this framework is the concentration of human interactions, and their consequences, in space and time, and subject to a variety of constraints imposed by environmental conditions, culture, technology, and institutions [5, 6]. The empirical hallmarks of treating settlements as physically embedded social networks are systematic socio-economic effects induced by population size (scale) and population density for settlements in a given system [7-10]. This framework accounts for a series of patterns that have been robustly-identified in multiple settings spanning different eras, geographies, and cultures, including: 1) a consistent densification effect, such that larger settlements take up less land area per person on average; 2) intensified use of infrastructure, such that larger settlements use less material per person, again on average; 3) increasing returns to scale in a variety of socio-economic outputs, including productivity measures and invention (measured through GDP and patenting), but also crime, pollution and infectious disease; and 4) increasing levels of functional diversity, such that larger settlements generally support a greater range of skills or occupations [1, 5, 11].

The formal models built from of settlement scaling theory predict and account for the specific quantitative form of the relationships mentioned above for contemporary urban data, but the processes and variables animating these models are very general and are not tailored to the particular socio-economic conditions of the modern world, nor are they restricted to city-sized settlements. It is therefore plausible to inquire about the extent to which the patterns observed in contemporary urban systems also characterized pre-modern and even ancient systems. To date, studies have found evidence that several of the patterns pertaining to the effects of population size and density, including the densification effect and increasing returns in economic outputs, are in fact apparent in historical and archaeological data from a
variety of pre-modern contexts [12-15]. Here, we extend this line of research by showing that Roman cities of the imperial period exhibit the same patterns of functional diversity with respect to population size observed for contemporary systems. The results presented here add further support to the view that human settlement systems throughout history have shared a common set of fundamental generative social processes which have led to consistent empirical patterns.

In this paper, we present a general model for the relationship between the population size and functional diversity of individual settlements within a settlement system. The functional (or skills) diversity is interpreted as an indicator of the division of labour. We avail ourselves of records on occupational associations to construct a novel dataset on associations that were present in specific urban locations throughout the Roman Empire. We then develop an index of functional diversity appropriate to cities in the Roman Empire, and analyse the relationship between this index and estimates of the numbers of inhabitants to assess the degree to which empirical patterns are consistent with theoretical expectations. Finally, we consider the implications of our results for the broader effort to develop a general approach to human societies as embedded and spatially circumscribed social, informational, and infrastructural physical networks.

**Population size and the division of labour**

The starting point of our analysis is Adam Smith’s famous aphorism that “the division of labour is set by the extent of the market” [16, 17]. The standard, and restrictive, interpretation of Smith’s observation is that larger markets support larger levels of production which, in turn, facilitate, and make economically advantageous, the specialization of production tasks [18]. But a richer sociological interpretation, not restricted to societies characterized by market economies, recognizes that the extent to which specialization—the division of production into separate components and the concentration of individuals
on specific tasks—can be implemented is related to the number of people who interact with each other in pursuit of their livelihoods. This relationship between group or population size and diversity of tasks, tools, and cultural outputs has also been studied by anthropologists [19-22].

At the level of individuals, societal specialization, broadly understood, implies performing fewer tasks while having to rely on others for the fulfilment of basic needs and attainment of luxuries. Following Bettencourt and others [11], we propose that the range of tasks that an individual performs is inversely proportional to their social contacts, by which we mean all connections through which an individual obtains goods, services, or information. Consider that in any given social context there is a range of “functions” (tasks or processes which when performed fulfil specific needs) that each person must either directly perform or have access to through others in order to survive. An isolated individual would have to perform all of these functions themselves, in which case that the range of functions that they perform, \( d \), would be equal to the total number of functions that need to be performed as a whole, \( F \). Humans have lived in social settings, such as small-scale societies and foraging groups, in which individuals had to carry out most of the tasks necessary for survival (beyond the division of labour by gender). But even in such settings there is some level of task coordination [23]. We therefore assume, as in much of the literature on the origins of sedentism and urbanization, that one of the hallmarks of sedentary living is task specialization [24, 25].

We specifically assume that in the case of permanent settlements individuals have access to necessary functions through their social contacts. As an individual’s social contacts \( k \) increase, the range of functions that person must perform, or her functional diversity, can, without loss of generality, decrease proportionately [11]. Because most regular social contacts through which goods, services and information are exchanged are local, an individual’s social contacts can be expected, on average, to be related to the size of the settlement in which she lives. As a result, the relationship between the number of social connections, functional diversity, and the size of each settlement can be expressed as:
\[ F = k(N) \times d(N). \]  

(1)

The relationship in equation (1) can be simplified by noting how an individual’s social contacts \( k(N) \) should change with the size of the settlement [6]. In a fully-connected network, the total number of links between individuals is \( N \times (N - 1) \), which is essentially \( N^2 \) for large \( N \), implying \( K(N) = N^2 \). However, in any social network embedded in space and time individuals are limited by the (energetic) cost of movement, as well as other implicit transaction costs entailed when interacting with others, such that only a fraction of the total potential connections are possible per unit time. If one further assumes that population of a settlement is distributed homogeneously within the settlement area, \( A \), then the total number of interactions that are possible per unit time is given by the portion of this area that a person can explore per unit time. We represent this explored area as \( a_0 l \), where \( l \) is the length of a person’s path and \( a_0 \) is a cross-section representing the distance at which interactions occur. Putting these assumptions together we can write the following expression for settlement connectivity:

\[ K(N) = a_0 l N^2 / A \]  

(2)

Note that the area taken up by a settlement can also be written as a function of the settlement population. Both theoretical and empirical considerations allow us to express the area taken up by a population of size \( N \) as:

\[ A(N) = a N^{1 - \delta}, \]  

(3)

where \( a \) is a baseline area per person and \( \delta \) reflects the rate at which the population density of the settlement increases with population. The value of \( \delta \) ranges from \( 1/3 \) to \( 1/6 \), depending on the degree to which settlements are defined in terms of circumscribing areas vs. built-up areas [1, 14]. From here, one can substitute Equation 3 into Equation 2 and simplify, leading to:

\[ K(N) = k_0 N^{1 + \delta}, \]  

(4)
where \( k_0 = a_0 l / a \) is a baseline level of social connectivity. Now, given that the average connectivity per person is \( k(N) = K(N) / N \), one can substitute this relation into Equation 1 and simplify:

\[
F = k_0 N^\delta \times d(N)
\]

\[
d(N) = \left( \frac{F}{K_0} \right) N^{-\delta}
\]

\[
D(N) = d(N) \times N = \left( \frac{F}{K_0} \right) N^{1-\delta}.
\]

Equation 5 proposes that, on average, the functional (skills) diversity of an individual decreases with population at the same rate as the population density increases. Because functional diversity is the reciprocal of the division of labour, this relation implies that division of labour increases at this same rate. In addition, Equation 6 suggests the total functional diversity of a settlement increases more slowly than population and at the same rate as areal extent increases. These relations indicate that the population of the settlement will expand faster than its total functional diversity; but the overall division of labour will still expand, such that the number of distinct tasks performed by the population will increase [11].

It is important to note that there is also a relationship between the division of labour and productivity. Typically, the gains following from an enhanced division of labour are attributed to the energy saved by increasing the intellectual and manual deftness of each worker through “learning by doing”, and by reducing the number of times individuals have to switch between tasks [26]. So, if the division of labour derives from levels of social connectivity, and connectivity increases with population density, one would expect economic outputs to follow suit; such that if total social connections are given by \( K(N) = k_0 N^{1+\delta} \), then total economic rates are given by \( Y(N) = y_0 N^{1+\delta} \).

Studies of the division of labour tend to recognize two different forms of division: horizontal and vertical. The first normally refers to the diversity of activities related to production and exchange in an economy; whereas the second typically refers to the division of different activities within specific activities (or crafts
and trades) [27]. Although this distinction is useful for some purposes, here we emphasize that horizontal and vertical divisions are actually related. As economies, or more generally social groups or settlements grow, individuals tend to concentrate on a narrower range of tasks, even as the overall set of possible socio-economic tasks (or roles) expands. Individual-level specialization presupposes and in turn induces specialization at the level of production, transportation, and distribution of goods and services (a distinction not restricted to modern economies). Due to these relationships, and the fact that functional diversity and division of labour are opposite sides of the same coin, it is feasible to measure the total functional diversity of a settlement in terms of the total number of roles within that group. We apply this logic here in a study of the division of labour in settlements in a pre-modern context, in this case cities in the Roman Empire.

**Materials and methods**

We utilize three different datasets to examine the relationship between urban populations and their levels of functional diversity. The first is Waltzing’s lists of associations, usually known as *collegia*, which identify the number of distinct crafts and trades that are known to have been performed in a given settlement [28]. The second is the total number of inscriptions recorded for each settlement in the Epigraphik-Datenbank Clauss/Slaby (http://db.edcs.eu/epigr/epi.php?_s_sprache=en, accessed 19th January 2017), which we use to characterize the amount of material from which Waltzing’s lists derive. The third is Hanson’s catalogue of cities and towns in the Roman world in the imperial period (Figure 1; described in more detail below) [29], which includes estimates of their inhabited areas that can be converted into population estimates based on densification patterns observed in a subset of these settlements [30]. We combine these three data sources: association counts, inscription counts, and settlement populations, to create an index suitable for testing the expectations of settlement scaling theory regarding the relationship between population and functional (professional) diversity. Below we discuss the details surrounding each data source.
Associations

Although there has been a limited amount of work done on occupations in the ancient world, such studies have tended to be of a general nature, focused on the range of occupations across settlements rather than instances of specific occupations in specific settlements. As a result, it is possible to count occupations but not to determine which ones occurred where. This stems from a tension between the sheer mass of evidence that might provide mentions of occupations, such as texts, inscriptions, papyri, and even graffiti and dipinti, versus the disconnected nature of historical and archaeological research that has been done on individual sites, regions, or classes of material. As a result, scholars are able to identify around 700 occupations for the Roman Empire as a whole, but are only able to count the numbers of occupations in specific settlements for a handful of cases, such as Rome and a few other sites [27, 31-33].

Although it is not currently possible to quantify individual occupations across settlements, it is possible to quantify functional diversity at a more general level by tracking the number of associations mentioned in various sources, most notably inscriptions. These associations were voluntary organizations of craftsmen or traders that were referred to using various terms, the most familiar of which is collegia [34]. These associations were modelled after the local governments of cities and towns; had their own magistrates, councils, and assemblies; and even had their own premises and treasuries. Associations were open to nearly all classes of men (including slaves and ex-slaves), but did not allow women or children. It is also clear that some associations were more influential than others, leading to intense competition between associations for status, as well as to the setting up alliances between associations or to the drawing of distinctions among their own members. Overall, associations were a conspicuous feature of settlements that played an important role in the social make-up of the community [35].

There has been significant debate among classical archaeologists and ancient historians concerning the extent to which associations fostered or defended their members’ economic interests. The traditional
view has been that these bodies were mainly set up for social reasons and had limited economic consequences [36]. However, in recent years there has been a shift in opinion and an increasing appreciation of the roles of social institutions in shaping economies under the influence of New Institutional Economics [37-39]. This work has emphasised the extent to which associations created networks of trust, which were only feasible because of their closed nature, internal traditions, and enforcement mechanisms built on the status and reputations of their members [34]. One would therefore expect these networks to have had economic implications since they helped to strengthen alliances between members, disseminate information, and lead to the sharing of knowledge and skills.

Most scholars have emphasized the multi-dimensional roles of these associations, including: attaining and maintaining social standing; enhancing status and demonstrating wealth; taking part in convivial activities such as drinking and feasting; offering surrogate familial environments to orphans, foreigners, and resident aliens; observing religious rituals, ceremonies, and festivals; ensuring that members had a suitable burial and looking after their memories (such as maintaining their tombs or performing certain rituals after their death); taking part in group attendance at events (although any suspicion of incitement was quickly suppressed); offering legal rights and privileges; and perhaps extending financial assistance. There is also evidence that associations were involved in the following areas: the arrangement of collective work; control of wages; organization of strikes; creation of monopolies; management of their own funds; extension of loans; inhibiting competition; regulating prices; creating and enforcing weights and measures; and taking care of the election and training of apprentices [40].

Based on this work, we expect most crafts and trades to have formed an association, meaning that it is reasonable to treat association diversity as a proxy for the overall diversity of socio-economic activities that occurred within settlements.
However, there are two concerns that need to be addressed before using associations in this manner. The first is whether evidence concerning associations is more or less abundant than evidence concerning specific occupations in the epigraphic record. We expect mentions of the former to be preserved more frequently than the latter due to the relative size, status, and wealth of associations; and the fact that associations regularly set up identifiable memorials for their deceased members. And even if associations were only related to certain sectors of the local economy, association diversity should still be a reasonable proxy for relative functional diversity across settlements. The second issue is whether evidence for associations is consistently preserved across the length and breadth of the Empire. The available information concerning associations is clearly structured by affordances, such as divergences in the epigraphic habits of different times and places (as a result of differences in wealth, education, fashion, acculturation, etc.), levels of preservation, rates of recovery, and levels of investigation by historians and archaeologists. Here, we control for these factors by relating the number of associations identified for each settlement to the number of inscriptions that have been studied, and by standardizing our index of association diversity by imperial province (Figure 2).

To estimate the numbers of associations in individual settlements we have relied mainly on Waltzing’s *Étude historique sur les corporations professionnelles chez les Romains* [28], which was considered ground-breaking when it was originally issued between 1895 and 1900 and which is regarded as the standard work on associations even now. The most relevant information is contained in one detailed list of associations in Rome, Ostia, and Portus and another for the other cities and towns, totalling 802 references to associations across 250 settlements [28, volume IV: 4-49 and 49-128, along with volume II: 145-157]. In addition, there is also some information about the numbers of more informal bodies (which are usually called societas), as well as associations that had an overtly religious or military character. We have not included these because they do not relate to crafts and trades.
Although there is an ongoing attempt to update Waltzing’s database of associations by other researchers, it will be some time before these new resources are available. In the meantime, we have attempted to deal with the most serious issues surrounding Waltzing’s data [41-47], but have not reviewed them in detail. We have adjusted these data slightly, however, by dividing references to associations whose titles encompass more than one trade into separate references for each trade (of which the most common are *fabri*, *centonarii*, and *dendrophori*). The resulting dataset is displayed in Figure 3.

**Inscriptions**

One would expect the number of associations identified as having once existed in a settlement to be a function, not only of the underlying productive diversity of that settlement, but also the number of inscriptions that have been preserved, recovered, and examined from that settlement. To control for these factors, we used the most comprehensive online resource currently available, the Epigraphik-Datenbank Clauss/Slaby (which at the time of writing contains over 500,000 entries), to tabulate the total number of Latin inscriptions recorded for each site. Because it proved difficult to link each inscription to a specific settlement using a name or a region, we linked inscriptions to settlements by associating the findspot of each inscription (given in latitude and longitude coordinates) to the nearest ancient city using a 5km buffer in a GIS. The size of the buffer reflects the relative accuracy and precision of the coordinates for each city. The Epigraphik-Datenbank Clauss/Slaby is an active database that includes more inscriptions than Waltzing had access to, and as a result the relationship between the Waltzing associations count and the Clauss/Slaby inscription count is approximate. Still, the ratio of associations to inscriptions should provide a better sense of association diversity density in a given settlement than the raw count of associations with no attempt to control for sample size (see below). We therefore divide the number of associations by the number of inscriptions for each settlement, generating a ratio, $R$, which effectively provides a measure of the diversity of associations per inscription. There are clearly errors between the sample ratios of associations to inscriptions and their actual, but unknown, population ratios. We would
expect these errors to be independent of settlement population, however, such that they would influence the dispersion of the data around the central tendency of the relationship as opposed to changing the relationship between population and functional diversity itself.

Sizes and populations

The results and analysis presented here presuppose the identification of cities in the Roman Empire which in turn assumes an answer to the seemingly straightforward query of what constitutes a “city”? Answering this question is difficult even for contemporary societies. One influential definition was offered by the sociologist Louis Wirth [48] who noted that a city is a permanent settlement of socially heterogeneous individuals. Architectural historian Spiro Kostof observed that “Cities are places where a certain energized crowding of people takes place” [49:37]. And in his book *Triumph of the City* urban economist Edward Glaeser describes cities as “the absence of physical space between people and companies. They are proximity, density, closeness” [50:6]. These characterizations encompass the perspective, prevalent among many who study modern cities and contemporary urbanization, that the essence of urban life are frequent and intense social interactions among a diversity of individuals and institutions. Settlement scaling theory is premised on similarly seeing cities and settlements across the whole of the urbanization experience as social networks embedded in space.

Operationalizing a view of cities as settings for social interactions, which is to say assembling a set of spatial units of analysis which capture the relevant social aspects of cities, requires choices about the use of existing data, the assignation of data to locations and the delineation of the boundaries of urban areas, all of which are far from trivial even for modern urban systems [7]. When identifying cities, archaeologists and historians must perforce rely on architectural features, artefacts, material culture, and information gleaned from primary or secondary sources to infer the social attributes of “energized crowding”. Here we use the same definition used by Hanson in his recent study of urbanism during the Roman imperial
period, which is based on various criteria for the sizes, monumentality, and civic statuses of each settlement [29]. The criteria include size thresholds of 10 or 50 hectares; the existence of features such as public spaces, associated public buildings, urban grids, leisure and entertainment structures, and religious, sanitary, and defensive structures; and whether they are documented as having had certain roles such as provincial capitals, conventus capitals, metropolis capitals, nome capitals, *coloniae*, *municipia*, *civitates*, and *poleis*, or various other rights and privileges. These features do not coincide perfectly so there are a small number of sites that do not meet the criteria for size but nonetheless have significant monumentality or civic status. We have also restricted the analysis to the region covered by the Roman Empire at its maximum extent in A.D. 117 and the period between the 1st century B.C. and the 3rd century A.D. We have drawn our estimates of the inhabited area of each city from the same resource [29]. To estimate the population of each settlement at its maximal extent, we apply a transfer function developed from a study of the relationship between inhabited area and house density across a sample of settlements dating from about the 4th century B.C. to the 4th century A.D. [30]. The empirical relationship between house density, number of inhabitants, and urban area observed in this study leads to a simple equation that translates the built-up area into an estimate of the population within that area:

\[ N = 41.834 \times A^{1.3361}, \quad (7) \]

where \( N \) is the number of inhabitants and \( A \) is the inhabited area in hectares. Note that this relationship implies that settlements grew denser, on average, as their built areas increased. The empirically-observed relationship between estimated population and area using the resulting estimates turns out to be \( A(N) = .175N^{.634} \), which in turns suggests \( 1 - \delta = .634 \), and thus \( \delta = .366 \sim 1/3 \). We use these population estimates (displayed in Figure 4) as the independent variable in the analyses that follow.

**Index of functional diversity and estimation framework**
The data discussed above provides evidence for a total of 802 associations (range = 1 to 155, average = 3) in 250 sites distributed throughout the Roman Empire. However, since inhabited areas (and therefore populations) and/or inscription totals are not available for all settlements, the dataset with no missing values includes information for 210 settlements. The resulting dataset is available at: http://core.tdar.org/project/392021/social-reactors-project-datasets.

For each settlement in our analysis we have a total number of distinct associations, a total number of inscriptions that have been documented, and an estimated population. We assume that all three values reflect conditions in that settlement during the period of peak occupation, and that inscriptions accumulated for comparable lengths of time across settlements.

We develop an index of professional diversity for Roman cities of the Imperial period in two steps. First, we divide the observed association diversity by the total number of inscriptions to yield the ratio $R$ of association diversity per inscription. This measure is analogous to the concept of species density in ecology (the number of distinct species observed per area or number of individuals examined). This measure has been shown to be problematic in an ecological context due to the asymptotic nature of species-area curves, which imply that the probability of obtaining a previously unobserved species declines as sampling intensity increases [51]. We do not have access to raw counts of mentions of each association type for specific settlements and as a result we are unable to test this possibility directly using rarefaction or its analogues from archaeology [52]. However, the relationship between inscription counts and association diversity across settlements (Figure 5) does not show an asymptotic pattern, but is instead surprisingly linear. This suggests the probability of encountering an additional association type does not decline with sample size in these data. We suspect the reason for this is that associations are only mentioned in a small fraction of inscriptions. As a result, the small probability of drawing an inscription that mentions an association plays a much larger role than the probability that one of these will be a duplicate mention in producing the observed pattern. Given this, it is reasonable to divide the
number of distinct associations mentioned by the number of inscriptions examined to generate a measure of association diversity density that controls for sample size.

Second, we assume that, because most inscriptions were memorials for or dedications to the achievements of specific persons, the number of inscriptions available for a given settlement is a measure of the number of people commemorated over time in that settlement. This in turn implies that the ratio $R$ is proportional to the functional diversity per capita, or $d(N)$, for that settlement. Thus, one can multiply this ratio by the number of inhabitants in each settlement to yield a measure proportional to $D(N)$, the total number of associations that existed in a given settlement during its period of peak occupation. Ultimately, we are interested in is the statistical relationship between $D(N)$ and the population $N$ across settlements, as represented by Equation 6 above. However, due to the fact that we estimate total functional diversity as $D(N) = d(N) \times N$, the population variable is involved in the creation of the dependent variable as well as playing the role of an independent variable. The multicollinearity effects introduced by this procedure makes it imperative to confirm that functional diversity per capita, $d(N)$, also relates to population as predicted by Equation 5. The discussion below describes the regression estimation framework used to arrive at these desired statistical destinations.

The data used in this investigation are for settlements located in different regions of the Roman Empire. Although it is meaningful to speak of is as a single “urban system” in which settlements were linked via political, administrative, juridical, fiscal, and military interactions, such interactions were of course not as strongly integrative as those that bind modern urban systems. Thus it seems plausible to assume that the differences across different region of the Roman Empire modulated a possible common relationship between settlement scale and functional diversity. For example, it is well-known that the so-called “epigraphic habit” was stronger in Latin-speaking provinces than in Greek-speaking provinces [53], and that associations were more important in Latin-speaking than Greek-speaking regions. Since the data sources we utilize focus on Latin inscriptions, one would expect the relative use of Latin to have affected
the underlying rate of inscription production and the rate at which associations are mentioned in these inscriptions. Also, it is likely that the inscription production rate was related to underlying economic conditions, and that these conditions varied across space, in part due to the length of time each region was part of the Empire.

One would expect these factors to introduce heterogeneity to the statistical relationship between functional diversity and population size at the settlement level. For this reason, we use a fixed-effects estimation framework using the province that each settlement was located within as a control variable. This controls for chronological and socio-economic variation, as well as the degree to which Latin was spoken in each region, because province boundaries reflect the history of Roman Imperial expansion. This procedure for obtaining location-specific counts is similar to the “Empirical Bayes Adjustment” method often used in epidemiological studies to generate place-specific counts of infected or diseased individuals on the basis of small samples of infection rates [54, 55]. All estimations were obtained using the AREG routine, which assigns a dummy variable to each province, and controlling for heteroscedasticity in Stata version12SE. Other FE estimation methods yielded similar results.

We estimated four equations, regressing the natural logarithm of the dependent variable against the natural logarithm of settlement population, \( \ln(\text{pop}) \), each of which generates a result of interest in its own right, with the first three equations as steps along the way to the fourth and most important result:

\[
\ln(\text{inscriptions}) = c + \beta_1 \ln(\text{pop}),
\]

\[ (8) \]

\[
\ln(\text{associations}) = c + \beta_2 \ln(\text{pop}),
\]

\[ (9) \]

\[
\ln(R) = c + \beta_3 \ln(\text{pop}),
\]

\[ (10) \]

\[
\ln(D(N)) = c + \beta_4 \ln(\text{pop}).
\]

\[ (11) \]
Concerns that Equation 11 includes the variable for population on both sides of the equals sign (given how the functional diversity measure is calculated) are assuaged by noting that the ratio of associations to inscriptions is specific to each settlement. Multiplying the ratio by settlement population produces an estimate of an aggregate count; Equation 6 postulates a systematic relationship between this count and population across the Roman Empire.

**Results**

Our estimation results are presented in Table 1. In all four analyses the scaling coefficient is statistically significant at the 95% confidence level. The relationship between settlement population and total inscriptions suggests the rate of increase in the inscription rate with population was comparable to the rate of increase of settled area with population (0.642 for inscriptions vs. 0.634 for area). This implies that inscriptions were generated proportionately to the settlement area, not necessarily population, and that one might therefore interpret inscriptions as a sort of information infrastructure in ancient Roman cities. In this scenario, the inscription viewing rate would be proportional to the population density, such that each inscription was viewed more frequently as settlement population and density increased. As a result, fewer inscriptions *per capita* were needed for the social information that they conveyed to percolate through the settlement.

The relationship between functional diversity *per capita* and population is also important in that it shows that the ratio of associations to inscriptions, which we take to be a measure of $d(N)$, declines with settlement population in accordance with the expectations of settlement scaling theory. Specifically, given that the point estimate for the value of $\delta$ for the Roman Empire is .366, based on patterns in housing density, one would expect $d(N)$ to decrease at this same rate as the settlement population grew. This is in fact what we observe, to within a single standard error of the estimate. Note also that the $R^2$ value of this relationship is reasonably high despite the many sources of noise affecting the data.
Finally, our index of total functional diversity in ancient settlements, which we calculate as the total number of associations divided by the total number of inscriptions, times the total population, also scales with population in ways that are predicted by theory. Specifically, the coefficient of this relationship indicates $1 - \delta = 0.671$, and thus that $\delta = 0.329$. This point estimate is once again within a single standard error of the value for delta estimated from housing density.

In sum, despite the many sources of noise in our data, and the many assumptions we must make in turning these data into proxies for functional diversity and population, the fixed-effects relationships between them are all consistent with the theoretical framework presented in this paper, and thus provide empirical evidence that the relationships between settlement population and functional diversity observed in modern urban systems [11], and predicted by settlement scaling theory [5], are also apparent in a pre-modern context—in this case, cities of the Roman Empire. Our results also add support to the assumptions we make in constructing our index of functional diversity, such as the notion that associations provide an index of functional diversity, and that inscriptions were made to honour specific individuals and thus have a connection to settlement demography.

Discussion and conclusions

Although the received wisdom has been that ancient economies were stagnant, there is increasing evidence for a great deal of change throughout the first millennia B.C. and A.D., including extended episodes of growth and decline [56-59]. This has led to an increasing awareness of economic efflorescences in specific regions and periods, including the Greek world and the Roman Empire.

Having said this, even if one grants that there were episodes of economic development in the ancient world, there are still questions about the nature and magnitude of the growth and decline that did occur, how much changed in absolute and relative terms, where and when it happened, how broadly its benefits were felt, what caused and terminated it, and how it compared to later eras. In addressing these
questions it is useful to distinguish two kinds of economic growth: extensive (or aggregate) growth and intensive (or per capita) growth. The first is normally understood as being caused by increases in the factors (inputs) of production or by a simple increase in population, leading to an increase in the total amount of output generated by any economy. The second is usually regarded as being caused by an increase in the efficiency of production, so that each worker creates more goods or provides more services, leading to an increase in the total amount of wealth generated per capita [60]. The second type of growth can in take one of two forms, which have been dubbed “Smithian” vs. “Promethean” growth by modern scholars. The first results from specialization made possible by increases in market size or trade, while the second type of growth is driven by the use of more energy intensive fuel sources or by technological change [61]. In this context, we suggest cities were an important driver of “Smithian” growth in the ancient world due to their ability to concentrate individuals in space and time and therefore enhance the opportunities for them to interact, share resources, exchange skills, knowledge, and ideas, and therefore stimulate economic development.

In this article, we have provided empirical support for the view that cities served as places of “energized crowding” in ancient societies by demonstrating that levels of functional diversity in Roman settlements changed with settlement population, on average, in ways that are consistent with a theoretical perspective that unifies population, density, connectivity, division of labour, and economic outputs. Our results suggest human economies in a wide range of contexts, past and present, evolved in accordance with a single set of social processes related to the structure of human networks and the ways in which their properties change as the number of people who are connected by them grow. These results have important consequences for the scope of application of settlement scaling theory since they not only add credence to the theory itself, but also add credibility to the idea that it applies broadly to both ancient and contemporary contexts [12-15].
Our results, if true, have significant implications for our understanding of the overall trajectory of urbanization and economic development over the very long run, since they suggest urbanism made an important contribution to economic development in both ancient and modern times. Although we do not have adequate data for a chronological analysis, our theoretical framework, and our results, imply that functional diversity did in fact change in accordance with the distribution of settlement sizes over time. There may also have been changes in baseline levels of functional diversity at the same time, but addressing this question will require more abundant and precise data than we have been able to marshal here. Also, despite the fact that we have not measured economic outputs directly, the fact that functional diversity scales with settlement population in a way that implies increases in social connectivity, and thus aggregate outputs, suggests that per capita economic outputs did change through time in accordance with changes in settlement size distributions. Indeed, our results suggest that, if one could track settled areas and inscription rates through time, one should be able to reconstruct not only demographic trends in settlements in non-modern contexts, but also trends in their aggregate outputs through time. We hope progress will be made in these areas in future work.

Acknowledgements

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References Cited

[42] Royden, H.L. 1988 The Magistrates of the Roman professional collegia in Italy from the first to the third century A.D. Pisa.
Table 1. Analysis results.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Inscriptions</th>
<th>Associations</th>
<th>Inscriptions / Associations</th>
<th>$D(N)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.39</td>
<td>-2.147</td>
<td>-1.807</td>
<td>-1.807</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.642</td>
<td>0.368</td>
<td>-0.314</td>
<td>0.668</td>
</tr>
<tr>
<td></td>
<td>(0.089)</td>
<td>(0.048)</td>
<td>(0.077)</td>
<td>(0.073)</td>
</tr>
<tr>
<td>$95% CI$</td>
<td>[0.461, 0.825]</td>
<td>[0.233, 0.424]</td>
<td>[-0.486, -0.141]</td>
<td>[0.613, 0.758]</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.57</td>
<td>0.38</td>
<td>0.59</td>
<td>0.67</td>
</tr>
<tr>
<td>$N$</td>
<td>210</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
</tbody>
</table>
Illustrations

Figure 1: Cities of the Roman world during the Imperial period, adapted from [29].
Figure 2: The provinces of the Roman Empire at the death of Trajan in AD 117, adapted from [29].

Figure 3: The numbers of associations mentioned for cities of the Roman world during the Imperial period.
Figure 4: The estimated numbers of inhabitants in cities of the Roman world during the Imperial period, in thousands, after [30].
Figure 5: The relationship between sample size (number of inscriptions available) and richness (number of distinct associations mentioned) for cities and towns of the Roman imperial period.

\[ y = 0.0016x + 1.8828 \]

\[ R^2 = 0.9445 \]