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Scott G. Ortman
Kaitlyn E. Davis
Jose Lobo
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Luis M. A. Bettencourt
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Scott G. Ortman*[a,b], Kaitlyn E. Davis[a], José Lobo[c], Michael E. Smith[d], Luis M. A. Bettencourt[b], and Aaron Trumbo[a]

Abstract

There is a longstanding debate in anthropology and history regarding the extent to which the determinants of past social and economic change are similar in any specific ways to those that operate today. In this paper, we examine the extent to which increasing returns to settlement scale in material outputs, which are apparent in contemporary urban systems, also operated in the Late Pre-Hispanic Tarma and Mantaro drainages of the Peruvian Central Andes. Proxy measures for material outputs across settlements and households show that this region experienced a marked economic expansion following its incorporation into the Inka Empire ca. 1450 CE. We apply settlement scaling theory to show that changes in the material conditions of life derived primarily from increases in the scale and intensity of local socioeconomic interactions. Our results thus suggest that intensification of human social connectivity and material flows—typically via the growth of settlements—can be sufficient to raise living standards in a variety of contexts.

KEYWORDS: Settlement scaling; Aggregation; Economic change; Wanka; Inka Empire; Andes

[a]Department of Anthropology, University of Colorado Boulder, Boulder, CO 80309-0233

[b]Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501

[c]School of Sustainability, Arizona State University, Tempe. AZ 85287

[d]School of Human Evolution and Social Change, Arizona State University, Tempe, AZ 85287

*Corresponding Author: scott.ortman@colorado.edu

1.0 Introduction

An important question in economic history and related fields is the extent to which human societies experienced economic growth—in the general sense of increased material output per capita and per unit time—prior to the onset of the industrial revolution. A longstanding view is that such changes were rare to nonexistent prior to the 18th century (Galor, 2005, Mokyr, 2006, Wrigley, 2013). However, as empirical data have accumulated it has become clear that many past societies—from Pre-Hispanic Mesoamerica to ancient Greece—did in fact generate substantial increases in material outputs (Allen, 2009, Fouquet and Broadberry, 2015, Scheidel and Friesen, 2009, Stark, et al., 2016) energy capture rates (Morris, 2010, Morris, 2013), farming surpluses (Sanders, et al., 1979), household consumption rates (Jongman, 2014a, Jongman, 2014b), and wealth accumulation (Morris, 2004, Ober, 2010). This growing awareness of the reality of past economic change has led to considerations of the determinants of that change, with proposals ranging from institutional structures (Acemoglu and Robinson, 2012, North, et al., 2009, Ober, 2010) to urbanization (Bowman and Wilson, 2011), expanding long-distance trade (Algaze, 2008, Scheidel, 2008, Temin, 2012) and technological progress (Greene, 2000, Kander, et al., 2014, Smil, 2008). In modern economies, these processes are not independent and none is sufficient to generate steady economic expansion on its own. Thus, the search for deeper mechanisms that articulate various mechanisms of socioeconomic change throughout history remains a topic of great interest.

Here, we consider the extent to which a process often associated with economic development in the modern era— productivity enhancements generated by the concentration of individuals in space (Bloom, et al., 2008, Henderson, 2003, Henderson, 2002, Quigley, 2009)—also operated in pre-modern contexts. Specifically, we analyze an episode of economic change in a portion of the Central Andes following its incorporation into the Inka empire ca. 1450 CE. First, we show that, following incorporation, this region experienced statistically-significant increases in population aggregation and average household wealth. We then use the analytical framework known as *settlement scaling theory* to show that economic change was driven primarily by aggregation effects as opposed to an expansion of long-range trade or technological progress. These findings suggest that increasing returns brought about by settlement growth and proliferation could and did occur even in pre-modern contexts, resulting in increases in various measures of socioeconomic production per capita. They also illustrate that settlement scaling theory can be used to disentangle different component of economic change in archaeological studies of past societies.

2.0 Background

2.1 Previous Research in the Study Region

We analyze archaeological data from the Upper Tarma and Mantaro drainages in the central Andes of Peru (Figure 1). About 1900 km^2 of this region were surveyed as part of the Junin Archaeological Survey Project (JASP) in 1975 and 1976 (Parsons, et al., 2000, Parsons, et al., 2013), and in the subsequent decade the Upper Mantaro Research Project (UMARP) conducted intensive surface studies and excavations at a number of sites in the southern portion of the JASP study area, known as the Mantaro

Valley (Costin, 1986, D'Altroy and Hastorf, 2002, Earle, et al., 1987, Hastorf, 1993, LeBlanc, 1981, Russell, 1988). A combination of excellent architectural preservation, systematic full-coverage survey, targeted excavation and extensive publication of results has resulted in a rich dataset for the investigation of economic change in this region.

The JASP survey determined that most of the archaeological sites in this region date from the *Late Intermediate Period* (1000-1450 CE) and *Late Horizon* (1450-1532 CE) of the Central Andean cultural sequence, with far fewer sites dating to the *Middle Horizon* (500-1000 CE) and earlier. The Late Horizon represents the period during which the region was part of the Inka Empire, and ethnohistoric documents indicate that the people who lived in the region at this time referred to themselves as the *Wanka* (or *Huanca*). Follow-up studies by the UMARP determined that the Late Intermediate Period could be subdivided into two periods on the basis of changes in pottery assemblages. These were labeled Wanka I (1000-1350 CE) and Wanka II (1350-1450 CE), with Wanka III being an alternative designation for the Late Horizon. This refinement was not identified until after the JASP survey, but the majority of Late Intermediate Period sites were found to have been inhabited during Wanka II. We therefore consider sites assigned to the Late Intermediate Period by the JASP as reflecting the period from 1350 to 1450 CE (Wanka II), and sites assigned to the Late Horizon as reflecting the period from 1450 to 1532 (Wanka III), with the end point being the year of the Spanish conquest of the Inka.

JASP surveyors recorded the location, areal extent, and primary function of approximately 650 archaeological sites and 950 temporal components within the surveyed areas. In addition, excellent preservation of stone architecture led to the compilation of substantial architectural data including counts, dimensions, and functional interpretations of large numbers of structures from many sites. Most of the inventoried structures represent portions of domestic residences, but administrative buildings, storage structures, temples, and tombs were also identified on the basis of architectural details such as shape, masonry type, the location and size of doorways, and the spatial arrangements of structures.

We focus here on residential sites, which were identified primarily on the basis of domestic structural remains. *Herding settlements* are associated with stone corrals for keeping domestic camelids and are often located at elevations that are too high for reliable agriculture. *Farming settlements* occur in lower-elevation areas adjacent to arable land and are often associated with agricultural terracing. A*dministrative settlements* are farming sites that also contain public architecture. Surveyors also identified a number of Late Horizon *public storage* sites, containing circular or rectangular structures known as *colcas*, that were designed to provision the Inka administration with local agricultural surplus (D'Altroy and Earle, 1985, D'Altroy and Hastorf, 1984).

Follow-up investigations by the UMARP determined that the building blocks of residential sites in this region were compounds of 1-6 circular or rectangular structures surrounding a central patio (D'Altroy and Hastorf, 2002). These groups of structures were interpreted as houses and labeled *patio groups*. UMARP investigators distinguished "commoner" from "elite" compounds based on variation in: 1) elevation and proximity to public space; 2) construction quality; 3) the number of structures and overall size of the compound; and 4) the presence of rectangular structures that imitate Inka architectural canons (in Late Horizon sites). They also measured the areas of about 100 patio groups at selected sites and excavated portions of about 30, including samples of commoner and elite patio groups dating to the pre-Inka and Inka periods (D'Altroy, 2002a, DeMarrais, 2002).

2.2 Economic change following the Inka expansion

Archaeology and ethno-historic documents indicate that on the eve of the Inka expansion the Wanka region was home to a series of warring local polities centered on large fortified settlements. The Inka expansion led to pacification of the landscape, large-scale resettlement to lower-elevation areas, an increased focus on maize agriculture, and incorporation of the local polities into an inter-regional political economy (D'Altroy and Hastorf, 2002). Table 1 summarizes some of these changes as they are reflected in stone artifact assemblages from the area (data from Russell, 1988 Appendix I). The UMARP research design focused on the economic impacts of these changes for Wanka households.

These studies reached a number of conclusions relevant to our theme. First, the Inka provincial administration was essentially a scaled-up version of traditional Andean community practices in which local lords received labor for their fields, flocks, and houses, and provided hospitality and gifts to their followers in return (D'Altroy, 2002b:325). The Inka appropriated and redistributed agricultural land and then imposed corvée labor requirements such that local people had to work for the state on a variety of productive tasks a certain number of days per year, with the resulting product placed in public storage (*colca*) complexes for state use. In exchange, Inka leaders hosted fiestas involving maize beer in administrative centers and redistributed manufactured goods as gifts to local people (D'Altroy, 2014, D'Altroy and Earle, 1985).

Second, the Inka otherwise took a relatively "hands-off" approach to the local Wanka economy. There were no substantial technological or organizational changes in the production, exchange, and use of stone tools beyond an increased incidence of stone hoes in Late Horizon farming villages, presumably related to an increased emphasis on maize agriculture (see Table 1). Likewise, there were few changes in the organization of pottery production other than increased local production of Inka-style wares during the Late Horizon (Costin, 1986). Finally, despite substantial Inka investment in Imperial transportation infrastructure, long-distance exchange did not expand appreciably during the period of Inka rule (Earle, 2002). Although there is evidence of increased community-level specialization in the production of pottery and textiles, most goods were produced, exchanged and consumed within the Wanka region both before and after the Inka expansion (Costin, 1993, Costin, 2002), and there is no evidence of substantial technological change.

Third, there were substantial differences in wealth and status among Wanka households during both periods. Residences classified as "elite" were associated on average with a greater use of maize (as measured by the ubiquity of deposits with maize), greater meat consumption, higher prevalence of exotic and high-status pottery, greater ubiquities of luxury metal objects, and greater labor investment in architecture (Costin, 2002, Costin and Earle, 1989, DeMarrais, 2002, Hastorf, 2002, Owen, 2002, Sandefur, 2002). Since overall size was a primary criterion for distinguishing "elite" from "commoner" residences, these findings support the use of patio group area as a measure of household wealth, as has been done in a variety of other contexts (Abul-Megd, 2002, Morris, 2004, Ortman, et al., 2015, Smith, 1987). It is also important to note that artifact-based differences between elite and commoner residences were attenuated during the Late Horizon. In general, Late Horizon residences of both statuses appear similar to "elite" Late Intermediate Period residences, although Late Horizon elite residences still score higher on average for most wealth measures. This pattern has been interpreted as evidence for a leveling of status differences in Wanka communities as local leaders came to rely upon Inka administrators for access to prestige goods and political favors (D'Altroy, 2002b).

Finally, Wanka communities experienced a period of substantial economic growth—expressed as increases in material output (Pryor, 2005; Stark et al 2016)—following their incorporation into the Inka Empire. Metal objects, for example, increased in frequency and were more equitably distributed across households during the Late Horizon (Owen, 2002). Spindle whorls, indicative of the spinning of wool into yarn during textile production, almost doubled in density following the Inka expansion (Costin, 1993). Paleobotanical analyses show an increase in the ubiquity of maize and quinoa remains, and slight decreases in potato and legume remains, following the Inka expansion. This was likely due to the reorientation of the population toward maize-farming in lower elevation areas (Hastorf, 2002). Faunal remains show a concomitant increase in meat consumption (Sandefur, 2002), and age-at-death distributions in human skeletal remains indicate a marked improvement in life expectancy (Owen and Norconk, 1987). Collectively, this evidence suggests the material conditions of life improved markedly, despite the apparent *lasses-faire* attitude of the Inka to local economic development.

2.3 Quantifying economic change

We provide additional evidence of economic change associated with the Inka expansion, in a form that allows calculation of annual growth rates, through summaries of the JASP and UMARP settlement and architectural data. Many socioeconomic quantities typically take the form of log-normal distributions in which the raw data are strongly skewed with a long upper tail, but the log-transformed data follow a normal, bell-shaped curve that is well characterized by two parameters: a mean and variance (Gomez-Lievano, et al., 2012) (see Figure 2). The mean of a log-normal distribution provides a simple summary of the average value of the quantity, whereas the variance provides a measure of the skewness in the underlying raw distribution and is related to the better-known Gini coefficient of inequality (Smith, et al., 2014). The mean and variance of a log-transformed socioeconomic quantity thus provide simple summaries of the level and degree of inequality in the distribution of that quantity. Stochastic variables distributed log-normally most naturally arise from multiplicative (that is, strongly interacting) random processes, where several random quantities combine to generate the output of interest (Aitchinson and Brown, 1957, Limpert, et al., 2001, Montroll and Schlesinger, 1982). We take advantage of these features here to quantify changes in aggregation and household wealth from the Late Intermediate Period through the Late Horizon.

Figure 2 displays the distributions of raw and log-transformed settlement areas for the Late Intermediate Period (pre-Inka, 1350-1450 CE) and Late Horizon (Inka, 1450-1532 CE), and Table 2 presents numerical summaries of settlement areas and patio group areas. The table shows, first, that the distributions of settlement areas and patio group areas are approximately log-normal during both periods. Specifically, it is not possible to rule out the null hypothesis that the data are log-normally distributed for these measures. Second, it shows that the mean settlement area increased following the Inka expansion, from an average of 2.0 *ha* to 2.9 *ha*. This is equivalent to a growth rate of .5 percent per year. Third, the mean patio group area increased substantially, from 67.6 m^2 to 134.9 m^2, or a growth rate of .8 percent per year. Importantly, all components of patio group architecture—the number of structures, the floor area of individual structures, the total roofed space, and the patio space—all increased in size (D'Altroy, 2002b, DeMarrais, 2002). Finally, as indicated in Table 1, we find no statistical evidence for a change in the variance of log-transformed settlement areas or patio group areas.

The increase in mean settlement area may seem surprising at first because much of the Late Intermediate Period population resided in two especially large fortified settlements known as Tunanmarca and Hatunmarca. The former was abandoned during the Late Horizon and the latter persisted with a markedly reduced population. Nevertheless, the overall distribution of settlement areas shows that the average individual lived in a larger settlement following the incorporation of Wanka society into the Inka Empire. The increase in mean patio group area, in contrast, is consistent with the wide range of evidence, reviewed above, indicating improvement in average living conditions during the Late Horizon. This is despite the fact that the Inka appropriated portions of Wanka household outputs to fill storage complexes for state, not necessarily local, use (see Figure 1). Table 1 thus provides strong evidence that levels of aggregation as well as living standards increased in Wanka society following the Inka expansion. In the following section, we present a theoretical framework that allows us to assess the relationship between these two forms of change.

3.0 Settlement scaling theory

The specific theory we employ in this study was initially developed to account for empirical regularities in contemporary urban systems (e.g., Bettencourt 2013); however, its basic assumptions are so general that they should apply to Pre-Hispanic Andean settlements just as well as they apply to modern cities. Settlement scaling theory also connects a number of ideas in anthropology and comparative social science in ways that should be congenial to archaeologists. In the following sections we provide a historical background on settlement scaling theory, present its basic constituent models, highlight a few of its connections with broader currents in anthropology, and develop its specific application in the context of this study.

3.1 Background

Research in urban economics and geography has identified a number of relationships between urbanization and economic productivity, innovation rates, energy use and infrastructure needs (Bloom, et al., 2008, Glaeser, et al., 2003, Henderson, 2003, Quigley, 2009). In the past decade, these relationships have been revisited for modern urban systems using scaling analysis. In most basic terms, the scaling approach analyzes how properties of physical, biological, and social systems change with system size (Barenblatt, 2003, Brock, 1999, Brown, et al., 2000, Chave and Levin, 2003). Initial studies focused on *metropolitan areas* that represent human settlements as functional social units, leading to several basic findings. First, there are systematic *economies of scale* with respect to infrastructure and the use of space in modern cities, such that more populous metropolitan areas on average encompass less land area and utilize less urban infrastructure per capita (Bettencourt, 2013). Second, there are systematic *increasing 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, employment in but also crime and infectious disease) in comparison with less populous areas (Bettencourt, et al., 2007a, Bettencourt, et al., 2007b, Bettencourt, et al., 2010). Third, individuals in more populous cities tend to have more social connections than individuals in less populous cities (Schläpfer, et al., 2014). 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., 2014b).

Researchers have been aware of some of these regularities for decades (Batty, 2008, Glaeser and Gottlieb, 2009, Glaeser and Sacerdote, 1999, Nordbeck, 1971, Samaniego and Moses, 2009), but what has not been fully appreciated until recently is that these relationships have characteristic elasticities. So if the functional form of these relationships is $X = X_0 N^{\beta}$, with N representing the city population, the exponent β is typically about 5/6 when X is a measure of infrastructure, and about 7/6 when X is a measure of aggregate interaction or socio-economic output. What this means is that as modern cities grow, their socioeconomic rates increase faster than population, and their infrastructural needs increase more slowly than population. Importantly, these elasticities appear to be open-ended, such that the relative benefits of scale are consistent across many orders of magnitude in city population size.

The manner in which aggregated individuals produce more effectively, innovate more rapidly and utilize infrastructure more efficiently—namely through copying, learning, and the recombination of ideas and knowledge—is easily transposable between modern and pre-modern contexts (Glaeser, 2011, Henrich, 2015). What has been lacking until recently is a formal framework that can account for the many effects of settlement aggregation in such general terms. In the past few years such models have begun to appear (Bettencourt, 2013, Bettencourt, 2014). Several features of these models are new relative to previous work in urban economics and geography. First, they make arguments and predictions about the specific elasticities (scaling exponents) of a variety of urban quantities. Second, they replace the market-based micro-foundations of traditional economics models with a social network where individuals balance interaction benefits with costs. Third, they focus on aggregate (extensive) as opposed to per capita (intensive) measures, noting that traditional per capita measures conflate scale-driven effects with effects deriving from technology and institutions. Finally, these models frame the process of economic development in sufficiently general terms that they potentially apply to societies of the past as well as the present.

The basic ideas embedded in these models are: 1) human settlements are first and foremost concentrations of human interaction; 2) given a set of constraints imposed by technology and institutions, people arrange themselves in space 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 (links between individuals) that occur over a given period of time. These models succeed remarkably well in predicting the average aggregate properties of settlements in modern urban systems. Yet the parameters of these models—the cost of moving around, the average energetic benefit of social interaction, the typical distance traveled per person per unit time, a number of people, and a settled area—are very general and are not tailored to the specific technologies and institutions of the modern world. These models may therefore capture general properties of all human settlements, from the smallest Neolithic villages to modern megacities. The idea that there are systematic relationships between population and a variety of other properties of human settlements may not seem surprising. What we find more remarkable is the notion that mathematical relationships among these properties have specific, predictable values that transcend culture or level of socio-economic development.

3.2 Models

The basic models of settlement scaling theory have been presented in detail in previous publications, and interested readers should turn to these for detailed discussion (Bettencourt, 2013, Bettencourt, 2014, Bettencourt, et al., 2014a, Ortman, et al., 2015, Ortman, et al., 2014). Here, we provide a brief overview of these models, with Table 3 providing a reference for the mathematical symbols and concepts involved. The most fundamental assumption of our approach is that individuals intuitively arrange themselves within settlements so as to balance the costs of moving around with the benefits that accrue from the resulting social interactions. If the average cost for a person to interact with others by taking relatively straight paths across a small and amorphous settlement is given by $c = \varepsilon A^{1/2}$ (where ε is the energetic cost of movement and A is the circumscribing area); and the benefit of the resulting interactions is given by $y = \hat{g} a_0 l N/A$ (where $\hat{g}$ is the average productivity of an interaction, a_0 is the interaction distance, l is the average path length of an individual, and N/A is the average population density of the settlement); then by setting $c = y$ one arrives at $A(N) = (G/\varepsilon)^{2/3} N^{2/3}$, where $G = \hat{g} a_0 l$. Thus, in a given context, the area taken up by relatively amorphous settlements grows proportionately to the settlement population raised to the $\alpha = 2/3$ power. Note also that the coefficient or pre-factor of this relationship $a = (G/\varepsilon)^{2/3}$ varies in accordance with the productivity of interactions and transportation costs, but is independent of population.

However, in larger and more organized settlements, interaction occurs through movement within the access network of roads, paths and other public spaces as opposed to straight paths. So if one assumes space devoted to the access network d is added in accordance with the current population density, such that $d = (N/A)^{-1/2}$, then the total area of the access network $A_n \sim Nd = A^{1/2} N^{1/2}$. Substituting $aN^{2/3}$ for A in this equation, based on the relationship derived previously, then leads to $A_n \sim a^{1/2} N^{5/6}$. In other words, as settlements in a given context grow interaction becomes increasingly structured by the access network, and as a result the area taken up by networked settlements grows proportionately to the settlement population raised to the $\alpha = 5/6$ power. In both cases there is a clear economy of scale such that larger settlements grow increasingly dense, but the densification rate declines slightly, from $\alpha = 2/3 \rightarrow 5/6$, as settlements grow in size and formality.

Now, assuming the total socio-economic output Y of a settlement is proportional to the total number of social interactions its inhabitants experience per unit time, and that human social networks involve as much mixing as possible given spatial constraints, we can write $Y(N) = GN(N-1)/A \approx GN^2/A$, and one can compute the expected scaling of outputs relative to population by substituting $aN^{2/3}$ for A in the case of amorphous settlements, and $a^{1/2} N^{5/6}$ for A in the case of networked settlements. This leads to $Y(N) \propto N^{2-\alpha}$, with $2/3 \leq \alpha \leq 5/6$. This in turn implies that the average per capita output

$y = Y/N \propto N^{\delta}$, with $1/6 \leq \delta \leq 1/3$. This means that as human settlements increase in population their average per capita socio-economic outputs grow proportionately to population raised to the δ power, and total outputs grow proportionately to population raised to the $1+\delta$ power. In other words, there are increasing returns to scale such that more populous settlements are more productive overall.

Finally, if one assumes each individual requires access to a certain number of functions F and that increasing average connectivity per person k makes it possible for each individual to specialize in a decreasing range of functions per person d, then the product $k(N) \times d(N) = F$, with F a constant independent of N, and we can see that increasing connectivity enables increasing functional specialization, so that if $k(N) = K(N)/N = k_0 N^{\delta}$ then $d(N) = (F/k_0)N^{-\delta}$ and the total productive diversity $D(N) = (F/k_0)N^{1-\delta}$. Thus, as human settlements grow the total range of functions performed by individuals grows proportionately to population raised to the $1-\delta$ power. This means that new functions are added more slowly than people, and as a result settlements become more connected and diverse as they grow, but with each individual becoming increasingly specialized.

3.3 Connections with anthropology

Several strands of research in anthropology and related social sciences support the notion that settlement scaling theory—as described above—provides a useful framework for investigating premodern settlement systems as well as modern ones. For example, there is a long-standing line of research that considers the role of population size in generating a variety of social outcomes. Cross-cultural studies regularly identify a strong correlation between the size of a society and its organizational complexity (Carneiro, 1962, Carneiro, 1967, Chick, 1997, Feinman, 2011, Naroll, 1956, Peregrine, 2003). While most archaeologists today avoid assigning a causal role to population pressure or to population growth in the evolution of socio-political complexity, the basic idea of a correlation between population and social complexity is a well-established empirical regularity. A number of archaeologists have also explored the concept of *scalar stress,* which refers to psychological and organizational stresses that develop as the number of decision-making units in a society grows (Alberti, 2014, Fletcher, 1995, Johnson, 1982). The size and density of population in a region clearly has an effect on other aspects of society. Settlement scaling theory expands on these areas of research in two ways: it focuses on settlements, not societies; and it makes predictions about the specific quantitative effects of population for other social properties.

There is also a growing recognition that changing population size has similar social effects in both village and urban settlement systems. For example, several chapters in Birch (2013) identify generative outcomes of settlement aggregation in villages that parallel the effects of urbanization. Jennings (2016) disentangles the process of urbanization and state formation and identifies cases where aggregation and urbanization preceded, and contributed to, state formation, through the institutional requirements of accommodating larger populations in settlements. Finally, in a different approach, Smith et al. (2015) show that neighborhood organization is universal not only among cities, but also in agrarian and even hunter-gatherer aggregation sites. Their conclusions are that whenever sufficient people aggregate in one place—even temporarily—neighborhoods will form, and that this process is independent of the "urban" status of the settlement. These two strands of research suggest that the underlying assumptions and parameters of settlement scaling theory, particularly the derivation of scaling exponents from social network properties as opposed to market-based utility functions, are broadly consistent with existing research in archaeology and anthropology (Feinman, 2011).

Finally, Ortman and others (2015, 2014) have previously shown that several quantitative predictions of settlement scaling theory are borne out by data from the Pre-Hispanic Basin of Mexico; and more recent studies have found that these properties are also evident in small-scale farming villages and Medieval European cities (Cesaretti, et al., n.d., Ortman and Coffey, 2015). These results support the notion that settlement scaling theory applies equally well to the smaller-scale settlement systems of the past as it does to modern urban systems. Here, we apply this same framework to Late Pre-Hispanic settlements of the Upper Tarma and Mantaro drainages. The Pre-Hispanic Andes provides a particularly important test of the theory because scholars from Karl Marx to the present have remarked on the lack of markets and commercial institutions in the Pre-Hispanic Andes (D'Altroy, 2014:393, Isaac, 2013). This feature contrasts with the Basin of Mexico and Medieval Europe, both of which had commercialized economies (Smith, 2004). So the identification of scaling regularities in Pre-Hispanic Andean settlement systems would provide strong support for the notion that these patterns are generated from emergent properties of social networks and not from the institutions of capitalist or commercial economies.

3.4 Expectations

The models discussed in Section 3.2 lead to a series of quantitative expectations for the settlement data compiled by the JASP. First, one would expect the model for amorphous settlements to be most applicable. The settlements documented by these projects contain fewer than 5,000 structures, and only a few of the largest villages contain evidence of formalized paths that facilitated within-settlement movement (DeMarrais, 2002). In addition, the best population proxy in these data is the total number of residential structures estimated for the settlement. So if population is measured in terms of structures, one would expect the average relationship between structure count N and settlement area A to be $A = aN^{\alpha}$, with $\alpha \approx 2/3$ and a reflecting the average area taken up by the smallest settlements.

Second, because the productivity of a household can be assumed to be proportional to the number of interactions its members have with others outside the household, households in larger settlements should be more productive on average. Given that house area provides a good proxy for household wealth in a number of settings (Abul-Megd, 2002, Blanton, 1994, Bodley, 2003:97, Castro, et al., 1981, Maschner and Bentley, 2003, Morris, 2004, Olson and Smith, 2016), household productivity can be measured in terms of the roofed space in which household members lived and in which household production was stored. So one would expect average structure area to increase with settlement structure count according to $y = y_0 N^{\delta}$, with $1/6 \leq \delta \leq 1/3$ and y_0 reflecting the average area of a structure in the smallest settlements. In turn, one would expect the total productivity, or the area encompassed by houses in a settlement, to vary with structure count according to $Y = Y_0 N^{1+\delta}$, where Y_0 reflects the average roofed space in a settlement containing only a single structure.

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 is accomplished through movement 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 $y = G\,N/A = G\,N/aN^{2/3} \propto N^{1/3}$. However, even in amorphous settlements, movement can become constrained by the distribution of structures, and one would expect this constraint to increase as the size and density of the settlement increases, even when space is not explicitly set aside for an access network. Under these conditions, paths across the settlement become progressively less straight and thus longer than the transverse dimension. Thus, in compact settlements, 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 $y = G\,N/A = G\,N/aN^{5/6} \propto N^{1/6}$. Thus, the value of δ may be close to 1/6 even if $\alpha \approx 2/3$ in such settlements.

Third, given that per capita productivity $y = G\,N/A$ 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 N. G can be estimated for individual settlements as $G_i = y_i A_i/N_i$, and although one would expect this quantity 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 N and G should be approximately zero, the correlation between these two variables should also be approximately zero, and the regression between the two should not be statistically significant.

A final set of expectations derives from the way settlement scaling theory incorporates and reconfigures a variety of ideas about economic growth (as defined above). In discussing these it is helpful to imagine a scatterplot that compares a population measure with an output measure across settlements, on log-log axes, and with a best-fit line representing the scaling relation. Our theory proposes that settlement systems can change in one of two ways over time: 1) the position of settlements can move along the scaling relation (i.e. along the best-fit line of a scaling plot); or 2) the overall height of the scaling relationship (i.e. the y-intercept of the best fit-line) can move up or down. According to theory, the first type of growth derives from an increase in the level of aggregation, whereas the second derives from changes in the parameters incorporated into scaling pre-factors, including the cost of movement and the benefit of social interaction. The first type of growth is typically called extensive growth, which means an increase in total output due to increases in population or territory. Well-known to archaeologists in the form of Boserupian intensification (Boserup, 1965), extensive growth is not accompanied by per-capita increases in output. Intensive growth, in contrast, is defined as an increase in both per capita and total output (Goldstone, 2002, Jones, 2000).

The results reviewed in Sections 2.2 and 2.3 indicate that the Wanka region experienced substantial increases in aggregation and productivity following its incorporation into the Inka Empire. Settlement scaling theory provides a means of testing whether these two forms of growth were linked. If the pre-factor of the scaling relationship between population and total output changed from the Late Intermediate Period to the Late Horizon this would indicate that economic change was due at least partly to intensive growth. If this pre-factor remained constant, on the other hand, it would indicate that the changes discussed in Section 2.3 primarily reflect extensive growth.

3.5 Analyses

We evaluate the expectations in Section 3.4 by estimating a, y_0, Y_0, α and δ through ordinary least-squares regression of the log-transformed data. This is feasible because $X(N) = X_0 N^{\beta}$ and $\log X(N) = \beta \log N + \log X_0$ are equivalent. In all cases, the proxy for population N_i is the total number of residential structures estimated for site i. This number represents either a direct count of structures observed or an extrapolation based on the residential structure density in well-preserved portions of the site (Parsons, et al., 2000, Parsons, et al., 2013). Residential structure counts are only available for about fifteen percent of the recorded site components, but these estimates vary over more than four orders of magnitude (1 to 4750), and in all cases sample sizes are sufficient to satisfy the central limit theorem that comes into play in estimating regression parameters.

The proxy for per capita output y_i is the mean floor area of residential structures for which dimensions are recorded in the survey data. This is reasonable in this context because the unit of population is also the individual structure. In a few sites this mean is calculated from a sample of individually-measured structures, but in most cases it represents a weighted average of the counts and mean dimensions of groups of similar structures identified during the survey. The proxy for total output Y_i is thus the estimated total roofed residential space in the settlement, $y_i N_i$. We also calculate a measure of G_i for individual settlements by multiplying the mean structure area by the settled area and then dividing by the total residential structure count, and then we compare this measure with the structure count to assess the potential independence of G and N.

In our analyses of population vs. settled area we distinguish camelid herding settlements from farming and administrative settlements due to the fact that the former incorporate corrals in which camelid herds of the residents were kept overnight. Such corrals could be spatially-extensive but are rare in farming and administrative settlements. Thus, there is prior reason to believe the baseline area per person was greater in herding settlements than it was in other settlement types. In the discussion that follows we use the label “farming” to refer to both farming and administrative settlements, taken collectively.

Finally, we conduct an analysis of variance of the exponents and pre-factors of the estimated scaling relations for functionally distinct groups of settlements, and for settlements dating before and after the Inka expansion, to determine whether these parameters vary across settlement types and through time.

4.0 Results

Scaling analyses for various subsets of the JASP data are presented in Table 4. The results show that the predictions of settlement scaling theory are borne out in all cases for these data.

First, the exponent α for the relationship between residential structure count N and settled area A is approximately 2/3 for both herding and farming settlements. The regressions are statistically significant and account for a reasonable proportion of the total variance in the samples, and the residuals to the best-fit line appear normally distributed. It is also interesting that point estimates of the scaling pre-factor a suggest the baseline area per residential structure is somewhat larger in herding settlements than it is in farming settlements (see Figure 2). However, the standard error of the estimate for the herding sites is quite broad. This may be due to a situation where the number of animals corralled at a site varied somewhat independently of the number of resident people. This suggestion is supported by a linear regression of the residuals from the population-area analysis vs. the total area encompassed by camelid corrals in well-preserved herding sites (N=11, r^2=.738, F=33.799, P<.000). This result, combined with the consistent scaling exponents, suggests camelid corrals were designed to enclose a consistent area per animal; or at least, were not designed to facilitate social mixing of camelids. Nevertheless, the fact that the area per person declines on average with population across herding settlements suggests that these settlements formed to facilitate social interactions among their human residents.

Second, the point estimate of the scaling exponent δ for the relationship between residential structure count N and mean structure area y (and thus for the exponent $1+\delta$ between N and Y) is within one standard error of 1/6 (or 7/6). The r-squared value for the relationship between N and y is fairly low due to the shallow slope of the best-fit line, but the regression is significant and the residuals are roughly normally distributed. The relationship between N and Y is shown in Figure 3. These results show that Pre-Hispanic Andean settlements exhibit the same average returns to scale in socio-economic outputs observed in contemporary cities, despite being several orders of magnitude smaller in size, and despite the absence of a commercialized or monetized economy.

Third, there is no evidence for a relationship between N and G, as estimated via $G_i = y_i A_i / N_i$, for either farming or herding settlements. The 95% confidence interval for the exponent of the scaling relation includes zero in both cases, the regressions are not significant, and the r-squared values are extremely low. Since G also represents the baseline (in the absence of scale effects) average energetic benefit of social interaction in this society, these results indicate that the productivity of each interaction did not vary with settlement population. This evidence, in turn, supports our interpretation that increasing returns derived from increased human connectivity as opposed to increasing productivity of individual interactions.

Finally, Table 5 presents the results of an analysis of variance in scaling exponents and pre-factors for (A) the population-area relationship for farming vs. herding settlements; and (B) the population-roofed space relationship for Late Intermediate Period vs. Late Horizon settlements. The table shows that in every case the F-statistic is too small to conclude that scaling exponents or pre-factors vary across the compared groups. This is despite the fact that the individual regressions are each significant at the P<.000 level. These results indicate that the data are insufficient to rule out the possibility that differences in the pre-factor of the relationship for farming vs. herding settlements are due to sampling error. They also show that here is no evidence of change in the pre-factor of the population-output relationship through time. This is a striking result because it suggests the socioeconomic changes observed in Wanka society following the Inka expansion were due primarily to extensive or scale-driven growth associated with settlement formation and growth and not with more fundamental, intensive, “technological” change.

5.0 Discussion

We have shown that Late Pre-Hispanic, pre-industrial and non-urban settlements of the Central Andes exhibit relative scaling properties that are analogous to those observed in contemporary cities and other historical settlement systems and which are explained by settlement scaling theory. Similar results have been obtained for Pre-Hispanic Central Mexican settlements (Ortman, et al., 2015, Ortman, et al., 2014), but in a number of ways these Central Andean data provide an even stronger test of the theory. First, the Central Andean sites are in general better preserved and the population proxy—residential structure count—avoids the problem of correlating surface artifact density with population density that plagues the Central Mexican data (see Parsons, 2008:52-58 for discussion). Second, the socioeconomic context of the Central Andes is even more divergent from the modern socioeconomic context than is the Pre-Hispanic Basin of Mexico. The Mantaro sites are smaller than the Mesoamerican sites, confirming that scaling processes operate beyond the realm of large urban centers. And perhaps more importantly, the lack of markets and commercial institutions in this area extends the scaling regularities into societies with very different economic organization than modern urban systems.

These results thus provide striking support for the hypothesis that settlement scaling theory captures basic properties of human settlements as social networks embedded in space. The exponents of the scaling relations appear to be common to settlement systems regardless of the socioeconomic and cultural context in which such systems are realized, whereas the pre-factors (i.e., the constants in the regression equation) can vary with context in accordance with the specific technological, geographic and organizational factors that affect the costs of movement and benefits of social interaction. The theory thus accounts for both predictable regularities (exponents) and historical contingencies (pre-factors and deviations) in a single theoretical framework. That a single approach might accommodate both constraint and variation in the empirical analysis of human societies is a striking prospect for archaeology and other social sciences.

We have also employed settlement scaling theory to highlight two different types of economic change and to illustrate how one can distinguish between then using data from a specific historical case. Previous studies of the archaeological sites in the Upper Tarma and Mantaro regions have shown that Wanka society experienced a marked improvement in living conditions (larger house areas, longer life-expectancy, more meat consumption, greater ubiquities of luxury goods) following its incorporation into the Inka Empire, despite experiencing increased taxation in the form of corvée labor requirements, no significant technological progress, and no appreciable expansion in inter-regional trade. Given this, improved living conditions appear to have been driven almost exclusively by extensive growth, through increases in the average connectivity of individuals associated with increases in the average size and resident population of settlements. We can rule out intensive growth as a causal factor because settlements dating from before and after the Inka expansion follow the same population-output scaling relation characterized by a single pre-factor. In fact, we can use the scaling relations estimated in Table 4 to show that the observed changes in Table 2 are closely related. The mean farming/administrative settlement areas in Table 2A can be converted to mean settlement populations using the population-area relation in Table 4, and then converted to a mean output via the population-output relation. The resulting differences imply an average annual growth rate of .7 percent per year over the 82 years between the Inka and Spanish conquests of the area. This rate compares favorably to the .8 percent growth rate calculated on the basis of the increase in mean patio group areas in Table 2B, and implies that most if not all of the growth experienced by Wanka society was in fact extensive or scale-driven.

Ultimately, then, economic change in the Upper Tarma and Mantaro drainages should be viewed as having been driven by factors that promoted increased social connectivity among individuals. Inka pacification of the landscape was probably a major factor because it enabled Wanka households to spread out more evenly across productive agricultural land, resulting in a decrease in the maximum settlement size but an increase in the mean settlement size, and thus average social connectivity, across the region. Increases in community specialization (Costin, 1993, Costin, 2002, Costin and Earle, 1989) were also likely related to this process. Scholarship on economic growth distinguishes between growth fueled by changes in technology vs. 'Smithian growth", which is driven by changes in social organization, institutions, an expansion of the division of labor, learning among producers and even cultural transformations (Arrow, 1994, Goldstone, 2002, Kelly, 1997, Mokyr, 2006, Morris, 2013, Smil, 2008, Wrigley, 2013). Empirically it has proven challenging to identify episodes of economic growth in which it is possible to control for technological change. The findings reported here are thus important because they indicate that changes in the social milieu of a pre-modern society, and concomitant increase in average social connectivity among individuals, were sufficient to raise living standards in the absence of technological progress or expanding long-distance trade. In short, our results provide evidence that Smithian growth really does occur and has been responsible for improvements in living conditions in past societies.

6.0 Conclusions

We have examined an episode of economic change from the Late Pre-Hispanic Central Andes. Previous studies indicate this region experienced significant improvements in living conditions following its incorporation into the Inka Empire, and survey data from the region allow us to quantify the associated growth rates in settlement aggregation and household wealth. We have utilized settlement scaling theory to show that the system of settlements in this specific region and period exhibit the same scaling properties observed in modern urban systems and other past societies. We have utilized this same theory to show that in this case economic expansion was almost entirely due to inferred increased social connectivity, associated with an increase in mean settlement size, resulting from a pacified landscape.

Additional studies along similar lines will be necessary to determine whether intensive growth, of the kind observed in industrialized economies of the past few centuries, was rapid enough in pre-industrial settings to have made a difference on a human time-scale. Such studies will require longitudinal and cross-sectional data consisting of settlement areas, population proxy measures, and aggregate socio-economic quantities for large samples of settlements that vary over several orders of magnitude, similar to the Central Andean data examined here.

Our results are of interest because they extend the scaling framework to small settlements set in a non-commercial economy and add support to the hypothesis that settlement scaling theory captures several fundamental properties of all human settlements regardless of time, place, culture, technology, or level of socio-economic development. They also add support to the view that economic growth did occur in the past, and that increases in aggregation and associated human connectivity can be sufficient to raise living standards in a variety of contexts, both modern and pre-modern. Finally, our results provide additional evidence that the archaeological record provides a vast and largely untapped resource for disentangling the determinants of economic change and measuring their relative effects.

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Table 1. Changes in stone tool assemblages over time.[1]

Functional category	**Late Intermediate (1350-1450 CE)**		**Late Horizon (1450-1532 CE)**	
	Count	Prop.	Count	Prop.
Agricultural tools (hoes)[2]	35	.0021	197	.0158
Manufacturing debris	5,260	.3130	3,850	.3091
Ornaments	22	.0013	31	.0025
Pounding and grinding tools	267	.0159	170	.0136
Prismatic blades[2]	1,589	.0946	818	.0657
Weapons (axes, discoids, bolas, projectile points)[2]	35	.0021	17	.0014
Other tools[2]	9,597	.5711	7,372	.5919
Total	16,805	1.000	12,455	1.000

[1]Data are counts of stone artifacts falling into various functional categories in artifact assemblages from UMARP excavations (Russell 1988: Appendix I).

[2]These proportional differences across time periods do not overlap at two standard errors (P<.05).

Table 2. Evidence of economic change following the Inka expansion.

Units	**Measure**	**Late Intermediate (1350-1450 CE)**	**Late Horizon (1450-1532 CE)**
A. Farming/ Administrative Settlements[1]	Sample size	184	116
	Mean of Log[area] *(S.E.)*[2]	.3001 (.036)	.4622 (.044)
	Variance of Log[area][3]	.247	.228
	Normality tests for Log[area][4]	K-S *P*>.2; S-W *P*=.303	K-S *P*>.2; S-W *P*=.668
B. Patio Groups[5]	Sample size	82	13
	Mean of Log[area] *(S.E.)*[6]	1.8337 (.024)	2.1348 (.063)
	Variance of Log[area][7]	.047	.053
	Normality tests for Log[area][4]	K-S *P*=.069; S-W *P*=.205	K-S *P*>.2; S-W *P*=.866

[1]Excludes herding and storage sites; measures are in hectares.
[2]These means are significantly different (One-way ANOVA *F*=7.789, *P* = .006).
[3]These variances are not distinguishable (Levene's test *P* = .515).
[4]In all cases, it is not possible to reject the null hypothesis that the distribution is log-normal.
[5]Patio groups represent households consisting of 1-6 structures surrounding a courtyard; measures are in square meters.
[6]These means are significantly different (One-way ANOVA *F*=21.242, *P* = .000).
[7]These variances are not distinguishable (Levene's test *P* = .579).

Table 3. Definitions of symbols in settlement scaling models.

Symbol	Definition	Symbol	Definition
c	average cost of interaction per unit time	l	the average length of the path taken by an individual per unit time
ε	cost of movement per unit length and unit time	N	the population of a settlement
A	circumscribing area of a settlement	G	the total productivity of interaction across all modes per unit time
y, y_0	benefit from interaction per capita and per unit time; the benefit per person of the smallest settlements in a region	α	the exponent of the population-area scaling relationship
$\hat{g}$	average productivity of an interaction across all modes per unit time	a	the area per person in the smallest settlements in a region; ; the pre-factor of the population-area relationship
a_0	the distance at which interaction takes place	d	the space devoted to the access network that is added for each increase in N
Y, Y_0	the total benefit from interaction across the population per unit time; the total benefit of the smallest settlements in a region	A_n	the total area taken up by the access network
δ	the elasticity (deviation from linearity) in the population-output relationship	F	the total number of functions an individual requires access to
k, k_0	the average connectivity (number of social links, or out-degree) per person; per capita connectivity of the smallest settlements in a region	K	the total number of links between individuals in a settlement
d	the average number of productive activities performed by a person	D	the total number of productive activities performed in a settlement

Table 4. Scaling analysis results.[1]

Settlement Group	**Dependent Variable**[2]	**Sample**	**Exponent *(S.E.)***	**Pre-factor *(S.E.)***	**F-Statistic (*P*)**	**R^2**	**Residuals**[3]
Farming/ Administrative	Settled area (ha)	57	α=.696 (.065)	a=.167 (.040)	116.144 (.000)	.679	K-S *P*>.2; S-W *P*=.730
Herding	Settled area (ha)	39	α=.655 (.158)	a=.285 (.111)	17.237 (.000)	.318	K-S *P*>.2; S-W *P*=.475
All	Domestic structure size *y* (m^2)	91	δ=.139 (.037)	y_0=8.00 (1.05)	13.194 (.000)	.135	K-S *P*>.2; S-W *P*=.421
All	Total roofed domestic space *yN* (m^2)	91	1+δ=1.139 (.037)	Y_0=8.00 (1.05)	931.338 (.000)	.913	K-S *P*>.2; S-W *P*=.421
Farming/ Administrative	*G=y*A/N*	51	*γ*=-.126 (.074)	G_0=1.905 (.509)	2.885 (.096)	.056	K-S *P*>.2; S-W *P*=.683
Herding	*G=y*A/N*	39	*γ*=-.136 (.172)	G_0=1.862 (.775)	.622 (.435)	.017	K-S *P*=.144; S-W *P*=.549

[1]Results are from ordinary least-squared regression of the log-transformed data.
[2]The independent variable in all cases is total residential structure count, a proxy for *N*.
[3]In all cases it is not possible to reject the null hypothesis that the residuals are normally-distributed.

Table 5. ANOVA of scaling results.*

Analysis	**Settlement group**	**Sample**	***a (S.E.)***	***b (S.E.)***	***r^2***	***P (F-test)***
A. Area by function						
	Farming/Administrative	57	.696 (.065)	-.777 (.119)	.679	.000
	Herding	39	.655 (.158)	-.544 (.214)	.318	.000
	F-Statistic		.0245	.1858		
	P		1.0	.998		
B. Roofed space by period						
	Late Intermediate	70	1.147 (.040)	.872 (.064)	.925	.000
	Late Horizon	17	.998 (.082)	1.262 (.139)	.908	.000
	F-Statistic		2.1221	.6096		
	P		.374	.800		

*Ordinary least-squares regression of the log-transformed data ([log y] = a [log x] + b), thus $y = 10^b x^a$.

Figure 1. The Upper Tarma and Mantaro Region, with surveyed areas and settlement distributions for the Late Intermediate Period, left, and the Late Horizon, right. Insert at upper right shows the location of the study area within Peru.

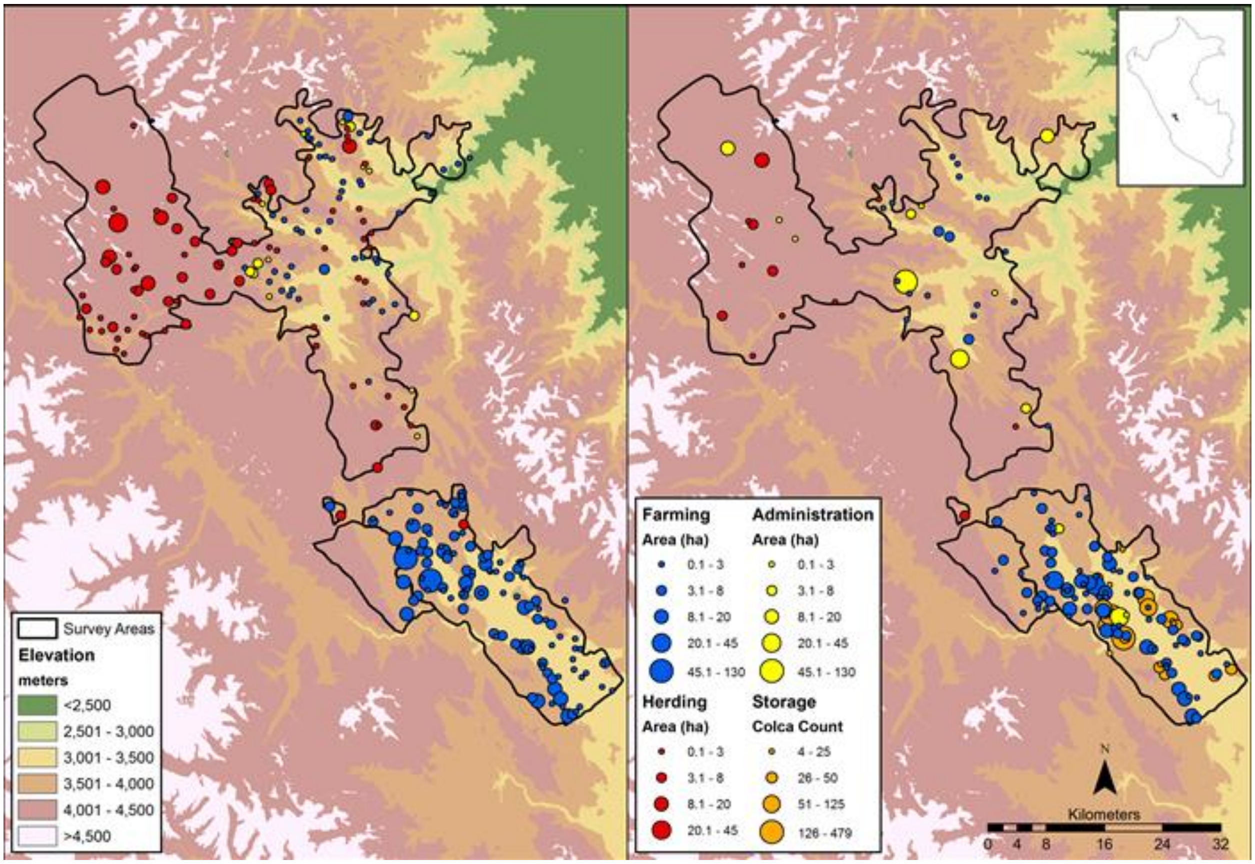


Figure 2. Histograms of raw and log-transformed areas for farming and administrative settlements.

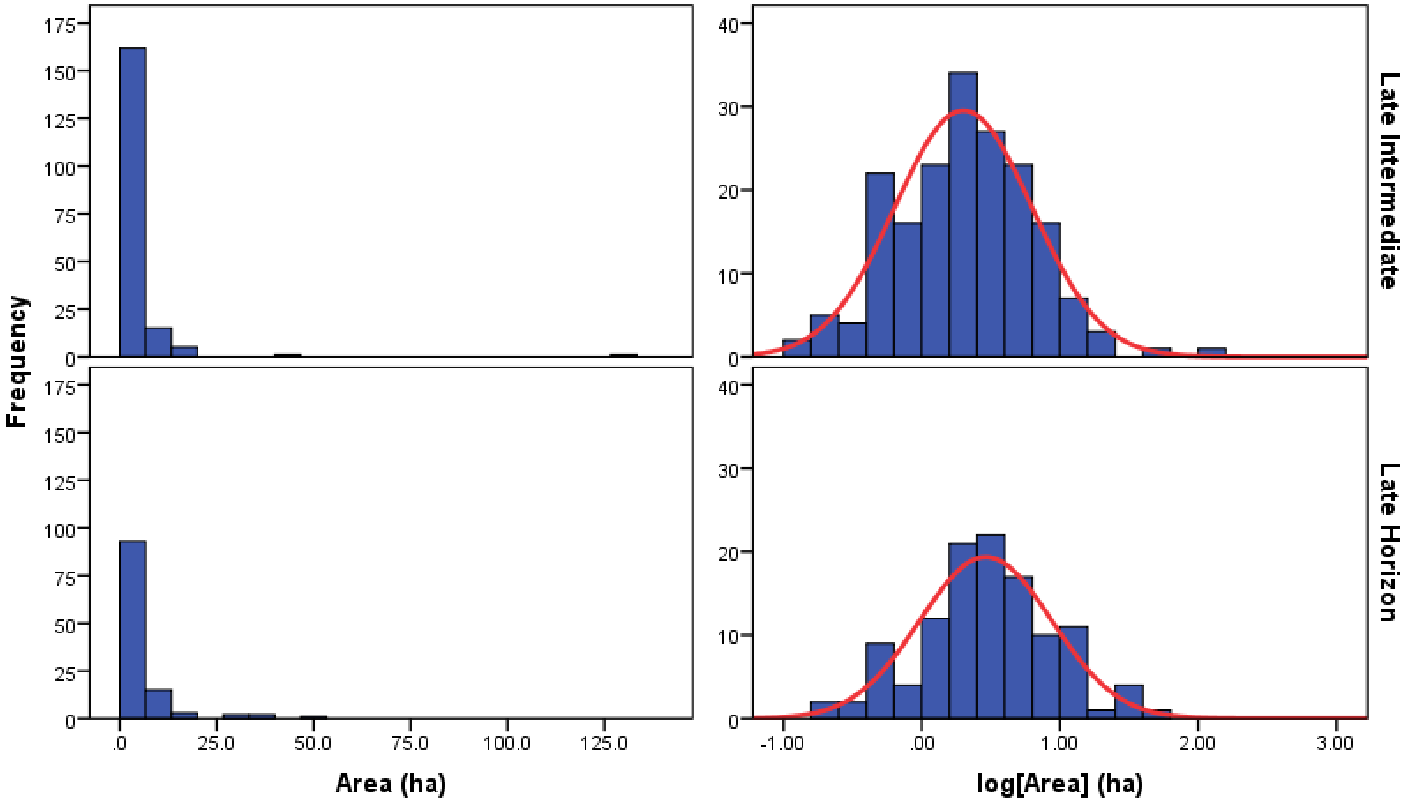


Figure 3. Relationship between population and settled area.

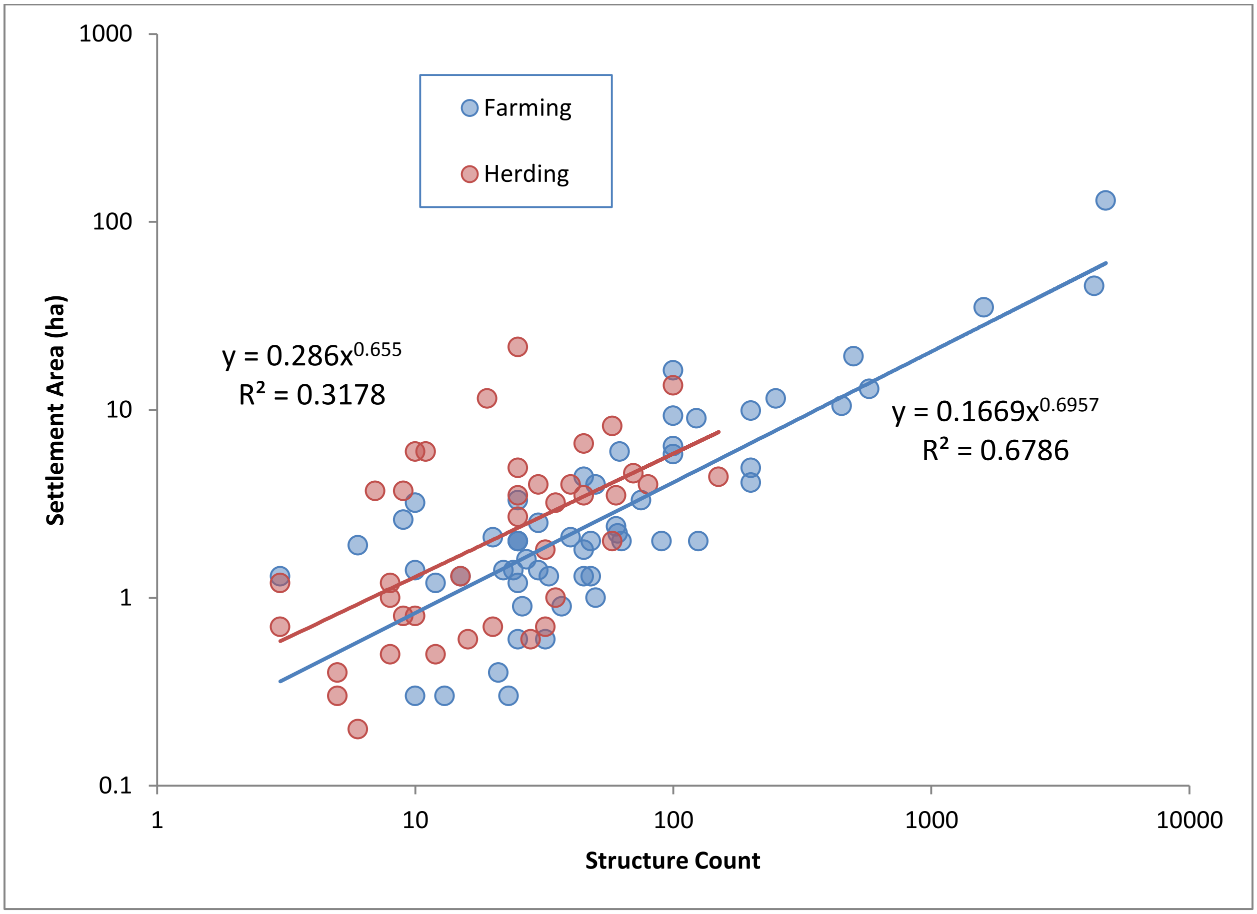
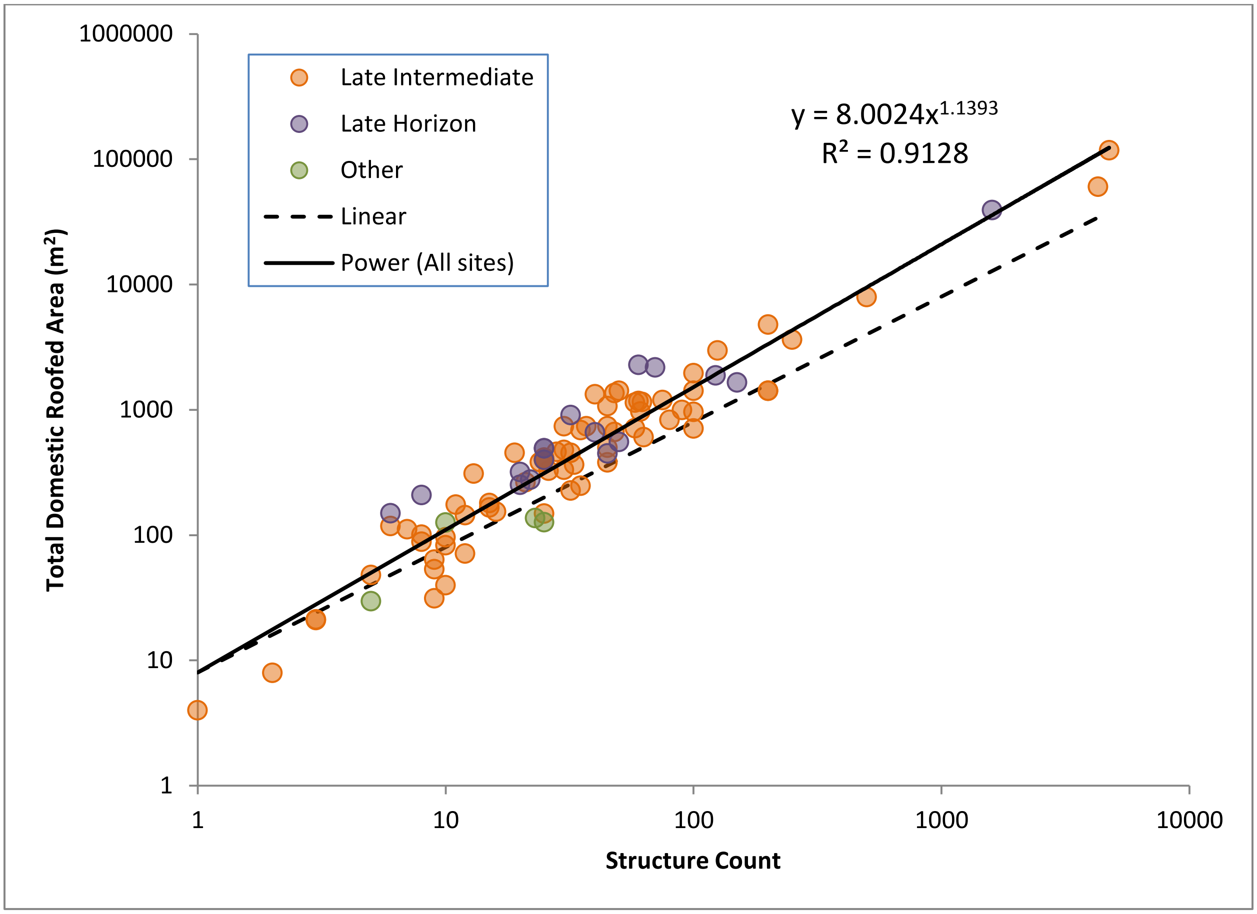


Figure 4. Relationship between population and total roofed space.



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