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Radiocarbon data may support a Malthus-Boserup model of hunter-gatherer population expansion

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ABSTRACT

Describing and explaining the population growth trajectories of prehistoric hunter-gatherers is an important research problem. Large radiocarbon data sets provide one empirical starting point for describing these trajectories; however, explaining trajectories of growth must always take place within the context of theory. In this paper, we formalize a ratchet model of long-term, mean population growth among hunter-gatherers and evaluate the plausibility of that model using two extensive radiocarbon data sets from Central Texas and the Texas Coastal Plain. Our analysis suggests that hunter-gatherer populations in these regions displayed waves of population growth separated by periods of population saturation and competition for resources. Our model and results suggest that hunter-gatherer populations in Texas may have experienced multiple demographic transitions to successively higher levels of population saturation (carrying capacity). Our results derive from a general model, a set of methods applicable across archaeological regions, and provide a basis for hypotheses that may explain changes in the socioecology of hunter-gatherers.

1. Introduction

In recent years, archaeologists have used radiocarbon records to push the bounds of research on human population ecology, studying the fundamental processes of synchrony, stability, and long-term growth (e.g., Tallavaara and Jørgensen, 2021; Lima et al., 2020; Bird et al., 2020; Robinson et al., 2019; Freeman et al., 2018a; Crema et al., 2016; Zahid et al., 2016; Kelly et al., 2013; Shennan et al., 2013). A widespread pattern of growth documented by these studies is a long-term, exponential-like increase in radiocarbon ages over the course of the Holocene, especially in N. and S. America (e.g., Bird et al., 2020; Freeman et al., 2018a). Central and Coastal Texas typify this pattern (Fig. 1). Yet, it is not clear what processes might generate a long-term exponential pattern of growth among hunter-gatherer populations. In this paper, we continue to push the bounds of research by asking a fundamental question about the long-term growth of hunter-gatherer populations. Does the long-term expansion of archaeological radiocarbon generated by Central and Coastal Texas hunter-gatherers potentially signal a Malthus-Boserup process of population growth?.

A Malthus-Boserup model of population growth integrates the core thesis of Malthus that resources limit population growth (Malthus, 1888) and Boserup's thesis that approaching resource limits spurs innovation in food production systems (Boserup, 1981). Qualitatively, Malthus-Boserup models propose a positive feedback process: As a population approaches population saturation or carrying capacity, competition for resources creates signals that individuals interpret and respond to in ways that reorganize society and technology. The reorganization of society and technology creates substitutes for lower density resources that increases the population saturation point of a given area. As a consequence, population grows toward the new, higher population saturation point of the modified social-technological system and, again, signals may or may not spur reorganization (for formal models see e.g., Wood, 2020; Anderies, 2003; Wood, 1998; Richerson and Boyd, 1998; Lee, 1986). Wood (1998) calls this positive feedback the MaB-Ratchet (Malthus and Boserup Ratchet).

The MaB Ratchet process predicts a basic macrodemographic pattern. Over time, human populations display waves of expansion (imagine sequential logistic growth curves over time). Several authors

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fit waves of density dependent growth models to historical population records (e.g., Hopfenberg, 2003; Meyer and Ausubel, 1999; Marchetti et al., 1996; Cohen, 1995). However, no one has attempted to discern whether such density-dependent waves of expansion describe the long-term growth of prehistoric populations. In the remainder of this paper, we propose a simple, formal ratchet model of long-term hunter-gatherer population growth, analyze large samples of radiocarbon ages to evaluate the plausibility of the model, and we conclude that waves of density dependent growth may fit the expansion of hunter-gatherer populations in Central and Coastal Texas. Identifying waves of density dependent growth within radiocarbon time-series allows archaeologists to more tightly constrain hypotheses and predictions about the socioecology of prehistoric populations. The basic descriptions of growth patterns provided by these time-series may contribute to evaluating and revising formal models of social and technological change among human populations.

1.1. A Hunter-gatherer MaB Ratchet Hypothesis

We propose that the pattern of growth displayed in prehistoric Texas results from the positive feedback process described by the MaB ratchet. Wood (1998) formally models the MaB Ratchet process, at a macro-demographic scale, and he proposes that population within a fixed area grows as long as surplus production is above that required to meet an average household's minimum subsistence needs for demographic replacement. The key variable in Wood's formal analysis is the culturally relative concept of well-being, which requires more calories than the minimum calories required for mere demographic replacement.

In Wood's model, as population density increases, surplus production declines until an average household can no longer achieve their desired level of well-being. The population density between stress on well-being and the minimum subsistence level defines a 'population pressure zone' where social and technological reorganization may occur. The reorganization results from households responding to signals–like failing to meet one's desired level of food output–'sent' by the macrodemographic state of the system to agents that the system is not working as expected. Reorganization toward more productive forms of technology and social organization relieves the pressure and ratchets the demographic system up to a new regime with, temporarily, more surplus production. However, surplus production declines as population grows (within a fixed area) toward the new population density of minimum subsistence, and the distribution of well-being in the new system ends-up in exactly the same spot as the old system. The macrodemographic result of the ratchet, holding the shapes of production functions equal, should be waves of density-dependent population growth that continually increase to a new, higher point of population saturation.

The MaB Ratchet rests on the assumption that agents–whether households or individuals–have the capacity to identify, interpret, and respond to the signals 'sent' by the state of the resource system. Wood himself considers the lack of a microdemographic theory of household response to such signals a shortcoming of the MaB Ratchet model (Wood, 2020). Puleston et al. (2014) concur, and they have built an elegant model to study a demographic system that links microeconomic decisions and macrodemographic patterns. Based on their analysis, Puleston et al. (2014) demonstrate a general three phase pattern: (1) A prosperous population growth phase, (2) a Malthusian Transition Interval, and (3) an indefinite Malthusian equilibrium phase described by a low quality of life (well-being). The Malthusian Transition Interval is similar, conceptually, to Wood's zone of population pressure in which a declining quality of life 'signals' a looming Malthusian equilibrium where capital and quality of life are so low that the reorganization of social relationships would be constrained. Puleston and colleagues call the Malthusian Transition Interval the 'Malthusian Cliff' because it can occur in one generation (Puleston et al., 2014). They conclude that the

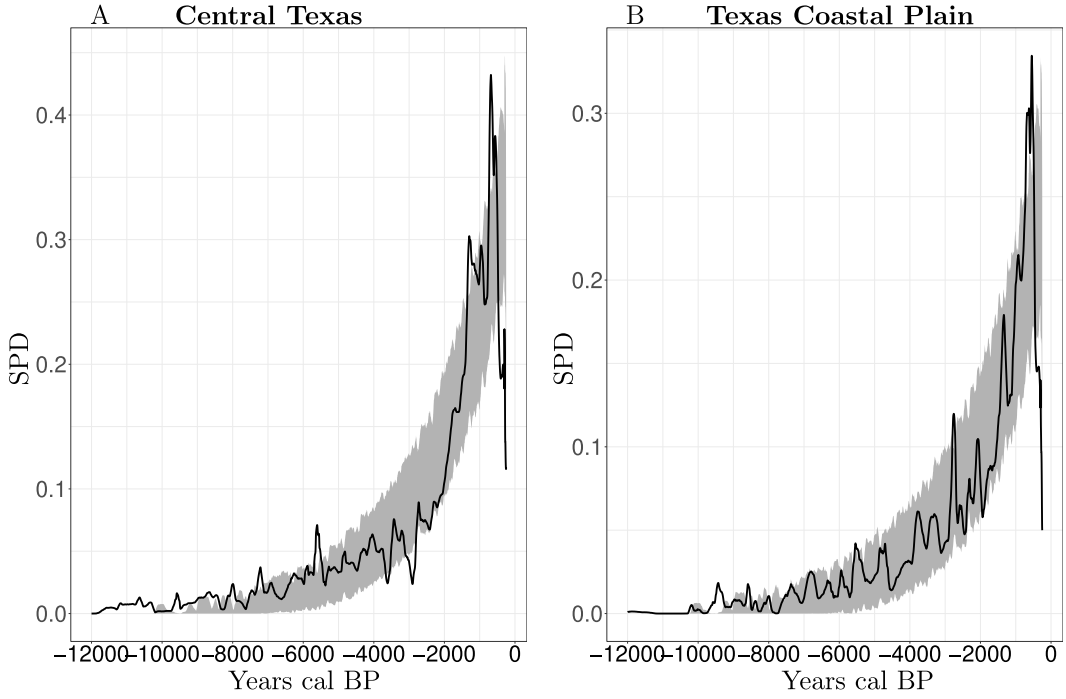


Fig. 1. Comparison of Central Texas and Texas Coastal Plain summed probability distributions (calibrated using the rcarbon R package using Intcal13). Exponential models are fit using rcarbon via Monte Carlo simulation to define the 'confidence envelopes' of the exponential curves. An exponential model provides a global, statistically significant fit to both time-series, but has very little basis in demographic theory. This has become know in the literature as the null model approach. This approach was designed to evaluate the 'significance' of fluctuations in an SPD at time-scales of typically less than 1000 years (Shennan et al., 2013; Timpson et al., 2014). There is no one correct null model; a null model may be informed by the shape of the distribution of the data and/or by one's research question and theory. Identifying the significance of a sub-millennia fluctuation is a distinct issue from our research question: Exploring a dynamic model that may explain the apparent exponential growth trajectories over millennia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Malthusian Cliff constrains or even precludes Boserupian type escapes that ratchet up a system's population saturation point (Puleston et al., 2014).

To be clear, Puleston et al. (2014) extrapolate from their model's dynamics, which includes an assumption that households can intensify their production at the margins, but does not include the key assumption that households begin to create novel substitutes for a current resource base (i.e., form a new niche). Thus, the conclusion that the absolute length of a Malthusian Transition Interval constrains the ability of populations to reorganize into a new niche may miss the mark in important respects.

To successfully process a signal (1) agents must detect the change in the state of the system through some fitness related dynamic variable, like the production of food (a key component of well-being/quality of life in the models discussed above). At minimum, food production outcomes 'send' information every year as individuals make judgments about the abundance and reliability of food produced by their current strategies. A transition interval of even one generation (30 years) could be plenty of time to detect a food production signal, which provides selective pressure for new strategies that, over generations (depending on the rate of adoption), leads to population growth as a population of foragers fills a more productive niche.

(2) If agents detect signals, they must have the capacity to change the social and technological relationships of production and consumption and create a new niche. Clearly, this may not always be the case. Agents may lack access to a requisite diversity of social and technological options within a population from which to select new modal strategies. Further, elites may benefit from entering a zone of population pressure via more profitable rent seeking, and runaway status competition among these elites may create an incentive for elites to resist, even violently eliminate, a fundamental reorganization of society (Turchin and Nefedov, 2009).

We hypothesize that prehistoric foragers in Texas had the ability to detect the signals of impeding Malthusian equillibria, and the capacity to change their social and technological relationships of production and consumption, generating a population ratchet. The basis for this hypothesis follows from Wood's (Wood, 1998) model and builds on the above critiques as follows.

Two models developed to study the process of intensification among human foragers suggest that foragers would detect signals of an impending Malthusian equilibrium (Freeman et al., 2019; Freeman and Anderies, 2012). These models illustrate the effects of slow changes in the ratio of population density to resource regeneration (population saturation in Wood's terms) on the dynamics of a forager-resource system. Freeman and Anderies (2012) illustrate that increasing the demographic saturation of a forager-resource system results in intensification *sensu stricto*–declining returns per unit of labor following (Wood, 2020; Morgan, 2015)–and, more subtly, a decline in the stability of a productive forager-resource equilibrium. This decline in stability corresponds with the novel vulnerability of a regime change into a kind of forager poverty trap (Malthusian equilibrium) and a longer return time to a productive equilibrium following random variations around a given climate's mean (Freeman and Anderies, 2012). This longer return time and potential flip into a poverty trap should manifest in more uncertainty about how to allocate time at an individual level. A powerful signal that affects the key fitness related variable of time allocation for social foragers, and could motive changes in the modal form of social and technological organization to reduce uncertainty in how to allocate time (see e.g., Freeman and Anderies, 2015).

Building on this work, Freeman et al. (2019) model a two habitat system in which foragers can cycle between habitats in a variable environment. The model helps clarify the above argument by studying the feedback between foraging effort (time spent searching for and collecting food), movement between habitats, and resource density in a variable environment. This model illustrates that moving between habitats increases the population saturation point of a landscape for foragers. The movement generates a flow of information about each habitat; the more foragers cycle, the more information they have and can use to best minimize variance in their harvest of resources. Still, as population density approaches maximum population saturation, the system becomes vulnerable to larger scale climate variation or social dynamics that push too many foragers temporarily into one habitat or the other. This creates a situation in which movement between habitats generates sequences of expected harvest, failure of expected harvest, expected harvest as foragers move between habitats. This is a signal that moving between habitats and sharing information widely no longer reduces variation in the harvest of food (Freeman et al., 2019). Note, this occurs before a flip into the kind of Malthusian equilibrium noted by Puleston et al. (2014) above with a low quality of life. The system is capable of flipping between consistent and inconsistent sequences of harvest depending on positive or negative sequences of variation around a given climate's mean.

The change in harvest sequences that emerges from foragers' own movement patterns that they expect to reduce variation in their harvest captures the spirit of a population pressure argument. A clear signal, increased variability in harvest, reaches the individual scale, and provides a fitness related reason to shift strategies of time allocation for reducing variation in one's harvest of food. The question then centers around constraints on the ability of populations to adapt in such a way that productivity increases and the system ratchets up to a higher population saturation regime. Well developed formal models of this situation do not exist; however, we can draw on the basic Darwinian principle that more variation in strategies at the individual level increases the likelihood of the ratchet (reorganization) as opposed to falling into a Malthusian equilibrium at a population level. The simplest shift that foragers can make is one of substitution. That is, when foragers maintain knowledge of and use diverse resources from large game to plants to fish, the underlying diversity exists for the substitution of dense and more predictable plant and fish resources for large game resources.

Fig. 2 illustrates cross-sectional data from hunter-gatherer societies published by Binford (2001) that lend some empirical weight to the second part of our hypothesis. As the percentage of a normalized forager's food coming from plants and fishing resources increases, the population saturation of hunter-gatherer societies increases. One way to interpret this pattern is that more concentrated plant and fish resources allow for a higher population saturation. Note, however, once about 70 % of foragers' supply of food comes from plants and fish, further gains in population saturation, it seems, must come from changes in social organization. For instance, territorial ownership associates with the highest population saturation values (Fig. 2B).

Certainly, in broad strokes, changes in the technology and social organization of prehistoric hunter-gatherers in Texas fits the proposal that the population saturation of the environment increased via a substitution like process. For instance, in Central Texas large earth ovens used to bulk process geophytes (wild onions, camas, etc.) were in use in the early Holocene; but we observe a spike in their frequency in the mid Holocene, and a large spike in the late Holocene peaking about 1000–800 cal BP (Freeman, 2007; Mauldin et al., 2003; Black et al., 1997). This pattern suggests punctuated increases in the use of bulk processed and dense plant resources through time. On the Texas Coastal Plain, foragers seem to have become more territorial throughout the Holocene and increasingly specialized in their use of marine resources along the coast up to 1000 cal BP (Hard and Katzenberg, 2011; Ricklis et al., 2005).

Fig. 3 (and Appendix B) summarizes the key processes in the hunter-gatherer version of the MaB ratchet hypothesis. First, the MaB ratchet hypothesis proposes that the expansion of radiocarbon curves in Texas results from waves of density dependent population growth in the past driven by changes in population saturation over time ($k(t)$). This is captured in Fig. 3A by the red dashed curve and the biologistic model (blue curve). The green curve illustrates a scenario in which population follows a single logistic population growth model with a fixed k_{s1}. The

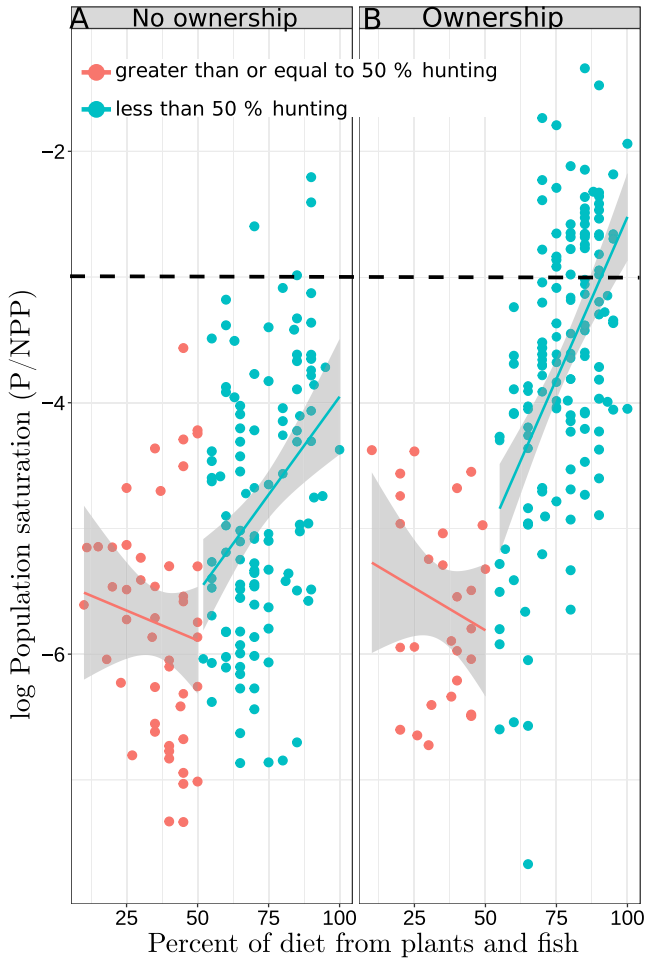


Fig. 2. Relationship between estimated population saturation (ln population density/net primary productivity–ln(P/NPP) and the proportion of a normalized forager's diet from plants and fish among ethnographic cases. Red dots = 50% of calories or more from hunting; blue dots = less than 50% of calories from hunting. A-No territorial ownership norms. B-Territorial ownership norms. Dashed line helps illustrate that groups who recognize ownership tend to live at higher population saturation for a given level of calories from plants and fish. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

gray area under this green curve is a zone of population pressure. By definition, this is the area under the green curve where the next unit of population growth is less than the previous unit, due to competition for resources, until the system reaches equilibrium.

Our hypothesis is that once the mean population of foragers crosses 50% of the population saturation value that defines the upper limit of the green population curve, competition for resources leads to more sensitivity in the food production and land use system to normal climate variation. This increased sensitivity spurs the adoption of resources via adjustments to technology and social organization that reduce this sensitivity, especially in the production of food. Such adjustments, in turn, unintentionally increase population saturation from k_{s1} to k_{s2} (Fig. 3B). This shift in technology and social organization, for instance investment in large earth ovens for bulk processing geophytes in Central Texas, temporarily releases competition for resources due to the increase in $k(t)$, which leads to a correlated increase in $p(t)$ (the blue curve) as the population transitions to a higher productivity niche. This process is not inevitable, though. If a foraging system lacks the requisite underlying diversity for innovation and/or elites suppress change, the system might get caught in a Malthusian Equilibrium for many generations (i.e., mean population simply follows the green curve with a fixed k_{s1}).

Three predictions follow from the hunter-gatherer ratchet hypothesis. (1) The sum of multiple density dependent (in this case logistic) models should fit the long-term trend of radiocarbon expansion well. (2) The component density dependent growth models fit to the overall expansion of a radiocarbon time-series should display ratchet like growth–increasing population saturation points (k) through time (like the jump from k_{s1} to k_{s2} in Fig. 3A). Finally, (3) new logistic growth components should begin after the previous component has passed 50 % of population saturation. This is the point on a logistic curve where growth flips from positive density dependence (growth rate increases as population size increases) to negative density dependence due to competition (growth rate declines as population size increases).

2. Data and Methods

We use radiocarbon data to evaluate the hunter-gatherer population ratchet hypothesis that waves of density dependent growth describe the expansion of Texas hunter-gatherer populations. The basis for using these data lies in the pattern that the more people in a given area, the more organic waste products they produce and will preserve for archaeologists to dig-up and radiocarbon date later (Freeman et al., 2018b; Rick, 1987). Activities such as burning wood for heat or processing food for consumption generate organic waste. Succinctly, organic waste results from political-economic activities that consume energy, and waste production may increase if population increases or, holding population equal, if political-economic activity increases (Freeman et al., 2018b). Here we do not attempt to disentangle the effects of population and political-economic activity since population and energy output correlate. Rather, we analyze radiocarbon records as energy records reflective of the growth or decline of the mean level of human activity at generational time-steps in a given area. In this context, we emphasize that such radiocarbon records provide an estimate of changes in the mean level of energy output over generations. This may be closely tied to changes in population saturation over time, $k(t)$ (Tallavaara and Jørgensen, 2021; Freeman et al., 2018a), and, indeed, the hunter-gatherer MaB Ratchet hypothesis proposes that increases in population saturation over time may explain the exponential-like increase in the radiocarbon curves of Texas and elsewhere.

We collected published and unpublished radiocarbon ages from Central and Coastal Texas and cleaned the data sets to remove geological and paleontological ages, ages without radiocarbon lab IDs, dates without errors reported, averaged ages, ages without a site trinomial (unique id for all archaeological sites in Texas), ages taken on shellfish and snails, and ages with standard errors greater than 200 radiocarbon years. To correct for potential oversampling biases, we used the binPrep function in the rcarbon package for R (Bevan and Crema, 2018) to combine different samples from the same site that were within 100 calibrated years of each other. All of the raw dates were calibrated using the Intcal13 (Reimer et al., 2013) calibration curve in the rcarbon package. We used the rcarbon package to construct a summed probability distribution (SPD) of each radiocarbon age time-series and summed these time-series (i.e, smoothed them) over 50 year intervals. All raw radiocarbon data and code to run our analyses are available in the SI.

We followed multiple steps to assess whether summed multi-logistic models fit the data. First, we ran a k-mediods cluster analysis on the size and growth rate of each respective SPD. A system that has undergone multiple ratchet like expansions of population saturation should display population sizes clustered aground a given population saturation point separated by brief periods of growth. We use the k-mediods clustering algorithm in the r package cluster because the k-mediods algorithm is less sensitive to outlier data points than the k-means clustering algorithm. We ran our cluster analysis on the two dimensional distribution of SPD values and growth rates. We calculated the growth rates of each SPD as $G_{SPD} = \ln(\frac{SPD_{t+1}}{SPD_t})$. Where G_{SPD} is the growth rate of the SPD;

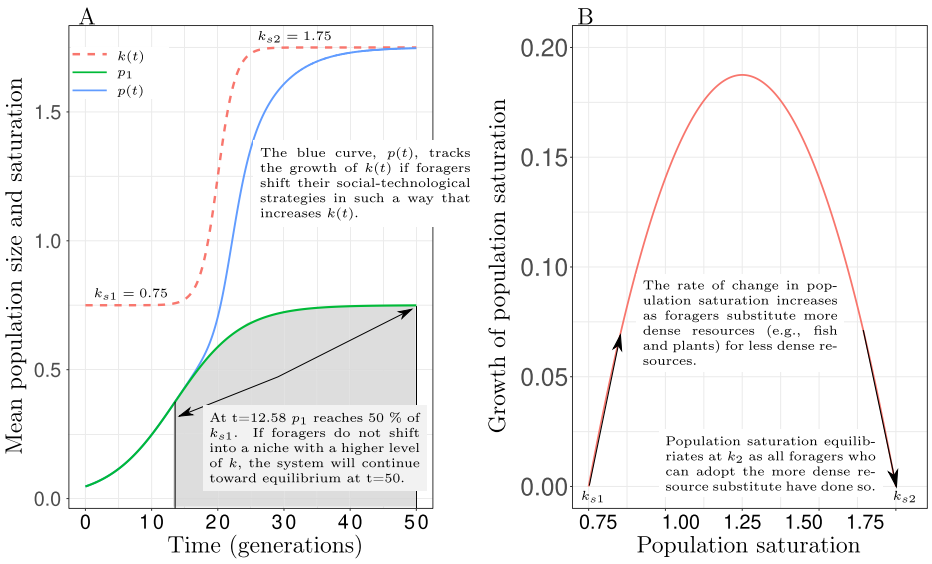


Fig. 3. A–Illustration of bilogistic population growth over time ($p(t)$) as population saturation ($k(t)$) changes over time due to the adoption of a new modal social-technological strategy. The new strategy substitutes more dense plants and fish for large game. Note that the bilogistic curve (blue curve- $p(t)$) provides the impression that a population expands exponentially. If we discretely sample $p(t)$ with error, an exponential model would provide a good statistical fit to the data. Yet, population expansion really occurs due to transient growth phases. B–Illustration of a logistic change in modal social-technological strategy that leads to a higher k. The substitution of more dense resources for less dense increases population saturation, and then population saturation moves toward equilibrium at k_{s2} as foragers reach the upper limit of more dense and predictable resources.

SPD_{t+1} is the value of the SPD at time $t + 1$, and SPD_t is the value of the SPD at time t. Clusters near a population saturation point should display points near equilibrium (i.e., $G_{SPD} = 0$) and differences in the median value of the distribution of SPD values. Cluster analysis allows us to assess if the best number of clusters in the k-mediods algorithm is > 1, as we would expect if there were a signal of multiple population equilibria in the dataset. Note that the clustering is independent of time. Individual summed SPD data points that fall into a cluster may fall anywhere in time. If there is a temporally ordered process, then the cluster mediods of SPD values should increase through time.

Second, we use the results of the above cluster analysis to estimate population saturation values for a multi-logistic (loglet) analysis. For example, in Fig. 4A and B we looked for points near equilibrium (zero growth rates within each cluster) followed by a large growth spurt to estimate initial starting values for k_1, k_2, and k_3 in a three component multi-logistic model. In the case of Central Texas, for instance, we used initial k values of 4.5, 9 and 15. There is a subjective element to this choice, even with the cluster analysis. It is important to note, however, that these parameters are not fixed. They just set the range of values over which an annealing algorithm searches for the best fitting summed multi-logistic model as discussed below. What matters is that the initial values are reasonable, given what we know qualitatively about the archaeological records in these regions and the SPDs. Choosing a k_3 of 30, for example, would be an unreasonably high value that would drastically alter the best fit models chosen as the annealing algorithm searched a parameter space, on average, double the highest actually observed SPD value.

Summed multi-logistic analysis was developed by Meyer et al. (1999) to study growth processes related to technological change, and the model fitting is implemented in an online tool called Loglet Lab 4 (Burg et al., 2017). Conceptually, multi-logistic analysis is similar to wavelet analysis, hence the moniker 'loglet'. A wavelet analysis attempts to decompose a real world signal (changes in some variable over time) into its component parts in order to study both trends and

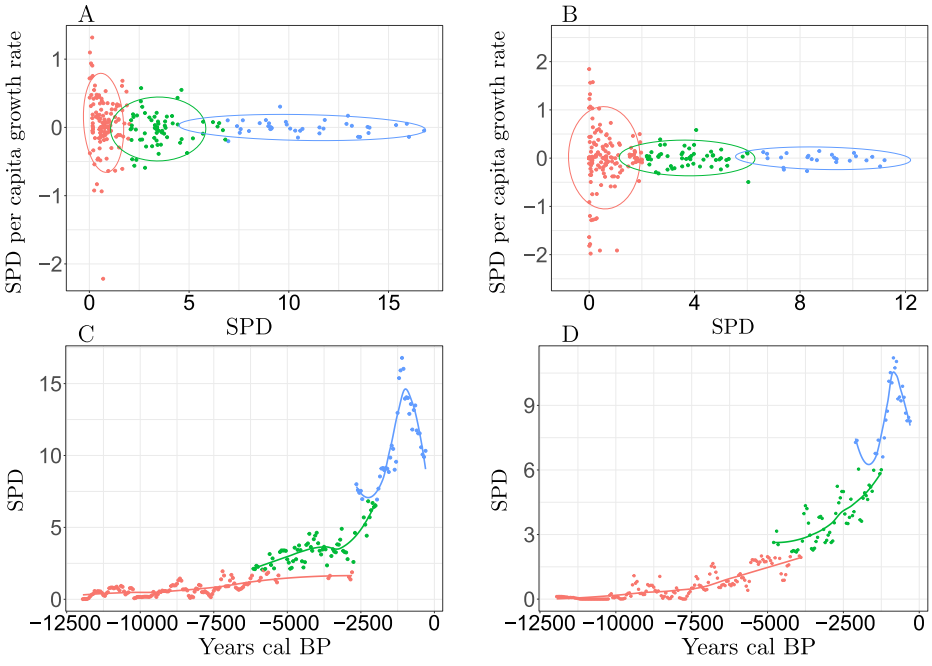


Fig. 4. Comparison of Central Texas (A) and Texas Coastal Plain (B) k-mediods cluster analysis. In both regions, three clusters describe the distribution of SPD size and growth rate better than a single cluster. We calculated the growth rates of each SPD as $G_{SPD} = \ln(\frac{SPD_{t+1}}{SPD_t})$. Where G_{SPD} is the growth rate of the SPD; SPD_{t+1} is the value of the SPD at time $t + 1$, and SPD_t is the value of the SPD at time t. Ellipses define 95% of the normal distribution of points. The clusters were run independent of time and then plotted over time in Central Texas (C) and on the Texas Coastal Plain (D). Fit lines are simply loess smoothed splines that indicate increasing central tendencies through time.

transient changes in a signal over time. The multi-logistic analysis, similarly, attempts to fit the component logistic models that compose an overall growth signal. In this case, the hunter-gatherer population ratchet hypothesis gives us a theoretical basis for predicting that a 'real world' signal of changes in hunter-gatherer populations should contain multiple component logistics and that population saturation increases over time. The multiple logistic components, when summed together, should explain both the long-term trend of the population signal and relatively short intervals (approximately 500–1500 years) of rapid growth (i.e., transients).

In general, the multi-logistic model is defined as

$$P(t) = \sum_{i=1}^{n} p_i(t) \quad (1)$$

where $p_i(t)$ is

$$p_i(t) = \frac{k_i}{1 + e^{-r_i(t-t_{mi})}}. \quad (2)$$

Note here the difference between Eq. (4) in Appendix B and Eq. 2. Eq. (4) captures a theoretical process in which the level of population at time t impacts the substitution of one form of social-technological organization for another, impacting the variable $k(t)$. Thus, changes in k and p are linked variables. In Eq. 2, k_i is a parameter along with r_i and t_{mi}. These parameters are estimated for each component logistic model thought to compose the multi-logistic signal. This treats each SPD times-series as if it is a completed experiment of changes in mean population. As noted above, we used cluster analysis to estimate initial starting values for all k parameters and estimated the remainder of starting parameters using the estimate function in Loglet Lab 4. All initial conditions used are reported in the SI Part II along with model fit information. Here, $r_i = \frac{\ln 81}{\Delta t}$, where Δt is the time it takes a logistic component model i to grow from 10 % to 90 % of population saturation k_i. The parameter t_{mi} is the point at which a component logistic model reaches 50 % of k_i.

Practically, estimating the above parameters means that a summed multi-logistic model may display a multitude of growth forms different from those displayed in Fig. 3. For example, in a two phase model, the curve for $p_2(t)$ could begin to grow before $p_1(t)$ ever reaches 50 % of k_1. Such a pattern would contradict the hunter-gatherer population ratchet because growth would occur before population saturation reaches a population pressure state and sends a signal of an impending Malthusian equilibrium. Fisher-pry transform plots (See SI Part I) allow us to understand the overlap of estimated component logistics by creating a typology of summed logistic growth curves estimated from data (Meyer et al., 1999).

To fit Eq. 2 to each SPD, we first estimate r_i, k_i and t_{mi}. We used our k-mediods analysis to refine our initial estimate of the parameter k_i for each component logistic. The parameter r_i is estimated by a in Loglab 4, which is equivalent to Δt above (the time it takes to grow from 10 to 90 % of k_i). Once the initial parameters are estimated for each logistic component, a range for each parameters defines the search space for a fitting algorithm. Monte Carlo Annealing is used as the default in Loglet Lab 4. Using this algorithm, parameter values are pseudo-randomly generated from the ranges discussed above. This results in synthetic curves that are compared to the data. In all of the models ran, we sought to minimize the root mean square error as our objective function over 10,000 Monte Carlo simulations. In each iteration of the Monte Carlo simulation, a sample of the best fitting models are retained. This method is one way to avoid the local minima problem in fitting nonlinear models to discrete data. Note, we fit a three phase summed multi-logistic in the main text, but evaluated the sensitivity of our results when fitting two and four phase summed multi-logistic models (See SI Part II). We chose the three phase model because it fits the data better than a two or a four phase model. However, all of the models display redundant results consistent with the hunter-gatherer ratchet hypothesis.

3. Results

Our results are consistent with predictions 1–3. Specifically, we find evidence that hunter-gatherer populations in Central and Coastal Texas display multiple waves of density dependent population growth, with three potential episodes of transient population growth, the last of which is synchronous between the two regions. Finally, our analysis suggests that new growth components begin after previous growth components passed 50 % of a previous component's population saturation (i.e., the new growth component beings under resource competition).

Fig. 5 displays the results of a multi-logistic analysis from Central and Coastal Texas. In each region, an overall model with three component logistic models (three phases of growth) fits the data better than a two or four component model (Fig. 5A and B, SI Part II). This supports prediction (1) that the expansion of Texas radiocarbon records is well described by the sum of a series of density-dependent growth models.

Further, consistent with prediction (2), the estimated population saturation parameters of each successive logistic curve increases through time. In Central Texas k_2 is 8.35 times higher than k_1 (i.e., $\frac{k_2=3.26}{k_1=0.39}$), and k_3 is 2.88 times higher than k_2 (i.e., $\frac{k_3=9.38}{k_2=3.26}$). On the Texas Coastal Plain, k_2 is 7.42 times higher than k_1 (i.e., $\frac{k_2=3.14}{k_1=0.42}$), and k_3 is 2.35 times higher than k_2 (i.e., $\frac{k_3=7.4}{k_2=3.14}$). Texas radiocarbon records ratchet up to ever higher estimated k, consistent with increases in population saturation throughout the Holocene.

Consistent with prediction (3), Fig. 5E and F display Fisher-Pry plots that make the component logistic curves linear. The slopes and intercepts of these curves provide information on when a new growth process began. In brief, if the linear curve of component 3 crosses component 2, this would indicate that component 3 growth began prior to component 2 passing 50% of k_2. If the linear curves do not cross, this would indicate that a new growth component began under the phase of previous logistic population growth in which competition for resource was present (see SI Part I for more details). In both regions, succeeding growth components parallel each other and do not cross, indicating that new components of growth began after the previous component had passed 50 % of population saturation (i.e., under resource competition). In both regions, the slope of component 2 is shallower than component 1. This indicates that the second component of growth began once the first component was very near k_1. The increase in slope from component 2 to 3 in both regions indicates that the growth of component 3 began before component 2 reached k_2 but after component 2 had passed 50 % of k_2. This may indicate that foragers were more sensitive and/or better able to respond to population pressure in the later Holocene than in the earlier Holocene.

Finally, the start of the third growth component is nearly synchronous between the two regions. The beginning of the third component of growth begins in Central Texas around 3,345 Cal BP and on Texas Coastal Plain around 3,300 cal BP. Interestingly, the Central Texas record expands from 10 % of k_3 to 90 % of k_3 in only 1,437 years for a maximum growth rate of 0.003, and it took the Texas Coastal Plain population 1994 years for a maximum growth rate of 0.0022. Why the growth rates differ is an interesting question for future research, and may have to do with the different underlying social and subsistence adaptations in the two regions.

4. Discussion

Exponential-like population expansion is well known over the last 1000–400 years for the world population and select countries (e.g., Meyer and Ausubel, 1999; Cohen, 1995). On the surface, these patterns imply that the industrial revolution ushered in a period of unconstrained population growth. However, several authors illustrate that the apparent unconstrained growth of the world population following industrialization is better modeled by waves of density dependent

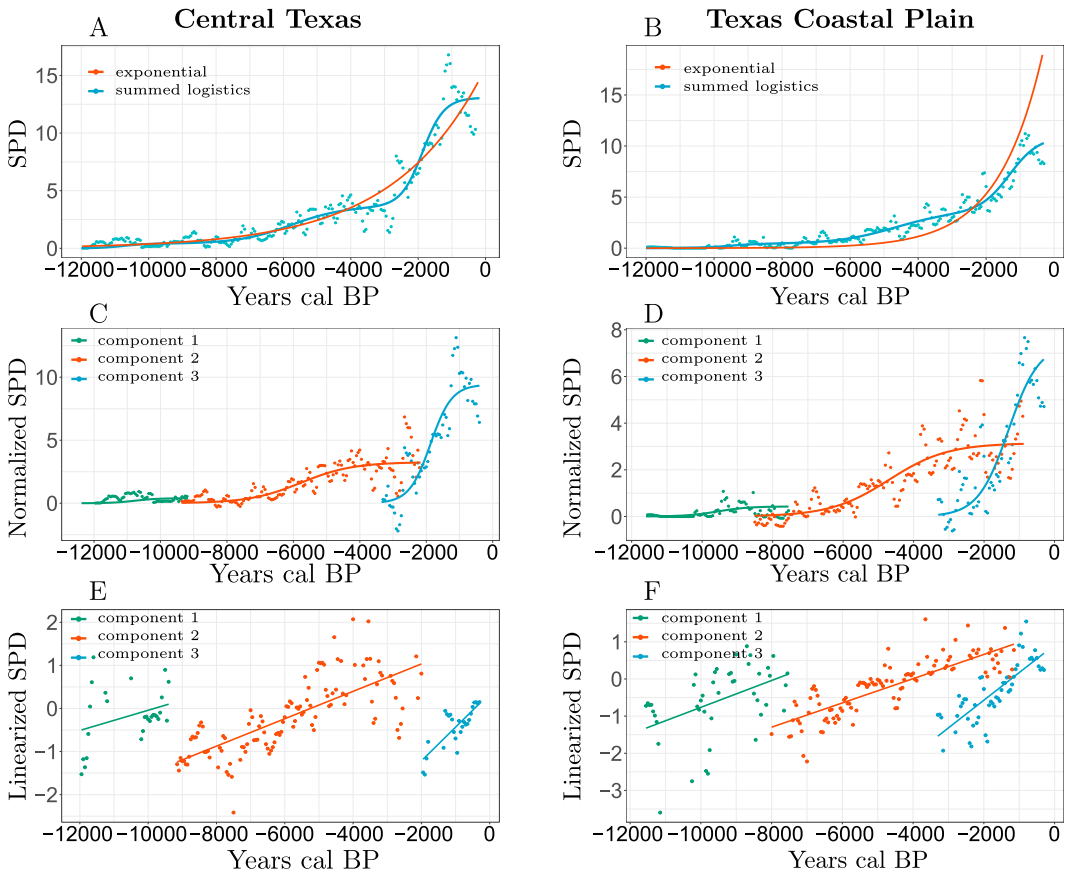


Fig. 5. Comparison of Central Texas and Texas Coastal Plain hunter-gatherer population expansion. In both regions, a multi-component logistic fits the trend as well as an exponential (A and B); both regions display three distinct logistical components (C and D); and both regions display a process of growth substitution and dramatic rise in population saturation (k_i) over time, and new growth phases begin under population pressure (E and F).

growth in which the population saturation point of systems increased over time due to social and technological change (Hopfenberg, 2003; Meyer and Ausubel, 1999; Cohen, 1995). As documented in Fig. 1, the growth of hunter-gatherer populations in Texas–as estimated by radiocarbon ages–is also well described by an exponential increase throughout the Holocene. This is a widespread pattern of radiocarbon expansion in N. and S. America (Bird et al., 2020; Freeman et al., 2018a). However, Texas radiocarbon records are perhaps better described by waves of logistic growth rather than a simple exponential. Thus, we asked: Does the long-term expansion of archaeological radiocarbon generated by Central and Coastal Texas hunter-gatherers potentially signal a Malthus-Boserup process of population growth?.

To answer this question, we first adapted a ratchet model of population growth to a hunter-gatherer social-ecological context. Next, we assessed the plausibility of a hunter-gatherer population ratchet model using radiocarbon records and summed multi-logistic analysis. Specifically, the sums of multiple component logistic models fit the SPDs from Central and Coastal Texas well, the population saturation points of the component logistic models increase through time, and new growth components begin under resource competition (i.e., after the previous growth component has passed 50 % of population saturation). This indicates that Texas hunter-gatherer populations expanded in a way consistent with the population ratchet hypothesis. The same may hold true for many radiocarbon records that display an exponential increase in N. and S. America. If so, this could indicate that a positive feedback between population change and changes in the organization of society and technology underlie the population ratchet-like patterns of growth among human societies in general, not just as a consequence of industrialization.

Our work is a starting point; as much a way of changing our perspective on archaeological records as an interpretation of the population growth dynamics of Texas hunter-gatherers. In the remainder of this discussion, we describe the complexities and challenges related to interpreting long-term population growth dynamics from archaeological radiocarbon records in light of the hunter-gatherer MaB ratchet model, and we conclude by describing how multi-logistic models can change one's perspective and help generate research questions about hunter-gatherer archaeological records.

4.1. Complexities and challenges associated with a Malthus-Boserup interpretation

At least three complexities and/or challenges make a clean interpretation of the multi-logistic curves that we fit to Texas radiocarbon records (or to any records) difficult and require more research and debate. The first two challenges are empirical and the third conceptual. To help pave the way for future research and generate debate, we first describe the logic of each challenge, and then we either add our voice to the debate or speculate about how we might address a given challenge through future research.

(1) We have modeled the change in population saturation as a result of cultural evolution: New forms of technology and social organization open up a new, more productive niche that releases population pressure and results in ratchet like growth. The multi-logistic models fit to the Texas data clearly show an increase in population saturation over time; however, more research is required on two fronts because we know that climate can also indirectly impact human population saturation. The causal linkages are as follows: temperature and moisture availability impact ecosystem productivity and diversity, which determines the availability of food and pathogens in an environment, and, in turn, the

availability of food and pathogens impacts mean human population density (Freeman et al., 2020; Tallavaara et al., 2018; Binford, 1983). There are two scales at which climate indirectly impacts the population saturation level of human societies. First, temperature and moisture vary around a long-term climate mean, creating shorter-term fluctuations in ecosystem productivity in a given area over decades to centuries. Second, the long-term climate mean changes over centuries to millennia, changing the long-term mean of ecosystem productivity and, thus, the long-term population saturation of a landscape for foragers. The empirical research question is whether cultural evolutionary processes moderate the effects of climate and, if so, by how much?.

At the smaller scale, we can investigate the role of climate as a short-term trigger of innovations in technology and social organization by integrating high frequency paleoclimate or other relevant paleoecological time-series with radiocarbon time-series (e.g., Lima et al., 2020). Indeed, climate variation drives the hunter-gatherer ratchet process that we propose. We propose that as foraging populations approach the population saturation of a given set of social and technological strategies, land use patterns become more sensitive to decade to century scale-climate variation, which creates a selective environment that favors social organization and technologies that reduce this sensitivity. Integrating paleoclimate/ecological time-series with radiocarbon time-series would allow researchers to assess whether including paleoclimate information in multi-logistic models, such as those developed above, would improve the fit of such models (which it should). This would also allow researchers to assess whether rates of innovation are highest during periods of more intense climate fluctuations and when millennial scale population growth is declining at the margin (which would signal competition for resources).

At the larger scale, we can investigate the relative importance of social and technological change vs. long-term climate control of ecosystems, again, by integrating paleoclimate and paleoecological time-series with radiocarbon time-series. If climate solely controls population saturation, then we should observe that the long-term trends in the radiocarbon time-series associate with the long-term trends in the paleoclimate records useful for understanding changes in ecosystem productivity. Similarly, if cultural evolutionary processes, such as those proposed by the hunter-gatherer ratchet hypothesis, play a role, then long-term radiocarbon trends (as a signal of mean population) may contradict the changes in population one would expect given a paleoclimate time-series. This is to say that as ecosystem productivity goes down over a millennia, mean population actually rises over that same time period. This would signal that a Malthus-Boserup innovation like process took place, given that such a pattern also associates with a shift in technology and social organization toward the intensive processing of high density, relatively low return resources.

For instance, paleoclimate/ecological synthesis from Central Texas indicates, "(i) a warming/drying trend from early to mid Holocene, (ii) a brief shift away from warm/dry conditions in the transition from the mid to late Holocene, and (iii) a dry interval in the late Holocene" (Wong et al., 2015, p. 170). Instrumental records from Central Texas indicate a short grass prairie to prairie with more oak and pecan forest cover as one moves east toward the Texas Coastal Plain. The dry and warm conditions in the early to mid Holocene (approx. 8,000 to 6,000 cal BP) favored more drought tolerant species characteristic of ecosystems with lower net primary productivity (Cordova and Johnson, 2019) than the ecosystems recorded in the instrumental records. Yet, despite the decrease in ecosystem productivity from 8,000 to 6,000 cal BP, the multi-logistic analysis from Central Texas indicates an over 800 % increase in population saturation, completely bucking the trend one would expect if ecosystem productivity solely controlled population saturation. This discrepancy could result from the fact that the multilogistic models are wrong (and we see the development of these models as an exercise in hypothesis building, so this is a possibility). The discrepancy could also result from a long-term cultural evolutionary process in which Texas foragers were filling a more energy intensive niche focused more on seeds, nuts, and tubers, potentially stimulated by a reduction in bison and other large game during the mid Holocene dry period (Mauldin et al., 2003). We speculate that the niche filling process described by our hunter-gatherer version of the MaB Ratchet played a role.

This speculation is further informed by Fig. 6, which graphs the summed probability of radiocarbon ages associated with fire-cracked rock features remnant of large earth ovens used to bulk process geophytes (tubers). The higher the summed probability, the more dated fire-cracked rock features. Note, there is an initial use of such cooking features around 9,000 cal BP, followed by fluctuations, and then a steady presence from 6,000 to 4,000 cal BP. Further, a sustained increase in earth oven frequency begins at 3,600 cal BP. This increase begins prior to the onset of cooler, wetter conditions in the Late Holocene after 3,000 cal BP (Wong et al., 2015) and peaks after a shift back toward warmer, dryer conditions after 1500 Cal BP. The key is that the third component logistic growth curve in Fig. 5C increases from 3,345 Cal BP to 700 Cal BP, tracking the increase in labor intensive earth oven technology. This growth component and increase in earth oven use begins before and continues through the long-term shift toward cooler and wetter conditions and peaks in spite of a shift toward warmer dryer conditions around 1,500.

Paleoclimate records need better temporal constraint in Central Texas, but this speculative exercise does suggest a path forward. If estimated levels of population saturation increase in the face of paleoclimate shifts that should decrease the productivity of ecosystems over the long-term, then this would suggests a role for cultural evolutionary processes that lead to more productive foraging niches and a rise in population saturation. This type of investigation, beyond the scope of our current paper, requires solving the methodological challenges of integrating time-series of changes in subsistence technology and social organization, estimates of changes in population, and paleoecological time-series useful for reconstructing ecosystem productivity.

(2) Surovell et al. (2009) suggest that organic materials are deleted via geomorphic processes at an exponential rate, with more material deleted earlier in time. Further, archaeological sites created closer to the present may be easier to find and, thus, archaeologists may have created larger, more redundant samples of material for radiocarbon dating. Both of these processes might contribute to the long-term trend of radiocarbon frequency distributions. We have attempted to mitigate the effect of the 'oversampling' of radiocarbon ages from archaeological sites via

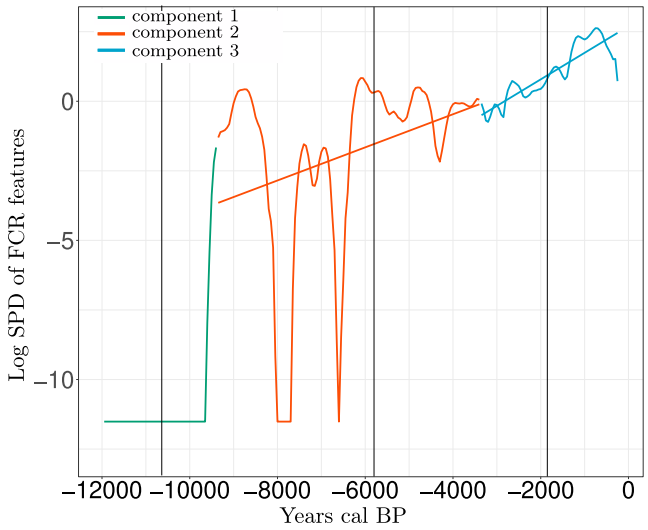


Fig. 6. Summed probability distribution of radiocarbon ages securely associated with earth oven features in Central Texas. Growth components are those derived from the entire database of radiocarbon ages and presented in Fig. 5. Vertical reference lines indicate the estimated date at which a growth component reached 50 % of estimated population saturation.

our methods. Interesting questions remain, however. Might taphonomic processes, alone, lead to a signal consistent with multiple waves of density dependent growth, or might the exponential-like signal just be a result taphonomic processes? An affirmative answer to the second question seems unlikely. For example, taphonomic loss is not the most relevant bias in the Late Holocene among larger, more sedentary populations (Bluhm and Surovell, 2019), and exponential-like distributions, while very common, are not universal. Comparative studies across a range of geomorphic environments could help sort this out. Further, simulations of large data sets of radiocarbon with known taphonomic biases could also help in this direction. In short, proof is not our claim; only a consistency between macrodemographic proxy data and theory.

(3) Finally, the coarse grained nature of archaeological data, radiocarbon data in particular, may hinder the usefulness of models drawn from population ecology and demographic theory for explaining the long-term trajectories of human population growth. This argument has been recently advanced by Tallavaara and Jørgensen (2021), who use simulation models to understand why the population growth rates of hunter-gatherers estimated from radiocarbon records are lower than population growth rates estimated from the ethnographic record. They conclude that radiocarbon records estimate changes in population at a much coarser scale than ethnographic data based on annual observations of population size. Based on this conclusion, Tallavaara and Jørgensen (2021, p. 6) make the inference that archaeologists should be cautious in using models, the logistic model in particular, drawn from demographic theory.

We share the conclusion that archaeological radiocarbon records provide a coarse grain estimate of changes in the mean population size or the energy output of a human system in a given region over generations; however, we do not share the skepticism about applying models from demographic theory to archaeological radiocarbon. First, archaeological radiocarbon, if indeed a reflection of mean population size, then, by definition, must reflect the dynamics that occur at smaller scales. For instance, in a closed system, the change in population is births less deaths. One can measure this in annual, generational, or in multigenerational time-steps. Population growth at multigenerational time steps reflects the sums of growth at smaller time-scales. Second, dynamic processes play out at all scales. Any population growth trajectory is composed of sequences of such trajectories at smaller scales. For example, a small group may grow to population saturation within a habitat over a decade and then start to exploit a neighboring habitat. This simple inclusion of another habitat doubles population saturation. If one zooms in on the first habitat, one will find large changes in population that, when viewed at the larger scale of both habitats, appear less dynamic. Mathematical models have no characteristic scale, and such models may be applied to population dynamics at whatever scale is relevant to one's research question.

In short, as a field, archaeologists should debate how to use models drawn from population ecology and demography to inform archaeological research, given the coarse grained nature of archaeological data. In our view, such models provide an essential tool. Here, we used a bilogistic model in which the mean field of population changes over generations and the mean field of population saturation (carrying capacity) does as well, itself as a logistic process of filling a more productive niche (see Appendix B). The fact that radiocarbon data are most useful for understanding large scale processes (coarsely estimated mean population size) does not necessarily mean that we should be skeptical of such models, just clear about the scale at which we apply them.

4.2. Conclusion: changing perspective

Describing the growth of human populations in general, and hunter-gatherers in particular, is necessary to explain the diversity of growth trajectories observed among human populations throughout the Holocene. The accumulation of radiocarbon databases and improvements in methodology are beginning to make this goal a reality. However, we must also develop and evaluate dynamic models of population expansion in tandem with database and methodological development. Theory development points up interesting social and ecological processes as well as limitations to methodologies difficult to notice without pushing the theory forward. We have contributed to this processes by proposing that a population-ratchet like process may have driven the apparent exponential expansion of radiocarbon records generated by prehistoric Texas hunter-gatherers.

Our results are as much about hypothesis building as they are about developing an interpretation for Texas radiocarbon records. For example, by fitting multi-logistic models, following an established Malthus-Boserup model, we can change our perspective on archaeological sequences. In many microeconomic models of human behavior the optimal strategy for an individual forager changes with the macrodemographic state of a system. The multi-logistic models allow us to potentially partition archaeological sequences around demographic/energy regimes rather than traditional cultural historical sequences per se, to actually estimate the macrodemographic state of a system and evaluate behavioral models related to patch use, habitat selection, resource selection, and status competition.

The use of large radiocarbon data sets to make inferences about human population processes is still quite new. The explosion of publications surrounding the topic both illustrates and tends to mask this fact. The research community is in an important exploration phase. Our work explores an unconsidered dynamic population model that may productively inform the analysis of radiocarbon records and the socioecology of hunter-gatherers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jaa.2021.101321.

Appendix B. A Bi-logistic model of population growth

Following Meyer and Ausubel (1999), a continuous time model of population growth, illustrated in Figure 3, with a population ratchet can be written as follows:

$$\dot{p} = pr(1 - \frac{p}{k(t)}) \tag{1}$$

where p is population size at time t; r is the maximum growth rate of the population; and $k(t)$ is the population saturation of an area that changes over time. Here, $k(t)$ varies over time as a consequence of a population of forager's model strategies for producing food. For concreteness, consider a system with two potential population saturation values that vary based on the proportion of calories that come from plant foods and fishing for an average forager: 30 % leads to a maximum population saturation of k_{s1} and 70 % leads to a maximum saturation of k_{s2}.
We can model the change in k as a logistic function that describes the substitution of fish and plants for large game

$$\dot{k} = \alpha(k - k_{s1}) * [1 - (k - k_{s1})/k_g] \tag{2}$$

where α is the maximum rate at which foragers substitute one modal strategy for another, and k_g is the interval between k_{s1} and k_{s2}. For example, if $k_{s1} = 0.75$ and $k_g = 1$, then $k_{s1} + k_g = k_{s2} = 1.75$. Figure 3B illustrates the logistic growth dynamic of $k(t)$. The model captures a basic process widespread in the adoption and spread of technology (Rogers, 2010). At first the alternative modal strategy (or technology) increases quickly, then the rate of increase slows down as most members of a population adopt the strategy. If we define t_p as the time at which a growing population reaches population pressure (i.e., start to experience instability in harvest), then we can write the solution to equation 2 as

$$k(t) = k_{s1} + \frac{k_g}{1 + e^{-\alpha(t - t_p)}} \tag{3}$$

where t is time.
Finally, we define p_0 as the the initial population density of a given area and write the solution to equation 1 as

$$p(t) = \frac{k(t)}{1 + (\frac{1}{p_0/k(t)})e^{-rt}}. \tag{4}$$

One can generalize equation 4 for more than two k. Here, we simply illustrate the basic prediction for macrodemographic data that follow from a hunter-gatherer population ratchet hypothesis. Figure 3A displays equations 3 and 4 in graphic form. Population, the blue solid curve, expands as it approaches k_{s1}. Once the blue curve crosses the threshold t_p, the sensitivity of the system may favor the adoption of a new mode of social and technological organization focused on more dense plant and fish resources. A rapid population growth phase results as foragers adopt the modal strategy with a higher k, and the system ratchets up to k_{s2}.

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