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Culture process and the interpretation of radiocarbon data

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Abstract

Over the last decade archaeologists have turned to large radiocarbon data sets to infer prehistoric population size and change. An outstanding question concerns just how direct of an estimate radiocarbon dates are for human populations. In this paper we propose that radiocarbon dates are a better estimate of energy consumption, rather than a direct one-to-one estimate of population size. We use a scaling model to describe the relationship between population size, economic complexity and energy consumption in human societies, and then parametrize the model using data from modern contexts. Our results suggest that energy consumption scales sub-linearly with population size, which means that the analysis of a large radiocarbon time-series has the potential to misestimate rates of population change and absolute population size. Energy consumption is also an exponential function of economic complexity. Thus, the radiocarbon record could change semi-independent of population as complexity grows or declines. Scaling models are an important tool for stimulating future research to tease apart the different effects of population and social complexity on energy consumption, and begin to explain variation in the forms of radiocarbon date time-series in different regions.

Keywords: Prehistoric Demography, Summed Probability Distribution, Macroecology, Deep-time Economics

Introduction

The objective of this paper is to critically discuss how to learn about prehistoric social and demographic processes from large samples of radiocarbon dates. Archae-

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ologists increasingly use large samples of radiocarbon dates to estimate human population sizes, long-term population growth rates and other demographic processes (e.g., Contreras and Meadows 2014; Crema et al. 2016; Kelly et al. 2013; Peros et al. 2010; Pettitt et al. 2003; Shennan et al. 2013; Shennan 2008; Wang et al. 2014; Williams 2013, 2012; Zahid et al. 2016). Making inferences from these data sets about demography, however, is not without challenges (Attenbrow and Hiscock 2015; Brown 2015; Williams 2012). The issues stem from processes external and internal to prehistoric human populations. The majority of archaeological studies focus on external processes that may bias inferences about population from radiocarbon date time-series, such as the effects of site sampling, sample size, radiocarbon date calibration and preservation bias (e.g., Brown 2015; Contreras and Meadows 2014; Shennan 2013; Surovell et al. 2009; Williams 2012). These studies constitute invaluable frames of reference for making more informed inferences about demographic processes from the frequency of radiocarbon date time-series. However, little attention has been paid to the ways that cultural process, internal to prehistoric populations, may affect the creation of the radiocarbon record.

Simply put, fundamental changes in the basic contours of a society might prompt shifts in the relationship between population size and the datable materials that people produce. As a first step in exploring this issue, we model the effects of population size and economic complexity on the production of waste products that archaeologists date, and explore how it might confound the ways we currently make inferences about demographic and other cultural dynamics from the frequency distribution of large samples of radiocarbon dates. We use modern data to parametrize the model and, from our results, make two points relevant to the study of dates as data. (1) Radiocarbon date frequencies arrayed in a time-series, based on large samples of dates, probably misestimate rates of population growth. This is because radiocarbon dates, all else equal, are one measure of the energy consumed by prehistoric populations, and the scaling relationship between population and energy consumption is often sub-linear in human populations, but may also fluctuate from sub-linear–to–linear–to–super-linear over time. (2) Understanding the previous point permits researchers to make predictions about how the radiocarbon record covaries with other classes of material culture and further evaluate the importance of changes in energy consumption in prehistoric social change.

Dates as Data and Energy Consumption

The premise behind using the frequency of radiocarbon dates in a time-series to infer population trends is that the number of person years a region is occupied is proportional to the production of cultural waste that archaeologists date. As Rick (1987:54) states,

> "Despite intervening biases, I assume that the number of dates is related to the magnitude of occupation, or to the total number of person-years

> of human existence in a given area. Using this premise, it is possible to assess and compare, in a relative fashion, the occupation histories within and between regions."

This is a reasonable starting point, but there are two related critiques of this basic assumption.[1]

First, it lacks an explicit theoretical basis in basic principles of physics. Thermodynamics provides such a theoretical basis. The organic materials that archaeologists date are created, most often, through the process of transforming matter from a state of higher potential energy to a state of lower potential energy. For example, burning wood transforms the wood from a higher to lowered state of potential energy (ash). This transformation is energy consumption. Such energy consumption is a continuous process in human societies because human societies function as complex, open systems, and individuals within such societies must continuously process energy to live and reproduce (Georgescu-Roegen 1971). The constant flux of energy through an open, complex system, in turn, maintains order far from thermodynamic equilibrium (Georgescu-Roegen 1971). The consumption of energy by humans, thus, creates waste products that archaeologists can date, such as animal bone, mussel shell, charred seeds, wood charcoal, etc.

Given that human populations function as complex, open systems, we propose that the frequency of radiocarbon dates in a given region, at a given time, is more reasonably conceptualized as an estimate of the energy consumed in that region

[1] See Attenbrow and Hiscock (2015) for different critiques.

over a given interval of time by prehistoric populations rather than a direct reflection of the person years of occupation. This proposition assumes that the materials we date (bone, charred wood and seeds, etc.) are the byproducts of energy consumption events that occur as populations live and reproduce, maintaining a social-economic system far from thermodynamic equilibrium. The more of such events that take place during a given time period, the more likely it is that organic waste products will preserve and accumulate. This assumption, we believe, is more informed by theory and closer to the data than the assumption that cultural waste products reflect, in some proportional way, person-years.

Second, following Rick's initial assumption, most studies assume that population size and the frequency of radiocarbon dates produced by prehistoric populations are proportional (Peros et al. 2010:659). A proportional relationship means that a one unit increase in population will result in a one unit increase in the production of material that archaeologists can radiocarbon date, and, in a large sample of dated cultural material, increases in date frequency reflect proportional increases in population. A subtle ancillary assumption of this relationship between population size and waste production is that individuals in a population are autonomous, and their production and consumption decisions that result in waste lack mutual interdependence.

This may be a poor assumption. Social networks and technological differences can create efficiencies of scale that lead to a sub-linear relationship between population and the consumption of energy, materials and information in human societies (Freeman and Anderies 2015; Hamilton et al. 2007). And, as noted above, the consumption of energy, whether burning wood to stay warm or consuming bone marrow to maintain metabolic needs, drives the accrual of datable materials. We simply do not know whether the accumulation of cultural debris, due to the consumption of energy, and population size are related in a proportional manner, and this may bias our ability to make inferences about demographic processes from large samples of radiocarbon dates. Thus, to make inferences from such data, we need to build models for understanding how population and energy consumption are related, based on the fundamental principles of thermodynamics that underlay all contemporary and historically documented societies.

Model and Methods

To build a model that scales population and the production of datable materials we assume the following: All else equal, the frequency of radiocarbon dates collected via unbiased sampling is one estimate of the quantity of energy consumed by prehistoric populations, and the waste products that result are proportional to the total amount of energy consumed. These assumptions are simple, but, we argue, more reasonable than assuming radiocarbon date frequencies are an unmediated reflection of population. Given the above assumptions, we propose a model of changes in energy consumption that shares the same structure as a widely used macroeconomic model of human impacts on ecosystems (York et al. 2003).

Formally,

$$E = F(A)P \tag{1}$$

where E is total energy consumed; $F(A)$ is a function that describes the energy necessary for an average individual to live and reproduce; and P is population.

We assume that $F(A)$ is defined by biological metabolism and economic complexity. By economic complexity we mean the number of specialties in an arbitrarily bound economy. We assume that as the number of economic specialties increases, it takes more energy to integrate populations through exchange, visitation ceremonies, and the like. This, in turn, increases the per capita level of energy needed for an average individual to live and reproduce. We assume here that biological metabolism is a constant across human populations (i.e., varies much less than complexity). Holding biological metabolism constant, the energy necessary per person is a function of complexity, C; where C is a unitless index of the number of niches or capabilities in a system.

In mathematical notation, we write the effect of C on energy consumption as an increasing exponential function:

$$F(A) = m_1 e^{\beta_1 C} \tag{2}$$

where m is a constant metabolic rate (energy per person per unit time); and β_1 is a coefficient that scales the rate of change in energy consumption per unit increase in complexity, C. This equation assumes that the consumption of energy compounds exponentially as the number of niches in a political–economy increases. Where the political–economy is very simple (has only one niche), then per capita energy consumption is very near an individual's biological metabolic rate. As C increases, however, the consumption of energy necessary for a given population to live and reproduce compounds exponentially to account for all of the new specialties in an economy and the need to integrate those specialties.

Holding complexity equal, Equation 1 captures the basic assumption that population scales linearly with total energy consumption, and that individuals in a population do not interact in ways that create increasing or decreasing efficiencies in the consumption of energy. Our working hypothesis here is that the relationship between population and energy consumption is sub-linear rather than in proportion as equation 1 assumes. This means that adding one more individual to a foraging camp does not require one more cubic meter of wood to keep that individual warm. We suspect that the relationship is sub-linear because of previous work on territory size in human societies.

Not unlike our assumption that the frequency of radiocarbon dates estimates energy consumption, ecologists have long assumed that the size of an animal's range (territory) is an estimate of the energy that an average individual needs to consume (Brown et al. 2004; Jetz et al. 2004; Lindstedt et al. 1986; Milton and May 1976; McNab 1963). For instance, the larger an animal's body size, the larger its range because big animals consume more energy than small animals (McNab 1963). Models of animal territory size applied to hunter-gatherers and subsistence agricultural societies also assume that the size of a group's territory is an emergent outcome of the area needed to consume energy by a population (Freeman 2016; Freeman and Anderies 2015; Hamilton et al. 2009, 2007). These studies indicate that, among both hunter-gatherers and agriculturalists, territory size is often a sub-linear function of population size (Figure 1). Why this is the case remains an open question, but current hypotheses concur that as population size increases, individuals become more efficient consumers of energy and information and, thus, have more overlapping individual home-ranges (Freeman and Anderies 2015; Hamilton et al. 2009).

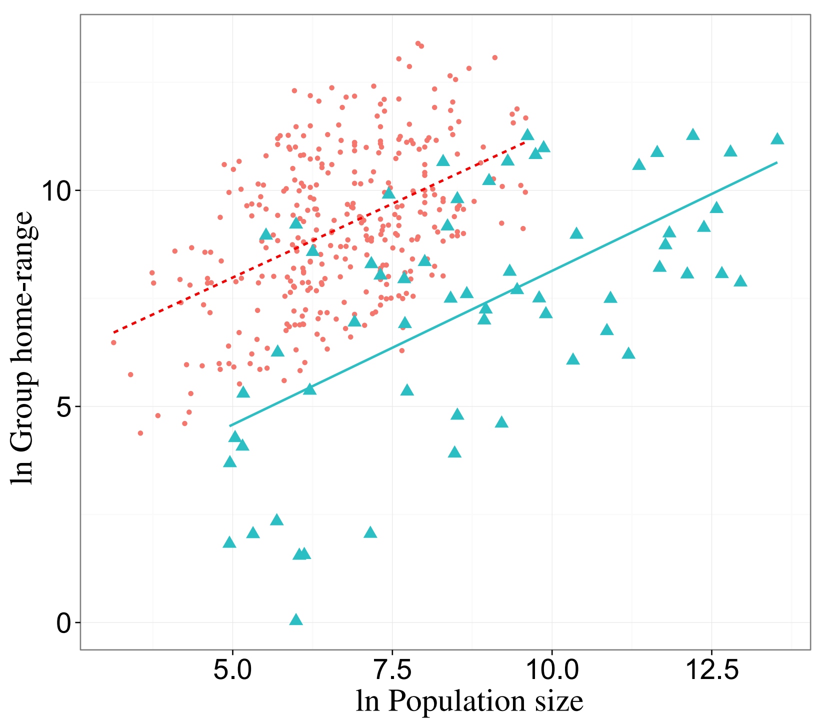

Figure 1: Population–territory size scaling Dots=hunter-gatherer societies; triangles=agricultural societies. The dashed line is an OLS regression line for hunter-gatherers; the solid line is the same for agriculturalists. Reproduced from Freeman (2016).

A common way to capture the possibility that the relationship between population and energy consumption might be sub-linear is with a power function, β:

$$E = m_2 P^{\beta 2}. \tag{3}$$

Where E is the total energy consumed by a population; m_2 is a scaling constant; and β_2 is the scaling exponent. Where β_2 is equal to one, population scales linearly with energy consumption; $0 > \beta < 1$ the scaling is sub-linear; and $\beta > 1$ the scaling is super-linear.

Given equations 2 and 3, we can combine the constants of m_1 and m_2 and set $m_1 * m_2 = M$ to re-write equation 1 as,

$$E = F(A)P = Me^{\beta_1 C} P^{\beta 2}. \tag{4}$$

In sum, equation 4 states that the total energy consumed by a population is biological metabolism times economic complexity, which defines a cultural metabolism per person to live and reproduce, times the total number of people in a population.

methods

Equation 4 allows us to investigate the scaling relationship between population size and energy consumption, holding economic complexity constant. We can evaluate whether the scaling of population and energy consumption is linear, sub-linear or super-linear in contemporary contexts using robust linear regression. By taking the log of the right and left hand sides of equation 4, we obtain a linear model:

$$\ln E = \ln M + \beta_1 C + \beta_2 \ln P + \varepsilon \tag{5}$$

where ε is the variance in the log of energy consumption not explained by population. We use the log transformations to make equation 4 linear, because this allows us to use robust techniques for estimating β_2 using a linear regression model.

To evaluate the relationship between population and energy consumption, we use four data sets that document the relationship in contemporary societies. In the first, we use International Energy Agency estimates of total energy consumption (IEA 2016) in 146 countries in 2013 and population estimates for each country from the World Bank in 2013 (TWB 2016). The energy consumption data are self reported by each of the countries in the data set. The data, thus, come from countries with mainly subsistence economies to countries with post-industrial knowledge economies (e.g., Tanzania vs. Japan), and the data vary in accuracy, which is a source of measurement error. We have made an attempt to control for variance in energy consumption driven by big differences in economic complexity by collecting data from Hausmann et al. (2014) on economic complexity. The data are available for 117 countries that also have population and energy consumption data. Hausmann et al. (2014) measure economic complexity as the diversity and ubiquity of products in an economy, which reflect the amount of information and the scale of networks in the economy. The larger the scale of information and networks, the more organizationally complex the economy. Using these data, we can examine the scaling relationship between population and energy consumption holding economic complexity constant.

In the second data set, we use estimates of total energy consumption in US states in 2014 obtained from the United States Energy Information Administration (EIA) (EIA 2016) and estimates of population in 2014 obtained from the US Census. These data are standardized estimates of energy consumption collected by energy professionals in the EIA. We treat economic complexity among US states as a constant because the variation in complexity is less than the global sample. This means that all US states are similar in economic complexity to say France, but no state approaches the lower 1/2 of the economic complexity distribution observed at a global scale. In the global and US data sets we combine all forms of energy consumption (e.g., wind, solar, nuclear, coal) and sectors (e.g., transportation, industrial, residential). We are not concerned that many of these energy sources would not result the production of datable materials, but, rather, with describing the general scaling relationship between population and energy consumption.

In the third data set, we look at the relationship between the number of families in villages and wood-fuel consumption in Bangladesh (Miah et al. 2009:Table 2). This last data set is not sufficient for a formal regression analysis because the sample size is well below 30 and, thus, standard errors are inflated. Yet, the data set is instructive because we can observe energy consumption at a much smaller scale and level of analysis than in the first two data sets. These data were collected among subsistence farmers as part of an ethnographic study on fuel consumption and deforestation. Again, economic complexity varies little from village-to-village in this data set, so we treat complexity as a constant.

Finally, in the fourth data set we observe the relationship between the population size of Kalahari Bushman camps and the number of hearths in each camp. We assume that the number of hearths is a proxy for the amount of fuel-wood and other organics consumed by the population of each camp to cook, stay warm, etc. Thus, we treat the number of hearths in a camp as an estimate of energy consumption among these hunter-gatherers. All data come from Yellen's (1977) ethnoarchaeological study of Kalahari Bushman. We tabulated the data from Yellen's camp descriptions. We estimated the total number of hearths in a camp by adding the formal hearths described for each camp with informal hearths. We estimated the number of informal hearths using Yellen's feature list for each camp site and tabulating the number of small one-time or special-purpose roasting pits, scatters or mounds of charcoal and ash that might be fire hearths. We avoided any that he specifically listed as hearth clean-outs, but it is possible that some informal hearths are clean-outs. This gave us a data set of 15 camps. As above, the caveat about small sample size applies, and economic complexity varies little from camp-to-camp, so we treat complexity as a constant.

We would like to emphasize that we are using data from three different scales (global, national, local), and these data come from a wide variety of economies. One might worry that differences in economic complexity might change the population-energy consumption relationship; this is why we have taken the time and care to build data sets at very different scales and range of economic contexts. Convergent results would suggest that population has a wide spread effect on energy consumption that transcends types of economies.

Results

In sum, our results indicate that, at a global scale of analysis, population size and economic complexity both have effects on the total energy consumed by a population. Further, at a global scale, the scaling relationship between population and energy consumption, holding economic complexity equal, is sub-linear. The sub-linear scaling of population and energy consumption is replicated at finer scales of analysis where economic complexity varies much less than at a global scale. The scaling of population and energy consumption is sub-linear among US states, Bangladesh villages and Kalahari Bushman camps. Remarkably, the scaling coefficients identified in our analysis are similar to the population–fuel-wood consumption (energy consumption) coefficient of 0.79 (s.e.=0.04), controlling for forest cover and GDP, found by Knight and Rosa (2012:Table 2) in their study of wood consumption in 87 developing economies. This means that a sub-linear scaling of population and energy consumption, holding other factors equal, occurs across five different data sets collected at different scales of analysis and with vary different levels of technological variation.

Table 1: Coefficients, standard errors and t-values of population and economic complexity regressed on ln energy consumption. R^2=0.78. P=population size; E_c=economic complexity; M=energy/person (y-intercept).

Variable	β_i	Std. Error	t-statistic	p-value
M	-11.983	0.781	-17.176	< 0.001
$\ln P$	0.891	0.042	21.237	< 0.001
E_c	0.533	0.059	8.966	< 0.001

Table 1 illustrates that the scaling relationship between population and energy consumption is sub-linear, even after controlling for economic complexity, at the global scale (Table 1). As expected, population has a positive effect on energy consumption, with a sub-linear coefficient of $\beta_2 = 0.89$ (se=0.042, 95 % C.I. 0.97-0.81). Also, as expected, economic complexity has a positive effect on energy consumption. The more complex a country's economy, the more energy the population of a country consumes. Finally, although both population size and economic complexity have effects on energy consumption consistent with theory; population size explains more of the variance in energy consumption than economic complexity. This is intuitively illustrated by Figure 2. Note that the points are a much tighter fit around the best fit line in Figure 2a vs. 2b.

Figure 3 illustrates that the scaling of population size and energy consumption is sub-linear at finer scales of analysis where economic complexity is much less variable among US states and Bangladesh villages. Among US states, a one unit increase in population results in a $\beta_2 = 0.86$ (se=0.04, 95 % C.I. 0.93-0.78) unit increase in energy consumption (Figure 3a). Among Bangladesh villages the scaling of population and fuel-wood consumption is again sub-linear, at $\beta_2 = 0.89$ (se=0.19). However, due to the very small sample size, the standard error of β_2 in

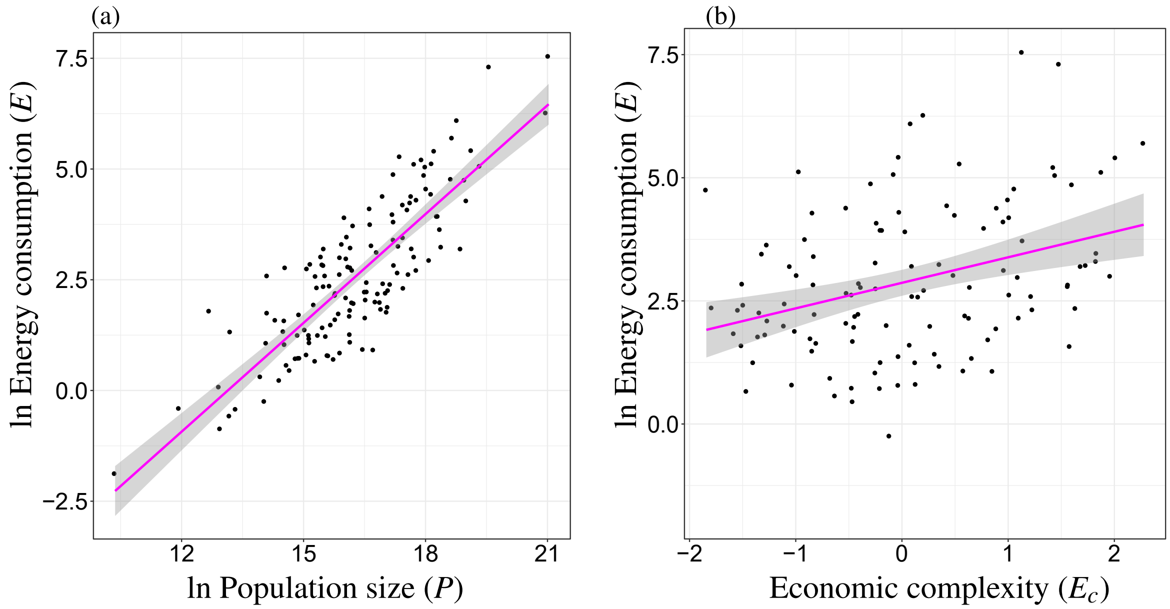

Figure 2: The relationship between population and total energy consumption among world countries (a); & the relationship between economic complexity and total energy consumption among world countries (b).

this case is quite large, and $\beta_2 = 1$ is within the 95 % confidence interval for the scaling exponent. Among Bushman camps the scaling of population and number of hearths is sub-linear, at $\beta_2 = 0.89$ (se=0.38). As with the Bangladesh villages, the sample size and standard error caveats apply.

Discussion

So far, we have proposed a model that scales population against the production of datable materials in social-ecological systems, and we have parametrized the model using modern data on population size and energy consumption. We assume that a one unit increase in the energy consumed by a prehistoric society results in a proportionate increase in the accrual of materials that archaeologists ultimately date. Contemporary data sets demonstrate a sub-linear scaling relationship be-

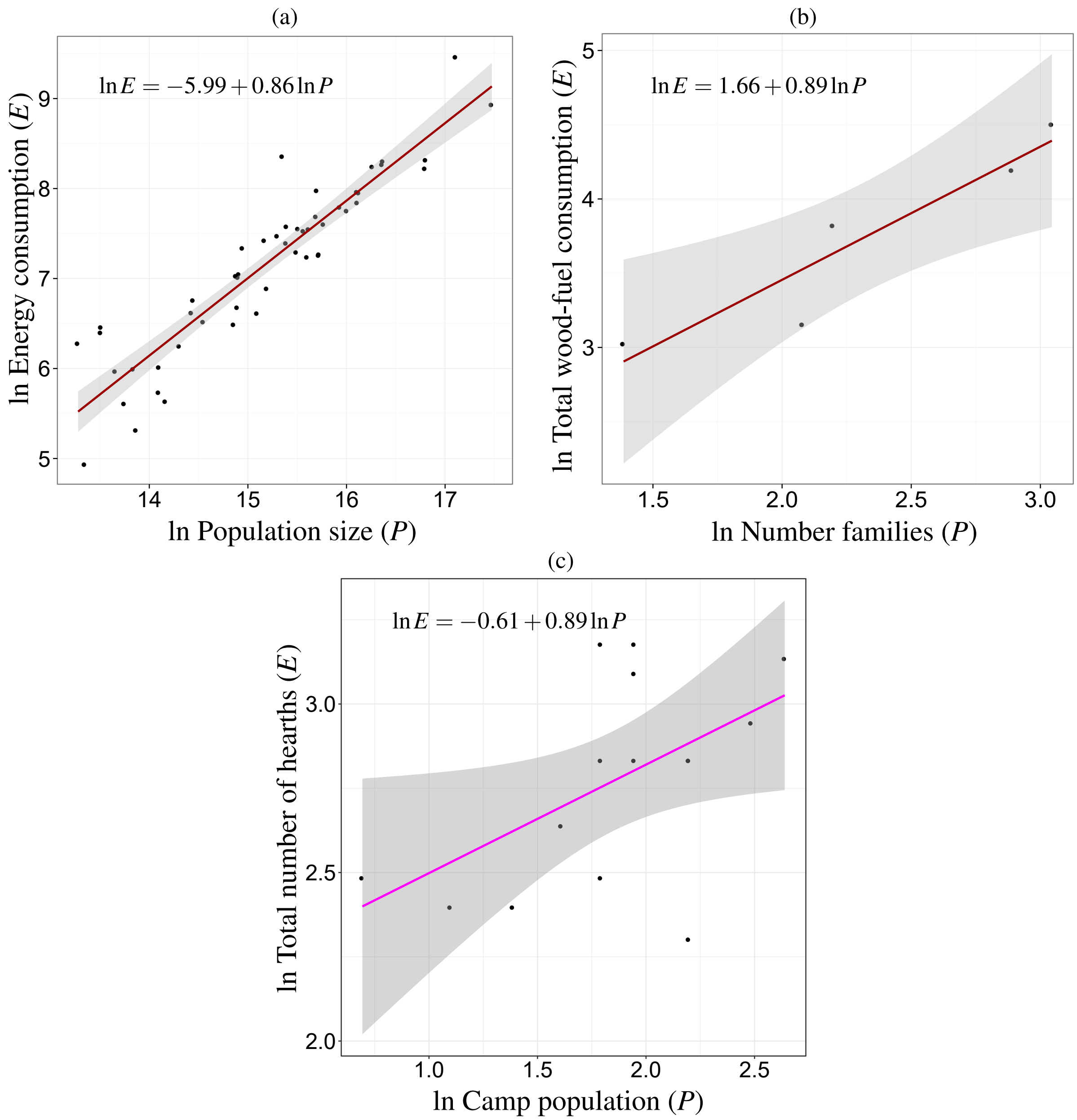

Figure 3: The relationship between population and total energy consumption among US states (a); number of families and total fuel-wood consumption in Bangladesh villages (b); & camp population and total number of hearths in Kalahari Bushman camps (c).

tween population size and total energy consumption, and do so at three different levels of analysis and in five different data sets (Figures 2 & 3). Further, at a global scale where variation in economic complexity is widest, economic complexity has a positive effect on the consumption of energy (Table 1 & Figure 2).

The model proposed by equation 4 and the results of our analysis, which are consistent with equation 4, suggest two points relevant to the study of dates as data. (1) Radiocarbon date frequencies arrayed in a time-series, based on large samples of dates, as currently constructed, probably misestimate rates of population growth. This is because radiocarbon dates, all else equal, are one estimate of the energy consumed in prehistoric social-ecological systems, and the scaling relationship between population and energy consumption is often sub-linear in human populations. (2) Equation (4) provides a framework to make predictions about how the radiocarbon record should covary with other classes of archaeological material culture and further evaluate the importance of changes in energy consumption in prehistoric social change.

Estimating population size and growth

The sub-linear scaling of population size with energy consumption documented above suggests that current approaches to interpreting radiocarbon date frequencies systematically misestimate population size over a given interval of time and growth rates. This is not a concern if we don't care about absolute population sizes and growth rates. For example, some researchers pool together dates that are associated with the same context/site (e.g. Shennan et al. 2013; Timpson et al. 2014). This is done to control for sampling bias by archaeaologists, and shifts the frequency of radiocarbon dates from an estimate of the number of individuals to an estimate of the number of sites. Counting sites is the classic method that archaeologists use to estimate changes in population. This method is probably pretty good for understanding relative changes in population over time. However, this method degrades the information contained within the radiocarbon record. We may want to know about absolute values of population size and change. In this case, we need to think about how to adjust frequencies of radiocarbon dates to account for the non-linear relationship between population and energy consumption, without simply using them to count sites, which has the benefit of controlling for sampling intensity but also has the cost of lost information.

Given our model and results, we propose, as a thought experiment, a method for rescaling radiocarbon datasets to estimate relative population sizes that accounts for a sub-linear relationship between population size and the evidence for energy consumption. To conduct this thought experiment we hold economic complexity constant because this factor appears to determine less variation in energy consumption than population size. It is the evidence of energy consumption events, not population size, that archaeologists analyze, and the available data suggest a sub-linear relationship between population size and the consumption of energy. Starting with equation 4, since M is a constant, we can let $M = 1$, hold $C = 1$, and solve for P at a given time t by raising each side of the equation to a power of $1/\beta$:

$$P_t = E_t^{\frac{1}{\beta}}. \tag{6}$$

Taking our contemporary data as a starting point, we could rescale the frequency of dates in any given time period by a scaling factor between 1.12–1.26, (i.e., $1/\beta$) for the range of values derived above from the modern data sets (Knight and Rosa 2012:Table 2; this study). It is important to note that by doing this we assume that the sub-linear scaling of population and energy consumption (and, inversely, the super-linear scaling of energy consumption and population) is an invariant law of human social-ecological dynamics. This is a strong assumption, and one we make with caution. For now, however, a hypothetical scaling exponent of 1.15 recognizes the sub-linear relationship between population and the production of datable material. Doing this does two things: It raises estimates of population size in any given time interval, and it increases estimates of population growth.

In this case, the rate of change in the scaled summed probability distribution (SPD) is 15 % faster, and, thus, the estimated growth rate 15 % faster than an unscaled SPD of radiocarbon dates (the dashed curve increases faster than the solid curve in Figure 4). In terms of real numbers, Zahid et al. (2016: 934) estimate the annual population growth rate of SW Wyoming and Colorado, using an SPD uncorrected for taphonomic loss, as 0.053 %. Our results suggest that this underestimates population growth from between 12 % to 26 %, which yields growth rates from 0.05936 % to 0.0667 %. Simply put, an unscaled SPD underestimates population size, and, because the relationship between energy consumption and population may be sub-linear, an unscaled SPD will also underestimate rates of population growth.

For context, Zahid et al. (2016:932) correct their raw growth rate of 0.053 % for taphonomic loss to obtain a growth rate of 0.041 % during the period from

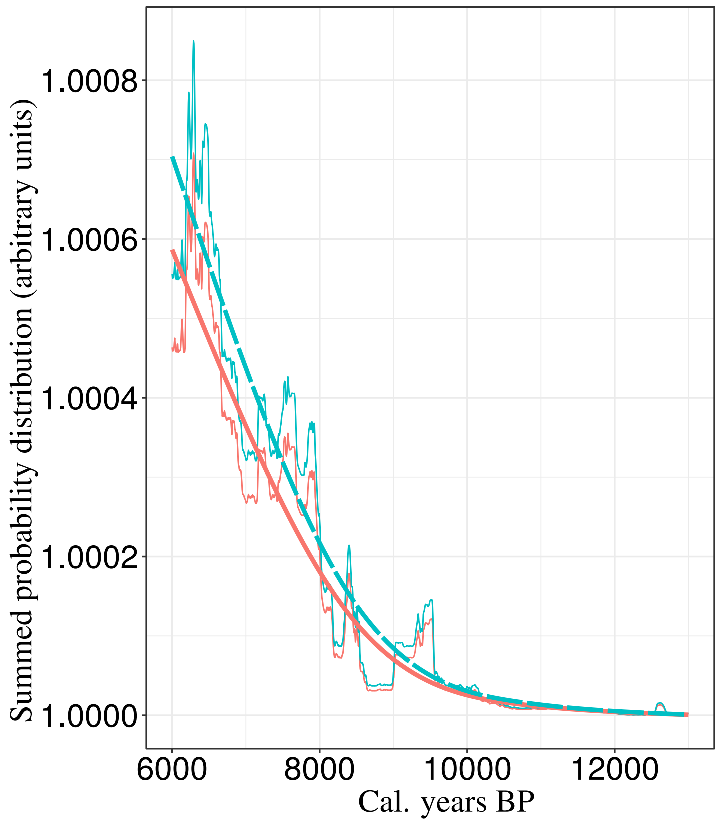

Figure 4: Raw and transformed SPDs. Dashed blue curve is the best fit for the transformed SPD; the solid red curve is the best fit for the raw SPD.

13000 to 6000 Cal. BP. Thus, in absolute terms, the energy scaling adjustment is comparable to the taphonomic adjustment. In fact, deep in time both adjustments cancel each other out. However, as one moves closer to the present taphonomic loss is less important and an adjustment for population–energy scaling would have more of an effect. In relative terms, at low population sizes, neither adjustment probably matters all that much.

However, the energy scaling adjustment applies through a whole time-series at a constant rate; and a change of 15 % in growth rate may be more meaningful for larger populations, and over time periods in which populations were growing at faster rates. For example, if a population of 1000 experienced a period of exponential growth at 1 % vs. 1.15 % over 200 years, the population growing at 1 % would have a population of approximately 7,316 people and the population growing at 1.15 % a population of approximately 9,844 people (about a 35% difference). Keep in mind also that the energy scaling adjustment factor also changes absolute population sizes and, holding space constant, population density. Theory suggests that critical population density thresholds fundamentally change the selective pressures put on individuals (Binford 1999; Freeman et al. 2015; Freeman and Anderies 2012; Winterhalder et al. 1988). If we are systemically underestimating population densities, we may be missing evidence that such thresholds were approached and crossed.

In sum, if the goal of a project is to reconstruct absolute population densities or growth rates, then an informed researcher might transform their radiocarbon date curve to account for the non-linear scaling of energy consumption and population size, as documented here. To be clear, we are not suggesting that all SPDs need to be adjusted to account for the sub-linear scaling of population and energy consumption. Rather, if absolute growth rates are important, then we need to build frames of reference useful for estimating absolute growth rates from SPD data. Conceptualizing radiocarbon date time-series as estimates of energy consumption, thus, does not preclude using SPDs to estimate demographic parameters, but rather, gives us a more informed way to do so. This is just one advantage of developing a model framework, from the factors that should drive energy consumption in human societies, for predicting variation radiocarbon date frequencies.

Predicting covariates in the archaeological record

We know from previous research that archaeologists must control for the effects of calibration, over sampling of single features or sites (sampling intensity) and, under certain circumstances, taphonomic processes before inferring population parameters from large radiocarbon time-series (Brown 2015; Contreras and Meadows 2014; Surovell et al. 2009; Williams 2012). Proper radiocarbon hygiene limits over-sampling induced bias, and recent research has shown that large sample sizes (1000+ assays) are more robust to the effects of preservation bias (Williams 2012). Much work has gone into these issues. Intuition probably tells most archaeologists that these issues are more important than the social dynamics of prehistoric populations that created the radiocarbon record through energy consumption events. This, however, is an empirical question, and our approach does not reject the importance of sampling bias and taphonomic processes. Our approach simply puts processes external and internal to prehistoric systems on a more equal footing so that we can begin to tease apart the most important factors.

As a final discussion point, the theoretical framework developed above provides a starting point to observe the relationships between radiocarbon date frequencies and other classes of phenomena related to energy consumption in the archaeological record. We do not argue that radiocarbon date frequencies are a sufficient measure of energy consumption. Rather, the radiocarbon record is one estimate of energy consumption. We can correlate the radiocarbon record with other estimates of energy consumption using other classes of material culture to evaluate this idea further. For example, if the radiocarbon curve is an estimate of total energy consumption, we would expect to see spikes in the radiocarbon curve correlate with the use of more energy dense biomass, like grass seeds and nuts, as opposed to less energy dense resources on the landscape. So macrobotanical evidence of seed use should spike or evidence of agricultural intensification should spike as the radiocarbon record spikes, depending on the region and economic context. The model we have proposed is not an end product, but is a beginning theory, justified by basic relationships between population and energy consumption in modern contexts, and these modern relationships suggest that the model may prove useful in archaeological contexts as well.

Conclusion

The purpose of this paper has been to critically discuss how to observe prehistoric social and demographic processes from large samples of radiocarbon dates. While much thought has been given to non-cultural biasing agents, much less attention has been paid to how prehistoric culture process may affect the accumulation of datable materials in prehistoric social-ecological systems and, thus, the amount of material available for archaeologists to come along date. Consequently, we suggest that understanding the energy consumption dynamics of human societies represents both a critical and logical next step to make predictions that explain variation in radiocarbon date time-series.

We propose that large, regional-scale samples of radiocarbon dates estimate changes in the consumption of energy in prehistoric populations rather than population *per se*. It is important to note that this is just one estimate. If this approach has validity, then future research will show clear positive covariation between frequencies of radiocarbon dates and other material estimates of energy consumption, like the frequency of ground stone or the size of middens. Our results suggest that energy consumption is a sub-linear function of population size and is positively related to economic complexity, at a global scale. Given these relationships, if one is interested in using radiocarbon data to estimate population growth rates, it may be productive to adjust a resultant time-series to estimate relative population sizes and changes in population over time. This adjustment should not be viewed as a "correction" of a radiocarbon curve. Correction implies that a given curve is wrong. Rather, the adjustment represents an informed judgment that should be made if one's research goal is to estimate absolute population growth rates, and if future research supports the hypothesis that the scaling of population size and energy consumption is sub-linear. We have presented this correction example as a thought experiment; as a challenge to make us think about what kind of correction we might need and when.

Large samples of radiocarbon dates are a potentially informative way to measure prehistoric culture process. More work is needed, however. We suggest three lines of research that may complement the already vigorous research into how best to make inferences from radiocarbon time-series.

- Collect more data on contemporary or ethnographically recorded economies to empirically investigate the scaling relationship between population and energy consumption. If the scaling of population and energy consumption is an invariant law driven by basic metabolic processes (Brown et al. 2004; Hamilton et al. 2007), this would be incredibly convenient for archaeologists interested in making inferences from large radiocarbon data sets. However, the scaling may vary with technology or social institutions over time and space (DeLong and Burger 2015; Freeman and Anderies 2015), which would mean that different parts of the radiocarbon date time-series would need to be rescaled, from the perspective of estimating population size and growth rates, by different scaling factors over different segments of time.

- Evaluate the scaling of population and energy consumption in archaeological contexts. We would simply need an area in which researchers have invested in collecting many radiocarbon dates and there are preserved structures that are partly independent of the radiocarbon record due to recording on survey that would allow for traditional population estimates based on structure counts in the same region.

- Study further the effects of economic and political complexity on energy consumption. Fluctuations in radiocarbon date time-series curves, holding all else equal, also result from changes is social and economic organization (Crombé and Robinson 2014). Holding population constant, changes in economic organization, as well as complexity, should affect how much energy an average individual consumes.

To end, we would like to emphasize again that our contribution is theoretical. We have proposed a quantitative model to describe the relationship between the production of radiocarbon dates and human population. The practical relevance is twofold. First, the model we have specified allows us to predict how radiocarbon dates should covary with other classes of archaeological material culture. Second, and the nominal focus of our paper, the model allows us to make better judgments about how to infer prehistoric population parameters from large samples of radiocarbon dates. Our approach is not a finished product, but it is an initial step toward a more mature, deductive approach to learning about social and demographic processes from large samples of radiocarbon dates.

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