

A note on the use of temporal frequency distributions in studies of prehistoric demography

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Abstract

Temporal frequency distributions of archaeological sites and radiocarbon dates are commonly used as proxies for prehistoric population levels based on the assumption that more people create a stronger archaeological signal. While this assumption is certainly correct, we question whether relative frequencies of sites or dates observed from prehistoric contexts are necessarily linked to human demography. In this paper, we demonstrate that the typical positive curvilinear frequency distributions observed in archaeological contexts also regularly occur in paleontological and geological contexts and are thus likely caused by the operation of time-dependent destructive processes, what we call “taphonomic bias.” Using a simple model, which assumes a constant rate of site loss over time, we show how taphonomic bias can produce positive curvilinear frequency distributions through time even in cases of population stasis, decline, and fluctuation. We conclude that caution must be used when attempting to infer demographic trends from frequency distributions alone.

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1. Introduction

A logical outgrowth of almost six decades of radiometric dating is the compilation of databases of dated archaeological, paleontological, and geological contexts. One increasingly common application of such data is the study of temporal frequency distributions, examining changes in the abundance of past phenomena through time (Adams et al., 2001; Barton et al., in press; Brantingham et al., 2004; Frison, 1991; Gamble et al., 2004; Holdaway et al., 2005; Kuzmin and Keates, 2005; Rick, 1987; Surovell et al., 2005; Walker and Johnson, 2003; Waters and Kuehn, 1996). In archaeology, changes in the relative temporal frequency of dates or dated components are commonly interpreted to reflect changes in human demography based on the simple and reasonable assumption that as

the number of people increases, so does the strength of their archaeological signal. In this paper, we argue that extreme caution must be used when interpreting temporal frequency distributions because the operation of simple taphonomic/destructive processes will create patterns that mimic approximately those of exponential human population growth. In the spirit of full disclosure, this finding is not only problematic for the interpretations reached by others, but we have made similar assumptions and interpretations of temporal frequencies distributions in our own work (Barton et al., in press; Brantingham et al., 2004; Surovell et al., 2005).

We begin by reviewing a number of studies which directly or indirectly incorporate temporal frequency distributions of dated archaeological, paleontological or geological deposits. Such distributions almost ubiquitously appear to conform to a nearly monotonically increasing pattern through time. In a simple sense, this means that recent things overwhelmingly outnumber older things, and the form of the function relating abundance to age is nonlinear. We develop a simple model to

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show that the operation of a constant taphonomic process on the archaeological record will, in most cases regardless of the prior distribution (before taphonomy), produce a positive curvilinear frequency distribution through time. We illustrate this phenomenon for the cases of: (1) population stasis and decline; (2) a climate-based model where human population densities fluctuate in concert with climatic variability; and (3) a predator–prey model wherein a prey species is hunted by an invasive human predator.

2. Temporal frequency distributions in the Quaternary

There are many factors which affect the temporal distribution of events recorded in the past (Bryson et al., 2006; Holdaway et al., 2005; Mandel, 1995; Meltzer and Mead, 1985; Rick, 1987; Waters and Kuehn, 1996). These may be reduced to three primary issues: (1) the original distribution of the population sampled; (2) factors which introduce biases into the distributions we observe; and (3) chance in sampling. The third factor becomes negligible in large samples, so we focus on the first two. When using temporal frequency distributions in archaeological research, we are ultimately trying to infer things about the distribution of the original population being sampled, but we must be aware of the potential biases serving to modify our sample of it. It seems clear to us that all authors who have studied temporal frequency distributions are aware of the major factors which serve to introduce bias into such data, but it is our contention that in most cases the bias introduced by destructive processes (e.g., physical weathering, erosion, oxidation, and dissolution) may override the form of the original distribution rendering it virtually invisible, particularly over large time scales.

When no bias occurs in sampling, every object in a population has an equal probability of being sampled (meaning discovered or excavated in archaeology). Bias occurs when portions of populations are more or less likely to be sampled for any reason. Some of the major biases impacting temporal frequency distributions of archaeological sites or deposits include research, discovery, and taphonomic bias, the focus of this paper. By taphonomic bias, we mean biases introduced by processes which destroy the archaeological and/or geological record. Only one assumption is necessary to demonstrate that taphonomic bias will wreak havoc on temporal frequency distributions: the longer something exists, the greater the probability that it will be destroyed and therefore be undiscoverable. In other words, the probability that something will be removed from the geological/archaeological records is in part a function of time. While this is not a novel observation, it is one that should not be taken lightly. This simple fact alone can insure that in most cases, young things will outnumber old things in the archaeological record.

We are not arguing that other types of bias have no effect. Research/discovery bias due to greater visibility of archaeological sites is likely of increasing importance for frequency distributions which include agricultural time periods with highly visible monumental and/or domestic architecture. Also, because older archaeological components are

deeper in stratigraphic sections, there is a necessary bias in favor of younger components deriving from the Law of Superposition because all sites are not excavated down to sterile deposits. Our general point, however, is that over long time scales, we believe that taphonomic bias drives the emergence of positive curvilinear temporal frequency distributions.

In Table 1, we list a number of studies/datasets from the late Quaternary which show positive curvilinear temporal frequency distributions through time, and we present examples of such distributions in Fig. 1. Frequency distributions are most commonly presented as summed calibrated probability distributions of ^{14}C dates (Barton et al., in press; Bryson et al., 2006; Gamble et al., 2004; Surovell et al., 2005), or histograms/frequency polygons of sites of calibrated or uncalibrated ^{14}C dates (Adams et al., 2001; Brantingham et al., 2004; Frison, 1991; Kuzmin and Keates, 2005; Rick, 1987; Walker and Johnson, 2003; Waters and Kuehn, 1996). With few exceptions (Erlandson et al., 2001; Rick, 1987), most archaeological studies with large sample sizes (generally $n > 100$) show the same pattern—the number of sites and/or dates increases through time in a curvilinear fashion (Fig. 1a). That such patterns are commonly interpreted to represent human population growth (e.g., Kuzmin and Keates, 2005; Rick, 1987; Surovell et al., 2005; Walker and Johnson, 2003) is logical since biological populations should grow exponentially and/or logistically. The ubiquity of such patterns, however, raises a red flag as it would seem to imply long-term exponential population growth for humans in most places and times in the late Quaternary, something which seems very unlikely (Pennington, 2001).

Most temporal frequency distributions also show a decline in frequency in the most recent time period of the sample (Fig. 1). In our examples involving Pleistocene fauna, this usually can be explained by extinction. In our archaeological examples (e.g., Fig. 1a), it is more difficult to explain. Our working hypothesis is that declines in the most recent sampled intervals are caused by research bias. For example, it may be that archaeologists are less likely to use radiocarbon dating in trying to determine the age of sites with historic period artifacts. For the New World examples, it is possibly attributed to the combination of research bias and post-contact disease epidemics.

We also examined a number of similar studies which incorporate temporal frequency distributions that should be independent of human population growth. First, we examined studies incorporating date lists or frequency distributions involving Pleistocene fauna in time periods preceding human colonization (Agenbroad, 2005; Guthrie, 2003; Meltzer and Mead, 1985; Miller et al., 1999). While animal populations should also grow exponentially, humans are uniquely capable of dramatically increasing carrying capacity by resource intensification and food production. Thus, once carrying capacity is reached, theory suggests that animal populations should maintain relatively constant levels which vary in concert with environmental carrying capacity and predation intensity. Nonetheless, frequency distributions of Alaskan, North

Table 1
Case studies showing positive curvilinear temporal frequency distributions

Case	Region	Time span	References
<i>Archaeological</i> ¹⁴ C dates	Siberia	50–10 ¹⁴ C ka	Brantingham et al., 2004; Kuzmin and Keates, 2005; Surovell et al., 2005
¹⁴ C dates	China	45–10 ka	Barton et al., in press
¹⁴ C dates	Europe	30–10 ka	Gamble et al., 2004
Hearth ¹⁴ C dates	NSW, Australia	2.5–0 ka	Holdaway et al., 2005
Hearth ¹⁴ C dates	Nevada, USA	4.2–0 ka	Bright et al., 2002
¹⁴ C dates	California, USA	10–0 ¹⁴ C ka	Walker and Johnson, 2003
¹⁴ C dates	Wyoming, USA	12–0 ¹⁴ C ka	Frison, 1991; this paper
¹⁴ C dates ^a	Peru	12–0 ¹⁴ C ka	Rick, 1987
Archaeological sites	Europe	50–10 ka	Adams et al., 2001
Archaeological sites	South Dakota, USA	11–10 ¹⁴ C ka	Waters and Kuehn, 1996
<i>Paleontological</i> ^b			
Pleistocene Fauna ¹⁴ C dates	N America	50–10 ¹⁴ C ka	Meltzer and Mead, 1985
Mammoth ¹⁴ C dates	N America	40–10 ¹⁴ C ka	Agenbroad, 2005
Pleistocene fauna ^c	Alaska, USA	30–12 ¹⁴ C ka	Guthrie, 2003
<i>Genyornis</i> eggshell amino acid racemization dates	SE Australia	130–45 ka	Miller et al., 1999
<i>Geological</i>			
Fire-related erosion events	Wyoming and Idaho, USA	8–0 cal ka	Pierce et al., 2004
Volcanic eruption ¹⁴ C dates	Global	40–0 cal ka	Bryson et al., 2006
Alluvial deposit ¹⁴ C dates ^d	Central Plains, USA	11–0 cal ka	Mandel, 1995
Flood deposit ¹⁴ C dates	Arizona and Utah, USA	6–0 ¹⁴ C ka	Ely et al., 1993

^a Based on the distribution of all dates. The sample of dates from highland regions does not fit this distribution (Rick, 1987).

^b Paleontological cases examined include date frequency distributions on extinct fauna prior and up to human colonization to examine changes through time which should be independent of human action.

^c Based on ¹⁴C dates excluding individual dates considered by Guthrie (2003) to be infinite (beyond the limits of the radiocarbon method).

^d Based on the summed temporal frequency distribution of dates from all geomorphic contexts.

American, and Australian Pleistocene fauna show precisely the same pattern; largely monotonic increases through time until human colonization. While it is possible that all animal populations grew consistently and exponentially during the Pleistocene, it is not particularly likely. It is also noteworthy that the same pattern is observed over very different time spans—for North American fauna from 40 to 10 ka, and for *Genyornis* in Australia from 130 to 60 ka (Table 1).

This pattern also is evident from geological contexts which should be largely independent of biological population dynamics. For example, sedimentary deposits linked to fire in Central Idaho and Yellowstone National Park (USA) become more abundant through time (Pierce et al., 2004). Although it could be argued that fires in this region were set by humans, such that fire frequency is simply tracking human population growth, but the same pattern appears elsewhere in the geological record. For example, positive curvilinear growth is seen in large databases of radiocarbon dates tracking the frequency of alluvial deposition in the American Central Plains and Southwest (Ely et al., 1993; Mandel, 1995) and global volcanic eruptions (Fig. 1c) (Bryson et al., 2006).

There are two likely explanations of this repeated pattern: (1) human populations, animal populations, sedimentation, and volcanic eruptions all increased in frequency in similar ways over the course of the Quaternary, or (2) some consistent bias is affecting all or some of these datasets. We obviously favor the second hypothesis and believe that bias to be taphonomic.

3. Modeling taphonomic bias

To demonstrate how taphonomic bias can produce positive curvilinear frequency distributions, we present the results of a very simple modeling exercise. We begin by generating hypothetical distributions of population sizes through time. We then modify these underlying distributions using the simplest possible taphonomic model, a constant rate of site loss per unit time. We intend the results of these models to be interpreted as expected post-taphonomic frequency distributions of archaeological deposits or sites that could be observed by archaeologists.

If we assume that archaeological sites are formed in numbers that are exactly proportional to the size of population then, in the absence of any taphonomic alterations, the observed frequency of archaeological deposits or site n_t from each time interval t would provide an accurate proxy of relative population sizes at those times. This is the general reasoning behind standard archaeological interpretations of deposit or site frequency distributions. To see if this reasoning remains valid under the simplest possible taphonomic case, we assume that the probability that a site is destroyed by any number of common taphonomic processes remains constant through time. Mathematically, the expected number of sites surviving from a time of initial deposition to be observed by archaeologists today is given as:

$$n = n_t e^{-\lambda t} \quad (1)$$

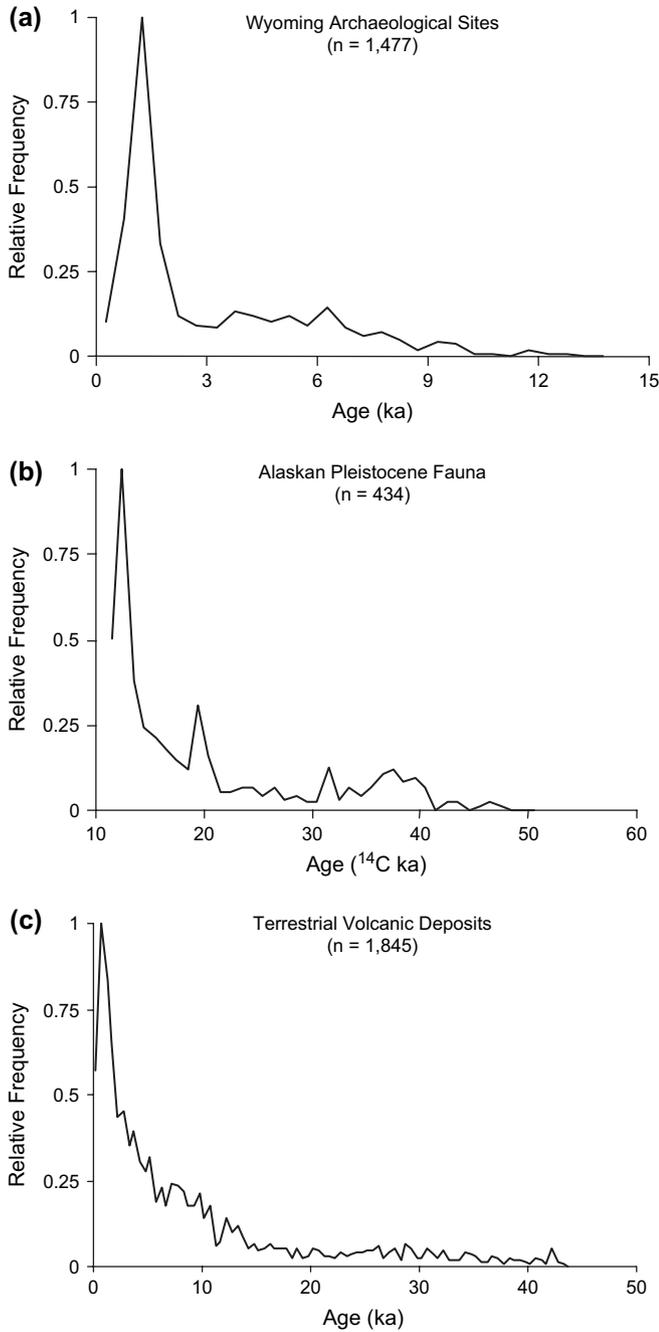


Fig. 1. Examples of positive curvilinear temporal frequency distributions (shown as frequency polygons) from archaeological (a) and non-archaeological contexts (b,c). (a) Frequency distribution of calibrated ¹⁴C dates from archaeological contexts in Wyoming (unpublished data from the Wyoming State Historic Preservation Office). (b) Uncalibrated ¹⁴C dates of Alaskan Pleistocene fauna. Data from Guthrie (2003). (c) ¹⁴C dated volcanic eruptions. Data from Bryson et al. (2006).

where n_t is the pre-taphonomic number of sites created at time t , λ is the constant rate of site destruction, what we refer to as the taphonomic rate (e.g. $\lambda = 0.0001 = 1/10,000$ sites destroyed per year), and t is the time elapsed from initial deposition of those sites to the present. Eq. (1) is a simple exponential decay equation and has a general monotonic-increasing form through time (Fig. 2). A straightforward

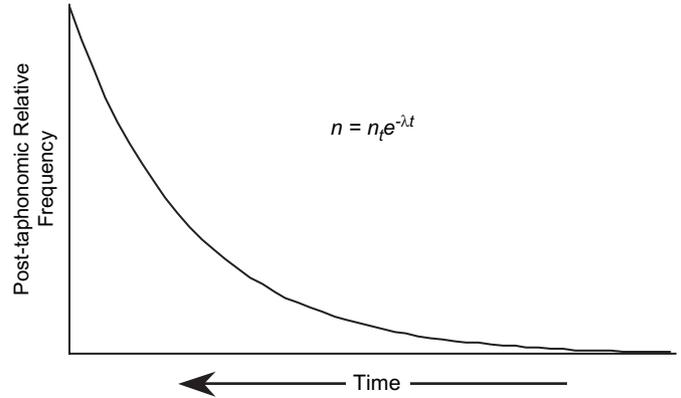


Fig. 2. A constant taphonomic rate of site destruction through time is expected to produce an exponentially increasing distribution of the relative frequency of archaeological deposits or sites through time.

derivation of Eq. (1) is found in Faure and Mensing (2005). In general, the number of sites surviving from more distant times tends to be small (i.e., $n \rightarrow 0$ as $t \rightarrow \infty$), and approaches the actual number of pre-taphonomic sites deposited as one approaches the present (i.e., $n \rightarrow n_t$ as $t \rightarrow 0$).

Surprisingly, perhaps, a constant taphonomic rate often drives the emergence of an exponential functional form in the post-taphonomic frequency distribution of sites through time regardless of the initial frequency distribution of sites. The simplest case to consider is the situation where populations existed at equilibrium in an environment; that is, population sizes remained constant through time (Fig. 3a). The pre-taphonomic numbers of sites deposited at each time is a constant proportional to the true underlying population size (i.e., $n_t = K$). The expected post-taphonomic frequency distribution of deposits or sites is given exactly by Eq. (1) (i.e., $n = Ke^{-\lambda t}$) and is exponentially increasing through time for all hypothetical taphonomic rates (Fig. 3b). In general, high taphonomic rates such as $\lambda = 1 \times 10^{-3}$ (i.e., 1/1000 sites destroyed per year) transform the underlying constant distribution of deposited sites into a strongly concave distribution. The impression is that population sizes remained low over the majority of the late Pleistocene and then grew rapidly at the onset of the Holocene around 10,000 years ago. By contrast, at a low taphonomic rate $\lambda = 5 \times 10^{-5}$ (i.e., 1/20,000 sites destroyed per year) the exponential increase in population sizes inferred from the post-taphonomic temporal frequency distribution of sites suggests a longer period of exponential growth. The seemingly reasonable inference of exponential population growth through time based on post-taphonomic frequency distributions of archaeological deposits or sites is demonstrably wrong in both cases.

Figs. 4 and 5 illustrate that a constant taphonomic rate can also override the archaeological signatures of even more complex population growth scenarios. In Fig. 4a populations are assumed to decline exponentially through time. Assuming, as in the above case, that the number of archaeological sites formed at time t is exactly proportional to population size, then

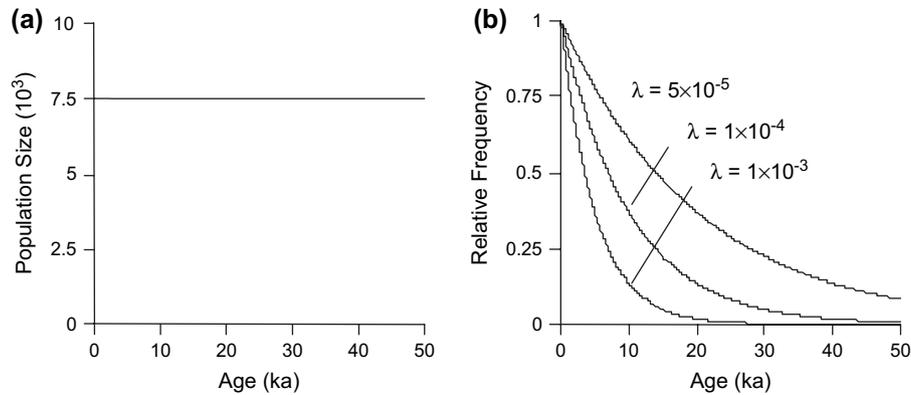


Fig. 3. The impact of constant rates of site destruction on the distribution of sites produced by a population that is not changing through time. (a) A constant or equilibrium population of 7500 individuals is expected to produce a constant number of archaeological sites per unit time. (b) The post-taphonomic relative frequencies of archaeological sites given different taphonomic rates λ .

$$n_t = Ke^{\alpha t} \quad (2)$$

Eq. (2) states that the number of sites initially deposited was exponentially larger in the past (i.e., $n_t \rightarrow \infty$ as $t \rightarrow \infty$), and declined towards some minimum number of sites K in recent times (i.e., $n_t \rightarrow K$ as $t \rightarrow 0$). Application of a constant taphonomic rate may override the true population pattern to generate an exponential increase in the distribution of sites through time. Fig. 4b shows that taphonomic rates of $\lambda = 1 \times 10^{-3}$ and 5×10^{-3} lead to a frequency distribution of sites through time that are qualitatively the opposite of the true population trajectory. One would be reasonably inclined to conclude that populations were actually increasing exponentially through time even though the reverse was true. However, at low taphonomic rates such as $\lambda = 5 \times 10^{-5}$ the pattern is qualitatively similar to (but quantitatively different from) the true population trajectory. Here the conclusion that populations were decreasing through time would be qualitatively correct. The general conclusion from this scenario is that population declines may be difficult to observe from post-taphonomic frequency distribution of archaeological sites when taphonomic rates are high.¹

Similar concerns may arise when attempting to infer cyclical or stochastic population fluctuations, as might be expected if periods of population growth and decline are correlated in some way with climatic cycles. Fig. 5a shows a hypothetical distribution of population sizes through time that is perfectly correlated with the NGRIP $\delta^{18}\text{O}$ sequence of climatic fluctuations over the past 50,000 years. According to this hypothetical model, populations are largest during warmer events, reaching a maximum size at the beginning of the Holocene, and smallest during cold events, reaching minima during Heinrich Events, the glacial maximum and the Younger Dryas.

As with the case above, applying different constant taphonomic rates to this underlying distribution produces strong

patterns of exponential increases in the frequency of archaeological deposits through time (Fig. 5b). At high taphonomic rates (e.g., $\lambda = 1 \times 10^{-3}$), most of the underlying stochastic fluctuations from all time periods are filtered out. At lower taphonomic rates (e.g., $\lambda = 5 \times 10^{-5}$) stochastic fluctuations are detectable back through the beginning of the archaeological sequence, but the magnitude of earlier fluctuations are dampened exponentially with respect to the true underlying population distribution. We conclude, in general, that a constant taphonomic rate in this case also leads to an apparent pattern of the exponential increase in archaeological deposits or sites through time even in the face of a stochastic population trajectory. The inference that populations were increasing exponentially through time would again be wrong. At a finer scale, the operation of low, but constant taphonomic rates (e.g., $\lambda = 5 \times 10^{-5}$) may not interfere with our ability to identify whether the timing of increases and decreases in the number of observed sites is correlated with climatic events, but the magnitude of those fluctuations may still be strongly biased. In other words, the relative size of population fluctuations may be difficult to infer. However, if taphonomic rates are high (e.g., $\lambda = 1 \times 10^{-3}$), then it seems that neither the timing of population fluctuations nor the relative sizes of those events can be inferred with any confidence. The critical issue in both cases is whether taphonomic rates are constant. If taphonomic rates are correlated with climatic events—a reasonable assumption in many cases—then further questions have to be raised about the reliability of temporal correlations between the timing of fluctuations in site numbers and climatic patterns.

In our final example, we examine the expected temporal frequency distributions derived from a predator–prey interaction. This example is perhaps most germane to hypotheses of human- and climate-mediated extinction events (Guthrie, 2003, 2006; Martin, 1984; Martin and Steadman, 1999; Miller et al., 1999), but our hypothetical example is not intended to simulate any particular extinction event. The model runs from 40,000 ka to the present. Human predators (founding population size = 50) invade at 20,000 ka. Population dynamics for both predator and prey are assumed to obey the logistic equation, and hunting is simulated using an annual *per capita*

¹ Substituting Eq. (2) for the term n_t in Eq. (1) shows that the observed distribution of sites will be exponential decreasing through time if $\alpha > \lambda$, consistent with the true population trajectory. The observed distribution will be exponential increasing through time, however, whenever $\lambda > \alpha$.

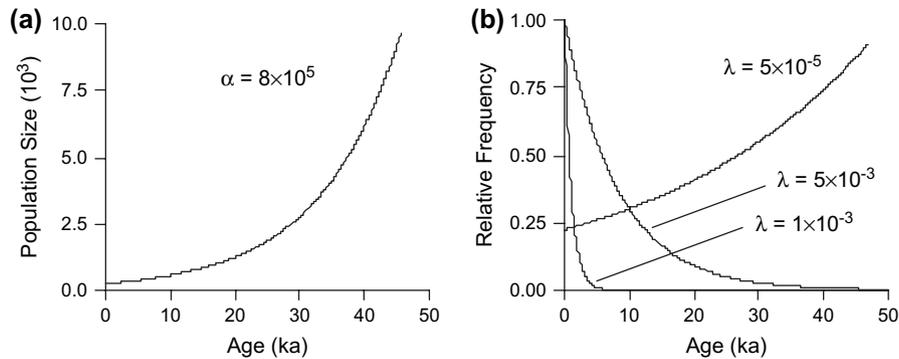


Fig. 4. The impact of constant rates of site destruction on the distribution of sites produced by a population that is decreasing through time. (a) A population whose abundance is described by the exponential equation $n_t = Ke^{\alpha t}$. The initially large population declines exponentially towards a minimum size K . (b) The post-taphonomic relative frequencies of archaeological sites given different taphonomic rates λ .

cull rate. In one model, the prey species is hunted to extinction, and in the second, it survives and persists at reduced levels.² In the absence of taphonomic site destruction, the surviving archaeological and paleontological records for predator and prey, respectively, are assumed to be proportional to population sizes for each.

Figs. 6 and 7 shows the results of the model. The prey, numbering one million individuals at the time of human colonization, reproduce at a maximum intrinsic rate of population growth of 25% per year, and extinction is complete within 750 years. The predicted post-taphonomic frequency distributions for humans (Fig. 6b) and prey (Fig. 6c) show similar overall trends, although they are largely mutually exclusive in time. Two general patterns are evident in the post-taphonomic archaeological (human) frequency distributions (Fig. 6b). At high taphonomic rates ($\lambda = 1 \times 10^{-3}$), humans appear to increase exponentially. At lower taphonomic rates, humans appear abruptly in the archaeological record and a step in the function occurs when humans reach the environmental carrying capacity. Once carrying capacity is reached, true human population levels remain constant (Fig. 6a), but after taphonomic effects, they appear to increase exponentially (Fig. 6b). A more realistic model of human demography, for example one in which carrying capacity is slowly or incrementally increased over time with intensification of resource use (Wood, 1998), would likely produce the more typical continuous upward curvilinear pattern without an intermediate step or transition.

All simulated post-taphonomic frequency distributions for prey show similar trends (Fig. 6c) regardless of the assumed taphonomic rate because prey maintain constant population levels (at carrying capacity) prior to human colonization (Fig. 6a). The prey species abruptly vanishes from the post-taphonomic record at the time of human colonization. Prior to human colonization, prey appear to exponentially increase

in frequency through time. A literal interpretation of the pattern shown in Fig. 6c might be that prey population levels increased through time and reached their maximum just prior to extinction. Here, as in the case illustrated in Fig. 2 above, the pattern apparent before human colonization is generated entirely by taphonomic effects.

In the survival model, human hunting reduces prey population levels to a stable size at approximately one-half its initial level (Fig. 7a). The modeled human demographics in this case are identical to those of the extinction model and thus the predicted post-taphonomic frequency distributions of archaeological sites are also identical (compare Figs. 6b and 7b). At high taphonomic rates, the prey species appears to exponentially increase in frequency through time with no detectable changes in frequency relating to human colonization (Fig. 7c). At reduced taphonomic rates, however, the frequency distribution of prey shows two periods of exponential increase separated by a precipitous drop. Here too the typical positive exponential pattern both before and after the drop are generated exclusively by taphonomic processes.

A possible empirical example of the kind of frequency distributions predicted by our theoretical predator–prey model comes from the work of Miller et al. (1999) who have dated large samples of *Genyornis* and *Dromaius* eggshells from southeastern Australia, dating between 130 and 0 ka (Fig. 8). *Genyornis* is a large ratite, which suffered extinction in the late Pleistocene of Australia between 50 and 45 ka. *Dromaius*, the extant emu, survived this extinction event. The frequency of dated *Genyornis* eggshells increases through time (130–60 ka) in an upward curvilinear fashion and drops rapidly around the time of extinction and human colonization. The frequency distribution for dated *Dromaius* eggshells also increases to a local maximum around 60 ka. With human colonization, the frequency of *Dromaius* eggshells is quickly reduced to approximately 15% of its previous high and then increases in a curvilinear fashion to the present. Patterns similar to that seen for *Genyornis* are evident for other extinct fauna in North America (see Fig. 1b) (Guthrie, 2006; Meltzer and Mead, 1985). This is not to say that temporal frequency distributions can necessarily be used to support or refute overkill or climate-change hypotheses for Pleistocene extinctions,

² In both models, human carrying capacity is set to 10^4 individuals, and prey carrying capacity is set to 10^6 individuals. The intrinsic rate of population growth (r) for humans is set to 0.01 (1% per year) and for prey, 0.25 (25% per year). In the extinction model, eight animals are killed per person per year, and in the survival model, 6.25 animals per person year.

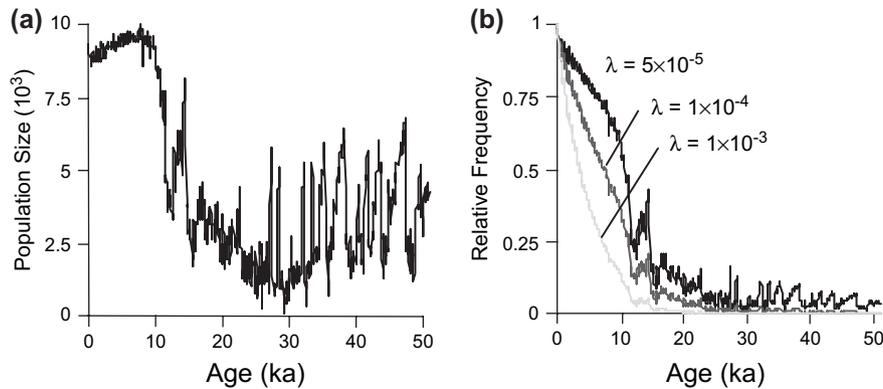


Fig. 5. The impact of constant rates of site destruction on the distribution of sites produced by a population fluctuating in phase with major climatic events. (a) A population whose abundance is proportional to the NGRIP $\delta^{18}\text{O}$ sequence. Large population sizes occur hypothetically during warm events and small population sizes during cold events. (b) The post-taphonomic relative frequencies of archaeological sites given different taphonomic rates λ .

only that trends in the relative frequencies of paleontological remains through time are not easily interpreted in terms of prehistoric animal demographic trends. A major step in prey species frequency distributions at the time of human colonization, however, might be indicative of human predation on prey species.

4. Discussion and conclusions

In 2005, in the context of discussing a temporal frequency distribution based on calibrated radiocarbon ages from Siberia, we wrote that “...radiocarbon dated archaeological deposits from Siberia support the conclusion that sustained human presence in the high arctic coincided with increased human population densities early in the post-glacial period <20 ka” (Surovell et al., 2005). After completing this study, we are much less confident about this statement, particularly the last clause. The argument that human populations increased in Siberia after the last glacial maximum was based on the finding that frequency of radiocarbon-dated archaeological sites increased dramatically during this time, but so do the frequency of dated volcanic eruptions, emu eggshells, and other things. This is not to say that we were necessarily wrong; we might have been right. Instead, we suggest that monotonic and curvilinear increases in site or date frequencies through time are expected signatures of the operation of processes which destroy the archaeological record.

Under most conditions, a positive curvilinear frequency distribution is expected to be produced by taphonomic bias, although specific taphonomic rates will likely vary by time period, region, and material (e.g., Pleistocene vs. Holocene, eastern vs. western USA, sites vs. artifacts, or stone vs. bone). Because these distributions can result even under conditions of stasis or decline, it is unlikely that a true demographic signal can be easily extracted using frequencies of dates or sites alone. This is not to say that examining such datasets is a worthless endeavor, but it is one that must be done carefully. Because positive nonlinear distributions are an expected outcome of the operation of a constant taphonomic process on the archaeological record, perhaps curvilinear

functions (e.g., exponential, power, logarithmic, etc.) should be used as statistical null models when first attempting to detect if a demographic signal can even be identified over long time scales. In other words, when a positive curvilinear frequency distribution is observed, it should be assumed to have been produced by taphonomic bias unless it can be demonstrated otherwise. How might this be done?

One approach might be to control for taphonomic effects using independent data from geological contexts. For example, by compiling distributions of radiocarbon ages from depositional units in small streams, large streams, and alluvial fans, Mandel (1995) has demonstrated that the paucity of Early and Middle Archaic archaeological sites (8–4 ¹⁴C ka) in the central Great Plains of the United States might be explained by extensive erosion which occurred across much of the landscape during that time (see also Holdaway et al., 2005; Waters and Kuehn, 1996). Thus, by examining contemporaneous geological frequency distributions from the same region, one might be able to “subtract out” the effect of taphonomic bias on an observed archaeological frequency distribution. This approach is not entirely straightforward because simply showing that a certain portion of the geological record has been removed or reduced in extent does not necessarily demonstrate that those lost geological deposits also contained archaeology.

A second approach might be to focus on the short-term variation which is superimposed on long-term trends. While taphonomic bias should also affect frequency distributions on short time-scales, the effect should not be nearly as severe. A good example of this is seen in our model of human population variation which tracks climatic variation where short-term fluctuations in human populations remain after moderate taphonomic bias despite the long-term signal having been dramatically modified (Fig. 5b). The wiggles in the pre-taphonomic curve survive because the rates of increase and decrease in population are rapid compared to the long, slow, and steady march of destructive processes. Bryson et al. (2006) have used this very approach to create a “volcanic index” from their frequency distribution of ¹⁴C-dated volcanic eruptions because it was clear to them that the long-term trend was

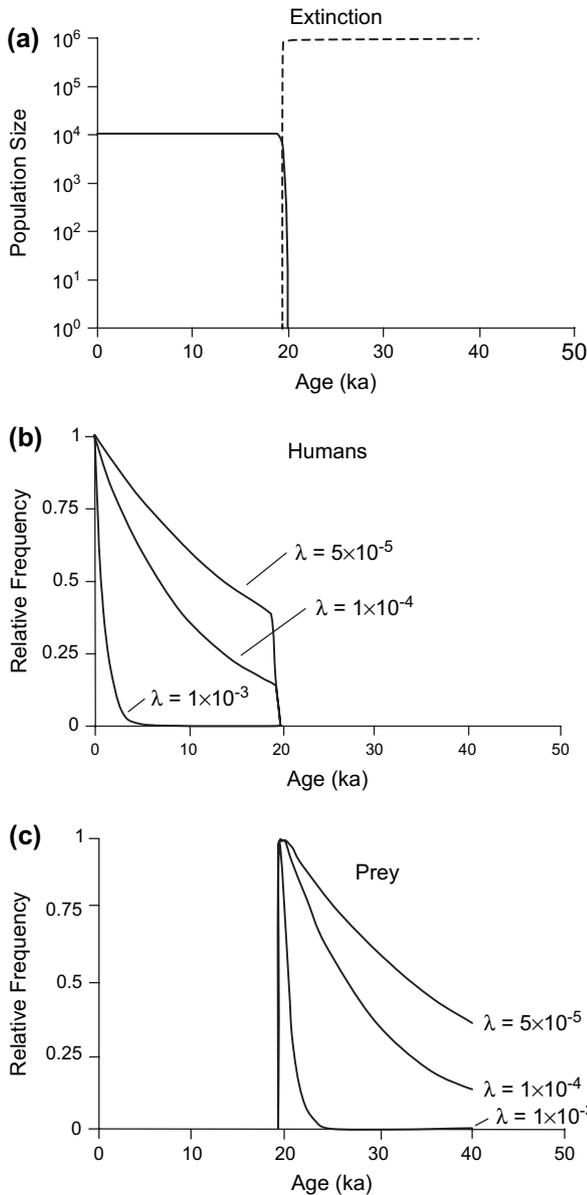


Fig. 6. Results of extinction predator–prey model. (a) Human and prey population levels (y-axis log-scaled). (b) The post-taphonomic relative frequencies of archaeological sites given different taphonomic rates λ . (c) The post-taphonomic relative frequencies of paleontological occurrences given different taphonomic rates λ .

tracking little more than taphonomic bias. The index was created by regressing the frequency distribution to power and serpentine functions, and using the residuals of that regression to map variation in volcanic activity over the late Quaternary. The regression in effect is a correction for taphonomic bias. Yet, even in the absence of such a correction it may be appropriate to compare date or site frequency distributions over short continuous time intervals since sites recognized within that interval are likely to have been impacted by taphonomic processes to the same degree. As a rule-of-thumb, if the frequency distribution being analyzed falls entirely *within* a time interval less than $1/\lambda$ —the inverse of the taphonomic rate—then the changes in site frequencies may be a reliable proxy for relative changes in the pre-taphonomic

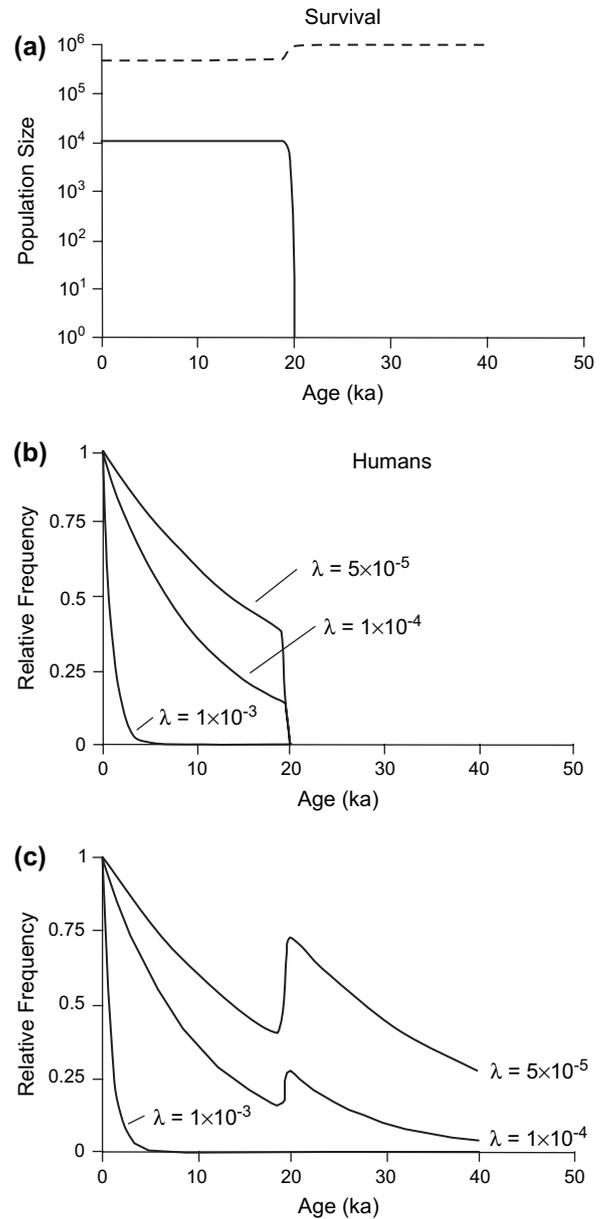


Fig. 7. Results of survival predator–prey model. (a) Human and prey population levels (y-axis log-scaled). (b) The post-taphonomic relative frequencies of archaeological sites given different taphonomic rates λ . (c) The post-taphonomic relative frequencies of paleontological occurrences given different taphonomic rates λ .

distribution. However, in either case, a couple of cautionary notes about “wiggles” in frequency distributions are necessary. Variation in the taphonomic rate through time could add considerable noise to frequency distributions. Similarly, if one is analyzing frequency distributions of radiocarbon dates then the shape of the radiocarbon calibration curve can dramatically impact the shape of summed calibrated probability distributions of dates (Bartlein et al., 1995). Finally, the amount of “noise” evident in simple histogram-based frequency distributions can largely be a function of small sample size and the choice of interval width.

Another potentially fruitful approach would be the use of independent lines of evidence to verify possible demographic

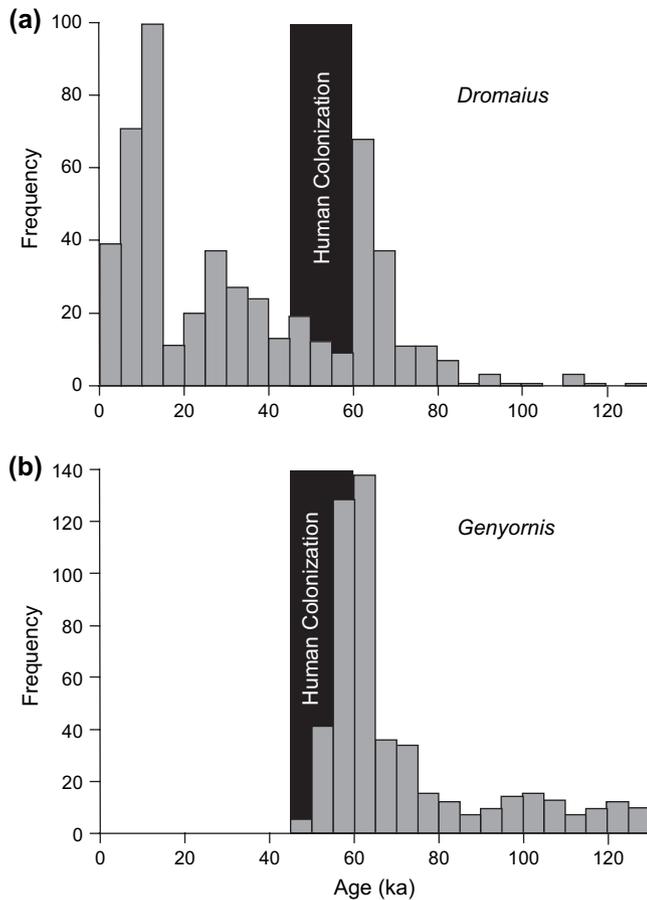


Fig. 8. Temporal frequency distribution of *Dromaius* (a) and *Genyornis* (b) eggshells from southeastern Australia dated by the amino acid racemization method (redrawn from Miller et al., 1999).

trends suggested by temporal frequency distributions. Demographic studies, for example, which rely on dimensionless ratio or proportion data may circumvent some of the effects of taphonomic bias. For example, Stiner et al. (1999, 2000) have argued that relative Paleolithic population densities can be estimated using the ratios of fast, rapidly reproducing prey such as hares to relatively sessile, slowly reproducing prey such as tortoises. Provided that the bones of fast and slow prey are equally susceptible to taphonomic destruction, then taphonomic effects are cancelled out leaving the pre-taphonomic ratio unchanged.³ Similarly, the use of the proportion of juveniles in human mortality profiles as a proxy for human population growth rate should also be largely independent of taphonomy (Bocquet-Appel, 2002; Bocquet-Appel and Naji, 2006). While destructive processes might over time reduce the numbers of sites containing faunal or human remains,

³ If we define n_f as the frequency of fast prey recorded in one time interval and n_s as the frequency of slow prey in the same interval then:

$$\frac{n_f}{n_s} = \frac{n_{ft}e^{-\lambda t}}{n_{st}e^{-\lambda t}} = \frac{n_{ft}}{n_{st}}$$

The observed ratio of n_f/n_s is the same as the pre-taphonomic ratio at the time of deposition.

the composition of the osteological assemblages which survive to the present should remain relatively unchanged.

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References

- Adams, J.M., Foote, G.R., Otte, M., 2001. Could pre-Last Glacial Maximum humans have existed in North America undetected? An interregional approach to the question. *Current Anthropology* 42, 563–566.
- Agenbroad, L.D., 2005. North American proboscideans: mammoths: the state of knowledge, 2003. *Quaternary International* 126–128, 73–92.
- Bartlein, P.J., Edwards, M.E., Shafer, S.L., Edward, J., Barker, D., 1995. Calibration of radiocarbon ages and the interpretation of paleoenvironmental records. *Quaternary Research* 44, 417–424.
- Barton, L., Brantingham, P.J., Ji, D., in press. Late Pleistocene climate change and Paleolithic cultural evolution in northern China: implications from the Last Glacial Maximum. In: Madsen, D.B. (Ed.), *Human Adaptation to Climate Change in Arid China*.
- Bocquet-Appel, J.-P., 2002. Paleoanthropological traces of a Neolithic demographic transition. *Current Anthropology* 43, 637–650.
- Bocquet-Appel, J.-P., Naji, S., 2006. Testing the hypothesis of a worldwide Neolithic demographic transition: corroboration from American cemeteries. *Current Anthropology* 47, 341–365.
- Brantingham, P.J., Kerry, K.W., Krivoschapkin, A.I., Kuzmin, Y.V., 2004. Time-space dynamics in the Early-Upper Paleolithic of northeast Asia. In: Madsen, D.B. (Ed.), *Entering America: Northeast Asia and Beringia Before the Last Glacial Maximum*. University of Utah Press, Salt Lake City, pp. 255–283.
- Bright, J., Ugan, A., Hunsaker, L., 2002. The effect of handling time on subsistence technology. *World Archaeology* 34, 164–181.
- Bryson, R.U., Bryson, R.A., Ruter, A., 2006. A calibrated radiocarbon database of late Quaternary volcanic eruptions. *eEarth Discussions* 1, 123–124.
- Ely, L.L., Yehouda, E., Baker, V.R., Cayan, D.R., 1993. A 5000-year record of extreme floods and climate change in the southwestern United States. *Science* 262, 410–412.
- Erlandson, J.M., Rick, T.C., Kennett, D.J., Walker, P.L., 2001. Dates, demography and disease: cultural contacts and possible evidence for Old World epidemics among Protohistoric Island Chumash. *Pacific Coast Archaeological Society Quarterly* 37, 11–26.
- Faure, G., Mensing, T.M., 2005. *Isotopes: Principles and Applications*. John Wiley and Sons, Hoboken.
- Frison, G.C., 1991. *Prehistoric Hunters of the High Plains*. Academic Press, San Diego.
- Gamble, C.S., Davies, W., Pettit, P., Richards, M., 2004. Climate change and evolving human diversity in Europe during the last glacial. *Philosophical Transactions of the Royal Society of London B* 359, 243–254.
- Guthrie, R.D., 2003. Rapid body size decline in Alaskan Pleistocene horses before extinction. *Nature* 426, 169–171.
- Guthrie, R.D., 2006. New carbon dates link climatic change with human colonization and Pleistocene extinctions. *Nature* 441, 207–209.
- Holdaway, S., Fanning, P., Shiner, J., 2005. Absence of evidence or evidence of absence? Understanding the chronology of indigenous occupation of western New South Wales, Australia. *Archaeology of Oceania* 40, 33–49.
- Kuzmin, Y.V., Keates, S.G., 2005. Dates are not just data: Paleolithic settlement patterns in Siberia derived from radiocarbon records. *American Antiquity* 70, 773–789.
- Mandel, R., 1995. Geomorphic controls of the Archaic record in the Central Plains of the United States. In: Bettis III E.A. (Ed.), *Archaeological*

- Geology of the Archaic Period in North America. The Geological Society of America Special Paper, No. 297 Boulder, CO, pp. 37–66.
- Martin, P.S., 1984. Prehistoric overkill: the global model. In: Martin, P.S., Klein, R.G. (Eds.), *Quaternary Extinctions: A Prehistoric Revolution*. University of Arizona Press, Tucson, pp. 354–403.
- Martin, P.S., Steadman, D.W., 1999. Prehistoric extinctions on islands and continents. In: MacPhee, R. (Ed.), *Extinctions in Near Time*. Kluwer Academic/Plenum Publishers, New York, pp. 17–55.
- Meltzer, D.J., Mead, J.I., 1985. Dating late Pleistocene extinctions: theoretical issues, analytical bias, and substantive results. In: Mead, J.I., Meltzer, D.J. (Eds.), *Environments and Extinctions: Man in Late Glacial North America*. Center for the Study of Early Man, Orono, ME, pp. 145–174.
- Miller, G.H., Magee, J.W., Johnson, B.J., Fogel, M.L., Spooner, N.A., McCulloch, M.T., Ayliffe, L.K., 1999. Pleistocene extinction of *Genyornis newtoni*: human impact on Australian megafauna. *Science* 283, 205–208.
- Pennington, R., 2001. Hunter-gatherer demography. In: Panter-Brick, C., Layton, R., Rowley-Conwy, P. (Eds.), *Hunter-Gatherers: An Interdisciplinary Perspective*. Cambridge University Press, Cambridge, pp. 170–199.
- Pierce, J.L., Meyer, G.A., Jull, A.J.T., 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* 432, 87–90.
- Rick, J.W., 1987. Dates as data: an examination of the Peruvian preceramic radiocarbon data. *American Antiquity* 52, 55–73.
- Stiner, M.C., Munro, N.D., Surovell, T.A., 2000. The tortoise and the hare: small game use, the broad spectrum revolution, and Paleolithic demography. *Current Anthropology* 41, 39–73.
- Stiner, M.C., Munro, N.D., Surovell, T.A., Tchernov, E., Bar-Yosef, O., 1999. Paleolithic population growth pulses evidenced by small animal exploitation. *Science* 283, 190–194.
- Surovell, T.A., Waguespack, N.M., Brantingham, P.J., 2005. Global archaeological evidence for proboscidean overkill. *Proceedings of the National Academy of Sciences of the United States of America* 102, 6231–6236.
- Walker, P.L., Johnson, J.R., 2003. For everything there is a season: Chumash Indian births, marriages, and deaths at the Alta California Missions. In: Swedlund, A.C., Herring, D.A. (Eds.), *Human Biology in the Archives*. Cambridge University Press, Cambridge, pp. 53–77.
- Waters, M.R., Kuehn, D.D., 1996. The geoarchaeology of place: the effect of geological processes on the preservation and interpretation of the archaeological record. *American Antiquity* 61, 483–497.
- Wood, J., 1998. A theory of pre-industrial population dynamics: demography, economy, and well-being in Malthusian systems. *Current Anthropology* 39, 99–135.