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RESEARCH

Landscape Taphonomy Predictably Complicates Demographic Reconstruction

Daniel A. Contreras[1] · **Brian F. Codding**[2]

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Abstract

Accurately reconstructing past human population dynamics is critical for explaining major patterns in the human past. Demand for demographic proxies has driven hopeful interest in the "dates-as-data" approach, which models past demography by assuming a relationship between population size, the production of dateable material, and the corpus of radiocarbon dates produced by archaeological research. However, several biases can affect assemblages of dates, complicating inferences about population size. One serious but potentially addressable issue centers on landscape taphonomy — the ways in which geologic processes structure the preservation and recovery of archaeological sites and/or materials at landscape scales. Here, we explore the influence of landscape taphonomy on demographic proxies. More specifically, we evaluate how well demographic proxies may be corrected for taphonomic effects with either a common generalized approach or an empirically based tailored approach. We demonstrate that frequency distributions of landforms of varying ages can be used to develop local corrections that are more accurate than either global corrections or uncorrected estimates. Using generalized scenarios and a simulated case study based on empirical data on landform ages from the Coso Basin in the western Great Basin region, we illustrate the way in which landscape taphonomy predictably complicates "dates-as-data" approaches, propose and demonstrate a new method of empirically based correction, and explore the interpretive ramifications of ignoring or correcting for taphonomic bias.

Keywords Archaeological demography · Landscape taphonomy · Dates-as-data · Radiocarbon SPD

✉ Daniel A. Contreras
daniel.contreras@ufl.edu

Brian F. Codding
brian.codding@anthro.utah.edu

[1] Department of Anthropology, University of Florida, Gainesville, FL, USA

[2] Department of Anthropology, University of Utah, Salt Lake City, UT, USA

Introduction

Accurately reconstructing past human population dynamics is critical for explaining major patterns in the human past, ranging from the development of behavioral modernity (e.g., Powell et al., 2009; Tallavaara et al., 2015; cf. Vaesen et al., 2016) to the emergence and spread of agriculture (e.g., Bevan et al., 2017; Codding et al., 2022; Timpson et al., 2014; Weitzel & Codding, 2016). More broadly, demographic proxies are also needed to explain general trends in past human–environment interactions, including human responses to climate change (e.g., Codding et al., 2023; Flohr et al., 2016; Kelly et al., 2013) and the extent and effects past of human land use (e.g., Ellis et al., 2013; Kaplan et al., 2010; Klein Goldewijk et al., 2011). These establish baselines for anthropogenic impacts and inform predictions about future human–climate–land use dynamics (see d'Alpoim Guedes et al., 2016). Past population dynamics are so fundamental that without a reliable method for discerning them, we will be unable to address most of archaeology's "grand challenges" (Kintigh et al., 2014).

Approaches to regional archaeological demography (recently summarized in Drennan et al. (2015)) are generally founded upon counts of some class of archaeological feature or artifact whose abundance can be theoretically related to population size. Counts of sites based on archaeological settlement survey are perhaps the simplest and most common proxy. These can be complemented or supplanted by counts of structures or hearths, adjusted by estimates of site area, and fine-tuned to take into account spans of occupation and site function(s). The centrality of archaeological demography, however, has driven hopeful interest in population proxies that are less dependent on systematic archaeological surveys, which are comparatively expensive, slow, and limited in their spatial coverage. Most salient among these over the last two decades has been the "dates-as-data" approach (Rick, 1987), which has become the dominant method for reconstructing past population histories (recently, e.g., Bird et al., 2020; Crema & Kobayashi, 2020; DiNapoli et al., 2021; Parkinson et al., 2021; Riris, 2018; for a recent review see Crema, 2022). This method assumes a relationship between population size, the production and survival of dateable material, and the corpus of radiocarbon dates produced by the last ±60 years of archaeological research and leverages temporal or spatial variation in the distribution of those dates to model past demography.

Methods of demographic reconstruction, like any archaeological endeavor, are fundamentally vulnerable to problems of differential preservation: any population proxy relies on comparing quantities that survive from different time periods, which can for a variety of reasons lead to the under-representation of some periods of time and consequent misinterpretations of population dynamics. As a result, estimates of past populations necessarily either assume that all periods are equally represented or attempt to identify which particular periods are underrepresented and apply some estimated correction.

Landscape taphonomy — the ways in which geologic processes structure the preservation and recovery of archaeological sites and/or materials at landscape scales — is one factor that potentially generates systematic bias in demographic reconstruction. This problem is broadly recognized in settlement survey (Banning, 2002; Drennan et al., 2015, 162–171; Stafford, 1995), and has been recognized since Rick's original dates-as-data paper as one of the factors that attenuates the relationship between a distribution of population over time in a given locale and the assemblage of radiocarbon dates recovered from that region. The most salient attempt at a generalizable solution is Surovell and colleagues' work (Bluhm & Surovell, 2019; Surovell et al., 2009; Surovell & Brantingham, 2007), which approximates global rates of loss of archaeological material over time by comparing the differences between sedimentary and aerosol (ice core–derived) records of vulcanism; those differences are argued to indicate rates of disappearance of sediments over time. Surovell and colleagues use those approximations to develop a global taphonomic correction, referred to as the "volcanic" correction (Bluhm & Surovell, 2019), which is now widely applied by dates-as-data practitioners (e.g., Barberena et al., 2017; Broughton & Weitzel, 2018; Downey et al., 2016; Edinborough et al., 2017; Jones et al., 2021; Peros et al., 2010; Williams, 2012) and implemented in the rcarbon package as "transformSPD" (Bevan & Crema, 2017).

However, as Surovell and colleagues recognized (2009, p. 1723), deposition and erosion are highly variable in space, and local rates of taphonomic loss can be expected to vary considerably from global ones. This variation will be particularly consequential in regions with active and varied sedimentary histories, leading to systematic biases in demographic reconstructions.

To evaluate the potential bias of local landscape taphonomy, and ways to address it, here we use simulated archaeological data to show that under many taphonomic scenarios, neither applying a generalized correction nor ignoring the problem is likely to constitute an adequate response. With a focus on dates-as-date approaches but with results that are broadly applicable to regional archaeological demography, we demonstrate that frequency distributions of landforms of varying ages can be used to develop local corrections that are more accurate than either global corrections or uncorrected estimates.

Using generalized scenarios and a simulated case study based on empirical data on landform ages from the Coso Basin in the western Great Basin region, we illustrate the way in which landscape taphonomy predictably complicates "dates-as-data" approaches, propose and demonstrate a new method of empirically based correction, and explore the interpretive ramifications of ignoring or correcting for taphonomic bias.

Background

Landscape Taphonomy

Taphonomic concepts in archaeology most commonly embrace the analysis of post-depositional modification of archaeological materials (Schiffer, 1987), but have also been integrated with insights from archaeological survey (e.g., Banning, 2002, p. 72) to address regional landscape taphonomy. This can range from regional variation in site formation processes (Borrero, 2014) to consideration of the differential survival of sites that are from different time periods and/or located on different landforms (Barton et al., 2002; Burger et al., 2008).

The problem is one that has been most thoroughly discussed in the geoarchaeological literature, in both relatively humid (e.g., Bettis & Benn, 1984; Bettis & Mandel, 2002; Borejsza et al., 2014; Mandel, 2008) and arid (e.g., Fanning et al., 2007; Ravesloot & Waters, 2004) environments. These approaches have generally focused on fluvial processes and particularly the problems posed by destruction or burial of archaeological sites through erosion and deposition. These studies demonstrate that preserved distributions of sites recorded by archaeological surveys of modern land surfaces can be strongly structured by geomorphic patterns as well as by patterns of human settlement and land use. As a result, as Bettis and Mandel conclude, "the accuracy of paleo-demographic…models based on archaeological data depends in large part on the amount and quality of data available for assessing differential temporal and spatial preservation, and regional and local sedimentation rates" (2002: 152). Various cases studies — e.g., the Middle Gila River (Ravesloot & Waters, 2004), the Central and Eastern Great Plains (Bettis & Mandel, 2002; Mandel, 2008), and southern Indiana (Herrmann, 2015) — show that both the distribution and the abundance of sites of any given period must be considered in light of the varying ages of extant/exposed landforms in fluvial landscape. The diversity of these examples, as well as modeling of fluvial landscapes (Clevis et al., 2006; Davies et al., 2015), suggests that the problem is pervasive and potentially significant. Ballenger and Mabry (2011) address this with specific reference to the recovery of dateable material used in dates-as-data approaches.

Although fewer case studies address the problem directly in other geomorphic contexts, landscape taphonomy is not limited to fluvial landscapes. For instance, MacInnes et al. (2014) address differential availability of landforms for settlement in the Kuril Islands, where landform creation or burial through volcanic processes is the primary process of concern, and Zvelebil et al. (1992) consider the impacts on archaeological survey in a southeast Irish landscape of alluviation, sea level change, and peat development. Bailey and Cawthra (2023) review the landscape taphonomic implications of global sea level rise in broad terms. The empirically grounded simulation that we present in the "A Realistic Coso Basin Simulation" section is based on the detailed work on Great Basin landscape taphonomy by Eerkens et al. (2007) in the Coso Basin.

For dates-as-data approaches, the role of taphonomy in structuring the distribution of surviving datable material is fundamental. Nevertheless, as Ward and Larcombe (2021) have recently detailed, even if the issue is acknowledged in dates-as-data projects, it is rarely treated in sufficient detail to enable consideration of the likely effects on demographic reconstructions. At best, the vast majority of dates-as-data literature assumes that, all else being equal, older material has been subject to deleterious processes for more time and is thus less likely to be represented in the archaeological record. Surovell and colleagues (Surovell et al., 2009; Surovell & Brantingham, 2007) recognized the importance of this issue, and approximated a solution by developing a "correction" for taphonomic bias using a database of geologic ^{14}C dates associated with volcanic deposits (Bryson et al., 2006) as a measure of the frequency distribution of terrestrial sediments of various ages. They compared this empirical distribution against an independent ice core–derived aerosol record of Quaternary volcanism, which is unaffected by landscape taphonomy, to produce a global estimate of the impact of taphonomic factors on the survival of terrestrial sediments of different ages. A recent evaluation of the volcanic correction (Bluhm & Surovell, 2019) produced largely similar results using an independent set of non-volcanic geologic dates.

While this approach is an ingenious solution to the problem of taphonomic bias, it assumes that local landscape taphonomy mirrors global patterns, smoothing over variation in local surface processes that may produce significant deviations in the post-depositional factors that structure the availability of dateable material in any given region. Since local taphonomy can significantly structure surviving distributions of dateable material, ignoring it can have significant effects on demographic interpretations. Surovell et al. (2009, p. 1723) acknowledged this issue and suggested their global correction only as a first approximation. Others (e.g., Attenbrow & Hiscock, 2015, p. 32; Rhode et al., 2014, p. 576) also emphasize the importance of attention to local landscape taphonomy and suggest that the appropriateness of a generalized correction should be demonstrated rather than assumed. In spite of this recognition, and although it is clear that in order for summaries of radiocarbon dates to accurately reflect the original distributions of dateable material these taphonomic effects must be accounted for, no systematic approach for dealing with taphonomic effects at local or regional scales exists. Crema's recent (Crema, 2022) comprehensive review of dates-as-data methods neither explores the magnitude of the problem nor suggests any solutions other than the volcanic correction. Moreover, Surovell and colleagues' global volcanic correction is widely cited (369 citations listed in Google Scholar as of November 2023, though certainly not all of these represent applications of the correction), often without justification of its appropriateness for the region under consideration (though sometimes, e.g., Barberena et al., 2017, with caveats about the applicability of the results).

"Dates-as-Data" Approaches

Embrace of meta-analysis of archaeological assemblages of ^{14}C dates can be traced to Rick's (1987) use of ^{14}C dates from the Central Andean preceramic period to argue that ^{14}C dates could be employed as population proxies. Other early efforts can be discerned (see Carleton & Groucutt, 2021, p. 2), but Rick's paper is increasingly cited, and its title commonly used to describe this genre of studies.

Following Rick, this "dates-as-data" approach has been founded on the argument that in addition to their traditional role in establishing chronological frameworks for archaeological sites and regions, ^{14}C dates could also figure in analyses of broad demographic patterns in space and time. The central contention is that in spite of various confounding factors, archaeological ^{14}C dates can serve as a population proxy, given an initial assumption that the production of dateable material is roughly proportional to population size at any given time.

This contention rests upon (a) the validity of the relationship between population size and production of dateable material and (b) dismissal of both the effects of research priorities and budgets on the recovery and analysis of dateable material and the effects of temporally and spatially variable preservation on the ultimate composition of the material record. The latter two processes can significantly structure ^{14}C assemblages in ways that strongly impact interpretation. Addressing these biases, consequently, is vital if "dates-as-data" approaches are to produce reliable results. We review below the principles and application of the "dates-as-data" approach, as well as the significant challenges yet to be overcome. These challenges are the product of three assumptions fundamental to the "dates-as-data" approach (see Fig. 1):

1) past population size is proportional to ($\propto$) the dateable material produced,
2) dateable material produced is proportional to the dateable material now available to sample, and
3) the dateable material now available is representatively sampled.

In order to accurately reconstruct changing populations, archaeologists must develop methods that address whether these assumptions are justifiable for a particular case and, if not, correct for the biases introduced. While this paper focuses on the second fundamental assumption, here, we briefly review each as well as the methods developed to try to reduce the impact of biases on dates-as-data. For additional detail, we refer the reader to Crema's (2022) recent comprehensive review.

Foundational Assumption 1: Population Size $\propto$ Dateable Material Produced

The foundational assumption of any attempt to use an assemblage of radiocarbon dates as a population proxy, articulated in Rick's, 1987 paper, is clear if not necessarily universally accepted: the production of dateable material at any given time is proportional to population size (Fig. 1A and B). Rick pointed out from the outset that this relationship was likely to be a function of technology and environment (Rick, 1987, p. 57) and argued that the population proxies were only appropriately compared in situations where these were similar, but this caution has not always been observed by subsequent researchers. With the exception of the recent work by Freeman et al. (2018), only critiques of "dates-as-data" approaches (e.g., Attenbrow & Hiscock, 2015; Mökkönen, 2014; Torfing, 2015) tend to raise this issue. Although in principle it is clear that the relationship between population and the production of dateable material may vary over time and/or space, dates-as-data practitioners seem to be content that this risk is either (a) unimportant, or (b) can be managed by confining analyses to populations within which that relationship is likely to be fairly constant — i.e., where technology and sociopolitical complexity are comparable.

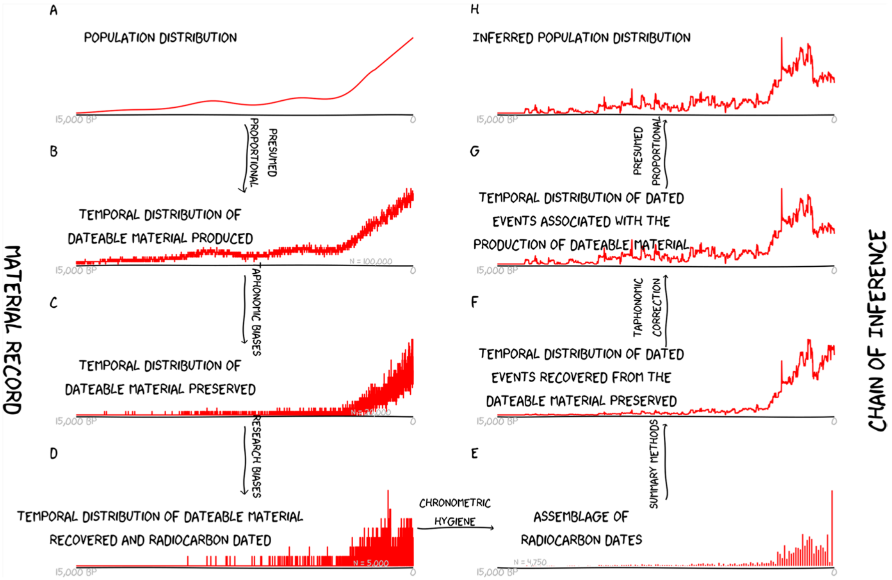

Fig. 1 Schematic of the “dates-as-data” approach, using simulated data. The creation of the material record (at left) involves the initial production of dateable material and the subsequent transformation of that material by successive processes. A population (**A**), derived from the Terminal Pleistocene–Holocene estimate produced by Weitzel and Codding (2016), produces dateable material (**B**) at a rate assumed to be proportional to population. That dateable material is subject to taphonomic processes, which though irregular are cumulative, making older material less likely to be preserved. Here, we simulate this taphonomic bias by sampling from the initial distribution with probabilities following the exponential curve described by Surovell et al. (2009). The remaining (preserved) dateable material (**C**) is the population of archaeological material available to be recovered and dated by archaeologists, who for intellectual and budgetary reasons (at least) do not select material to date at random. The resulting distribution of dateable material (**D**) is shaped by both the abundance of material available from different periods and the preferential recovery and analysis of material from particular periods. Here, we simulate research bias simply by sampling from the preserved distribution with probabilities uniformly equal to 1 for the period before 1000 BP and uniformly equal to .5 for the post-1000 BP period, reflecting the abundance of other dating techniques likely to be used for archaeological material dating to the most recent millennium. The process of making inferences about demographic history from the resulting assemblage of radiocarbon dates (at right) involves the summarization of calibrated radiocarbon dates and then application of a correction for taphonomic effects. After removing 5% of the assemblage to simulate the application of chronometric hygiene to a collection of radiocarbon dates, radiocarbon dates are simulated for each of the remaining calendar dates (using the `uncalibrate` function from the **rcarbon** package), which are illustrated here with a histogram binning the medians of those radiocarbon dates (**E**). These simulated radiocarbon dates are calibrated, and then a summed probability distribution (SPD) describing them (**F**) is calculated. This SPD is taphonomically corrected following the method described by Surovell et al. (2009), producing a corrected distribution (**G**) that is presumed proportional to the population distribution over time (**H**), and understood as an approximation of (**A**)

Foundational Assumption 2: Dateable Material Produced ∝ Dateable Material Available

Any approach whose logic relies on diachronic comparison — in the case of “dates-as-data” approaches to past population, of the quantities of dateable material

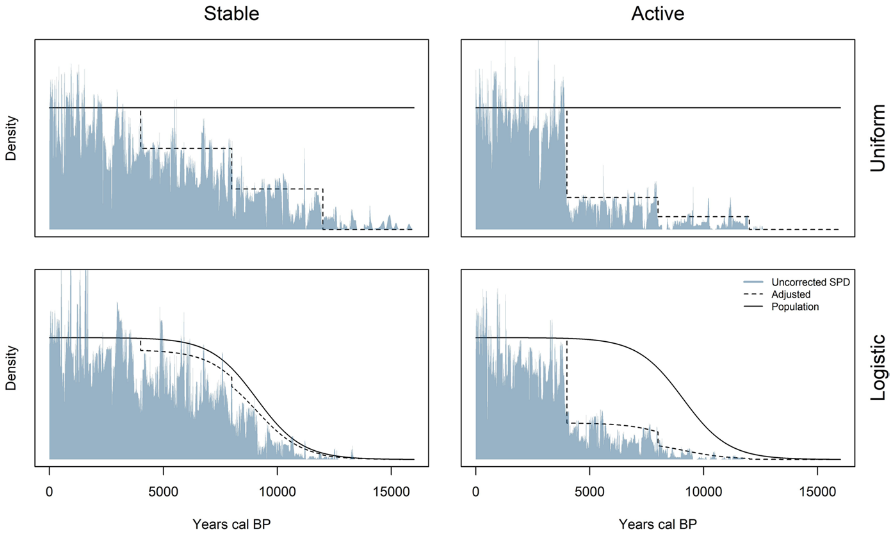

Fig. 2 Population/landscape scenarios showing that SPDs reflect geomorphic activity as well as population structure. Solid lines show the original population, dashed lines show the taphonomically adjusted population, and shaded polygons show the SPD resulting from sampling (n = 1000) the adjusted population

produced at different times — must confront the issue of taphonomy (see the "Landscape Taphonomy" section). Where radiocarbon dates are concerned, the issue is the differential survival of dateable material that might be recovered and analyzed (Fig. 1C). However, the "dates-as-data" literature has generally embraced the convenient assumption that (other things being equal) taphonomic patterns will have a neutral effect on a ^{14}C assemblage or at least an effect that can be simply corrected.

As early as 1987, however, Rick noted that "preservation processes will discriminate against older dates" (1987, p. 57). Ward and Larcombe (2021, p. 550) have recently reiterated this caution, and a series of studies have explored the potential interpretive ramifications of differential preservation. Ballenger and Mabry (2011) present a case study in which other factors overwhelm production as a determinant of the abundance of dateable material, wherein taphonomic loss cannot be simply modeled ("the conditions that determine preservation/loss have varied through time" [Ballenger & Mabry, 2011, p. 1322]). Holdaway et al. (2009), on the basis of dates on different kinds of archaeological components in southeastern Australia, and Davies and colleagues (Carney & Davies, 2020; Davies et al., 2015), on the basis of model simulations, argue that landscape taphonomy can produce an apparently complex ^{14}C record even if the generative process is simple.

Foundational Assumption 3: Dateable Material Available ∝ Material Dated by Researchers

The issue of research intensity, already recognized in the infancy of "dates-as-data" approaches by Rick (1987: 57–58), is similarly challenging (Fig. 1D). The tacit contention is that an archaeological radiocarbon assemblage can be treated as a random sample of the dateable material produced, in part because disparate research agendas focus on different time periods. A key risk is that research interests and/or budgetary realities may drive research practices: in addition to locally eclectic research preferences, the number of ^{14}C samples dated in any region may best reflect that region's economic fortunes rather than its population in prehistory. Even within regions of comparable prosperity, perceptions as to the relative importance of different archaeological phenomena or periods and the relative utility of ^{14}C and other dating methods mean that resources will be unevenly directed towards dating different periods. Further complicating factors are that researchers collecting ^{14}C results published in academic literature may be unaware of larger and perhaps less selective data sets generated by commercial archaeology (as Crombé & Robinson, 2014 observed) and that results may be structured by regional reporting conventions (notable, for instance, in the salience of Wyoming in the Canadian Archaeological Radiocarbon Database [CARD] data [e.g., Chaput et al., 2015, p. Fig. 1; Crema et al., 2017, p. 2]). The effects of even sampling that can be treated as effectively random can also produce patterns that are difficult to distinguish from fluctuations in the abundance of dateable material (Rhode et al., 2014).

"Dates-as-Data" Methodology

The majority of the "dates-as-data" literature has focused on the difficulties of summarizing ^{14}C assemblages (see recent reviews in Bronk Ramsey, 2017; Crema, 2022; Crema & Bevan, 2021) and interpreting the resulting summed probability distributions (SPDs); practitioners have generally preferred to take the foundational assumptions for granted (though see Carleton & Groucutt, 2021; Freeman et al., 2018).

Summarizing Assemblages of ^{14}C Dates Although a few alternatives continue to be explored — e.g., model fits on binned dates (Weitzel & Codding, 2016) and summed ranges (Drake et al., 2017) — addressing the uneven probability distributions of calibrated dates by using summed probability distributions has become the dominant method of summarizing ^{14}C assemblages (Fig. 1E and F), in spite of various methodological and theoretical critiques (e.g., Attenbrow & Hiscock, 2015; Bamforth & Grund, 2012; Chiverrell et al., 2011; Contreras & Meadows, 2014; Culleton, 2008; Mökkönen, 2014; Torfing, 2015). This is likely due in large part to the relative ease with which they can be calculated, coupled with the inability of critiques to suggest a more viable alternative. However, Bronk Ramsey's (2017), 1810–13) discussion of various methods of summarizing ^{14}C dates argues that an adaption of kernel density estimation (KDE) provides a more promising tool for separating signal (date frequency) from noise (effects of the calibration curve and sampling, primarily). Others (e.g., Brown, 2015; Codding et al., 2023; Wilson et al., 2023) have explored resampling approaches to explicitly address the uncertainty associated with each radiocarbon date.

Correcting for Research Biases Recent work using Sum distributions to summarize ^{14}C assemblages has in some cases attempted to "correct" ^{14}C assemblages for differential research intensity, by summing the calibrated pooled means of ^{14}C results from individual sites/site phases (e.g., Buchanan et al., 2008; Shennan & Edinborough, 2007; Tallavaara et al., 2010), by summing the calibrated dates for individual sites or site phases before summing the sums (e.g., Collard et al., 2010; Crema et al., 2016; Hinz et al., 2012; Shennan et al., 2013), or by combining dates from sites (e.g., Balsera et al., 2015), areas (e.g., Goldberg et al., 2016), or site phases (Timpson et al., 2014) before summing. Chaput et al. (2015) use the spatial distribution of the entire assemblage as a measure of the spatial distribution of research, thereby controlling (they argue) for variable intensity of sampling in space, and Crema and colleagues (Crema et al., 2017) address research and other biases by looking for local fluctuations relative to regional trends.

All of these techniques are intended to address the problem of well-funded excavations that produce significantly more ^{14}C dates than other investigations in a region, but they run counter to the fundamental assumption that larger populations would produce more dateable material: pooling gives equal weight to every site or site phase, thus conflating large and small sites and presuming site populations are static over time. That is, populations of different sizes separated by more than some minimum amount of time are expected to produce different amounts of dateable material, but populations of different sizes separated in space are not. Pooling in this manner leaves unaddressed the question of when the quantity of dates from a particular site, area, or time period represents an anomaly in the amount of research attention paid to that area/site/period, and when it represents a concentration of population. Just as Kent Flannery describes the risk, for a rigid sampling strategy of surface survey in the Basin of Mexico, of missing the metropolis of Teotihuacan (Flannery, 1976, p. Ch.5), uniformly binning multiple dates to minimize bias stemming from well-funded investigations may lead "dates-as-data" researchers to ignore sites that have many dates *specifically because* they are large sites that had large populations.

Correcting for Taphonomic Biases Surovell and colleagues' (2009) work stands out for its creative attempt to confront the issue of taphonomic effects and remains the preferred means of addressing the differential survival of datable material of varying ages (Fig. 1G). Although the authors note that their proposed correction is a coarse global approximation and suggest that the best approach would be to develop local corrections for any given study (Bluhm & Surovell, 2019, p. 328; Surovell et al., 2009, p. 1723), their correction is widely implemented (e.g., Barberena et al., 2017; Broughton & Weitzel, 2018; Downey et al., 2016; Edinborough et al., 2017; Fernández-López de Pablo et al., 2019; Zahid et al., 2016), reflecting recognition that taphonomic bias poses a potentially significant problem. However, taphonomic correction is not universally applied (e.g., Codding et al., 2022; Stewart et al., 2021; Tremayne & Winterhalder, 2017), and details of correction methods may vary. Williams (2012), for example, preferred a slightly modified version of Surovell and colleagues' empirically derived equation relating time elapses to survival of material, and argued that either correction produced "unrealistic values for time intervals >25.0 ka" (Williams, 2012, p. 584). That dissatisfaction with results that did not match expectations led Williams (2012, p. 586) to argue that "taphonomic correction should not be routinely applied without some discussion of whether time-dependent taphonomic loss is valid as an a priori assumption." Stewart et al. (2022, p. 2) make a similar point in more broadly theoretical terms, noting that Surovell's use of a monotonic function to describe taphonomic loss effectively implies that the environmental conditions controlling taphonomic processes were constant over time. Various empirical and simulation studies (e.g., Ballenger & Mabry, 2011; Davies et al., 2015; Holdaway et al., 2009; Rhode et al., 2014) — as well as landscape-scale geoarchaeology (see the "Landscape Taphonomy" section) — demonstrate that in fact taphonomic processes vary in both time and space.

Critiques of Surovell's approach, however, neither argue that taphonomy is unimportant nor suggest any alternative methods of correction. Although Surovell and colleagues explicitly presented their correction as a first approximation in need of further development, and in spite of subsequent cautions about the potentially significant implications of taphonomic effects, only Crema et al.' (2017) comparison of local and regional trends has any potential for detecting — much less correcting — taphonomic bias.

Interpretation The interpretation of a corrected distribution of archaeological radiocarbon dates (Fig. 1H) represents a final hurdle. Peaks and troughs in summaries of radiocarbon assemblages may result from significant fluctuations in the population that produced the dateable material that survived to be recovered and dated, or they may result from the vagaries of sampling, from the effects of biasing factors, or from unintended effects of methodology (see reviews in Bronk Ramsey, 2017; Carleton & Groucutt, 2021; Contreras & Meadows, 2014; Crema, 2022). Slopes — representing rates of change — are similarly vulnerable, particularly over short timespans. The more discerning an interpretation tries to be, the more susceptible it is to confounding factors introduced by taphonomic effects, patterns of research, and simple sampling. Attempts to address challenges of SPD interpretation though methodological improvements — e.g., comparison to growth models (see summary in Crema & Shoda, 2021) — tackle the problem of what can be inferred from a summarized ^{14}C assemblage, but do not address how well (or poorly) the sample of ^{14}C dates represents the population for which the SPD is argued to be a proxy.

Both research and taphonomic biases are especially pernicious in that they are spatially and temporally heterogenous, affecting different subsets of large ^{14}C assemblages differently as these biases vary both in space and over time. Interpretations that do not take this variability into account risk overgeneralizing in potentially problematic ways, depending on the questions involved.

Simulating Taphonomic Effects and Corrections

As we have detailed above, while taphonomic correction is not entirely standard in dates-as-data approaches, the possibility that older sites are underrepresented has been considered and means of correcting accordingly proposed (Bluhm & Surovell, 2019; Surovell et al., 2009; Surovell & Brantingham, 2007). Landscape taphonomy has also been identified as a — largely neglected — problem for archaeological assemblages more generally.

The correction developed by Surovell et al. (2009) attempts to deal with this by estimating *how much* less likely older material is to survive and adjusting the SPD accordingly. Their empirically derived function (Surovell et al., 2009, p. 1717) describes the relationship between time elapsed and probability of survival, positing that for a given age a predictable proportion of material will have survived. As a result, the observed quantity that has survived can be used to estimate how much originally existed by dividing the observed quantity by the expected proportion (Surovell et al., 2009, p. 1718). We mirror this approach here but addressing the particulars of preservation probabilities for a given assemblage. Specifically, we use simulated data to develop a means of spatially explicit estimation of local taphonomic effects and calculation of corresponding probability weights for ^{14}C samples from different periods. Simulation offers a way to explore the impacts of (a) landscapes composed of landforms of varying ages, (b) distinct demographic scenarios, and (c) various taphonomic corrections.

We consider four scenarios at extremes of these spectra and explore one empirically grounded realistic scenario based on the Coso Basin in the southwestern Great Basin. For each, we (1) simulate a population and a landscape taphonomic process, (2) produce a simulated sample of radiocarbon dates resulting from the interplay of these factors, and (3) apply dates-as-data methods to attempt to reconstruct the (known) population from which that sample was generated. The results generated in (3) are compared to the simulated population in (1) to explore challenges to demographic reconstruction and the efficacy of different corrections. We implement this approach in the R environment for statistical computing (R Core Team, 2021). All code required to replicate our simulations are provided in the Supplementary Material.

Developing and Applying a Local Taphonomic Correction Based on Landform Frequencies

Frequency distributions of landforms of varying ages enable estimation of the varying probabilities of preservation and recovery of archaeological sites of differing ages, and thus estimation of the probabilities of recovering dates from particular age ranges. Using these probabilities to weight dates of different ages in extant ^{14}C assemblage accounts for the differential likelihoods of survival of dateable material produced at varying times, in a process analogous to Surovell et al.'s (2009) method but empirically approximating local erosional and depositional processes.

We explore this method by developing a simulation that accounts for:

- production (of sites and dateable material, proportional to population),
- preservation (dependent on both time elapsed and landscape processes — burial and erosion),

- recovery (more possible/likely where landforms that *could* host sites are exposed), and
- reconstruction (of sites/dateable material as a proxy for population).

There are seven steps to the simulation process, summarized below and detailed in the annotated R code included as Supplementary Material:

1. Generate a landform age distribution.
2. Generate a population curve that will provide the probability distribution that governs the sampling in Step 3. This can be derived from a theoretical expectation (e.g., of exponential growth) or from an empirical or hypothetical approximation (e.g., a population reconstruction or inferred trajectory).
3. Use that population curve as a probability distribution governing the selection of a sample of calendar dates over a given span of time at the desired density, adjusting the probabilities according to the frequency distribution of landforms (i.e., sites can only be found on landforms that are at least as old as the sites are) and modeled decay over time (Surovell & Brantingham, 2007, p. 1872).
4. Use each of those calendar dates to simulate a radiocarbon date (using, e.g., `R_Simulate` in OxCal [Bronk Ramsey, 2009, 2020] or `uncalibrate` or `unCalibrate` from the **rcarbon** [Bevan & Crema, 2017] and **BChron** [Parnell, 2015] packages, respectively).
5. Summarize the resulting radiocarbon dates, using, e.g., `spd` from the **rcarbon** package. SPDs have been compellingly critiqued as a means of summarizing ^{14}C assemblages (Bronk Ramsey, 2017) but remain so common as to be standard.
6. Correct that SPD using both Surovell et al.' (2009) volcanic correction and a local correction (derived either directly from the landform distribution in Step 1 or from some empirical approximation). Either correction is applied by dividing the observed value for a given year by the correction-derived proportion expected to have survived for that year.
7. Compare uncorrected, volcanic-corrected, and locally corrected against the known starting population from Step 2.

In the "Simulating Population Scenarios and Geomorphic Extremes" section, we use this simulation process to explore the reconstruction of known population distributions in both active and stable landscapes. We illustrate the varying success of uncorrected, volcanic-corrected, and locally corrected SPDs in reconstructing the populations from which these proxies were derived, before considering the implications using a realistic scenario derived from the Coso Basin case study considered by Eerkens et al. (2007).

Simulating Population Scenarios and Geomorphic Extremes

We use notional populations, adjusted for landscape taphonomy and decay, to simulate assemblages of radiocarbon dates that can be subsequently summarized, adjusted for taphonomic effects, and used to approximate the initial population.

The correspondence between the reconstructed population and the initial population provides a means of assessing the utility of different approaches to landscape taphonomy (ignoring it, applying a global correction, and applying a local correction) under two scenarios of population growth over time (uniform and logistic) and under two geomorphic scenarios that make it more and less likely that older sites will survive (stable and active environments).

Comparing the uncorrected, volcanic-corrected, and locally corrected SPDs to the underlying populations from which they are sampled reveals five characteristics of SPDs:

1. Any SPD — corrected or not — is a far from perfect population proxy. The combination of landscape taphonomy, sampling, and calibration introduces significant noise even when an SPD is derived from a uniform distribution. Distinguishing signal from noise remains a fundamental challenge of "dates-as-data" approaches. SPDs are best considered like models: all SPDs are wrong; some SPDs are useful (Box, 1979).
2. Visual inspection makes clear that for any span of time, the locally corrected SPD (Fig. 3, blue polygon) more closely approximates the underlying population distributions (Fig. 3, black lines) than do the uncorrected SPDs (Fig. 3, yellow polygon) in all four scenarios. Although for a few spans of time the volcanic-corrected SPD succeeds as well as the locally corrected one in approximating the population distribution from which it is derived, for many more spans of time it performs less well.

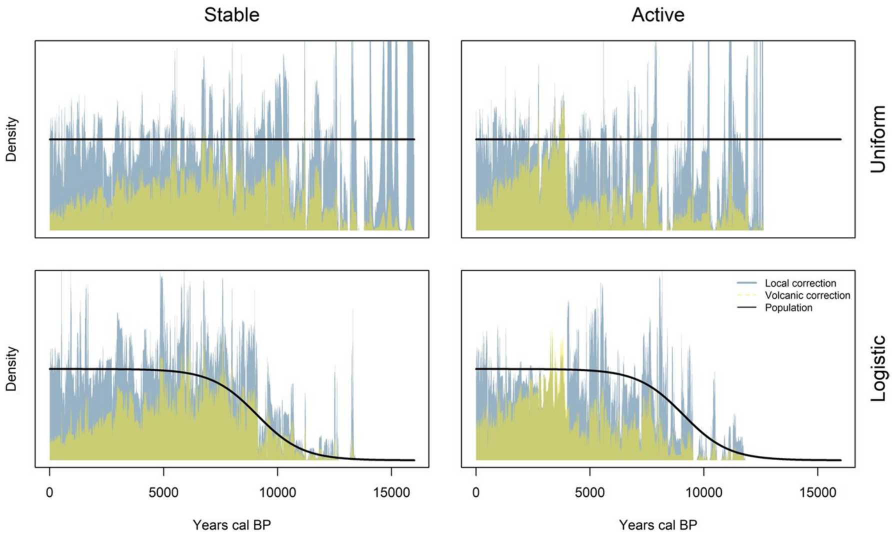

Fig. 3 Results of simulations showing the original population (solid line), volcanic-corrected SPD, and locally-corrected SPD under uniform and logistic growth scenarios in stable and active landscapes (all SPDs based on 1000 simulated ^{14}C dates sampled from the landform adjusted population; see Fig. 2)

3. All reconstructions retain artifacts of landscape taphonomy, wherein more active landscapes result in lower probability of recovery of dateable material and hence lower population estimates. All reconstructions do poorly under the conditions of uniform population growth on active landscapes. This is because there is a point where there are so few landforms remaining from which material can be sampled that recovering a sample of sufficient size to accurately estimate the population is very unlikely; the resulting sparseness of samples produces reconstructions that are spiky even when they correct sufficiently that a rolling mean would be high enough to reconstruct the original population.
4. There is greater variance in the locally adjusted SPD than the volcanic-corrected SPD, especially further back in time. This is not surprising as the older dates require greater adjustment, which also amplifies the variance. Future work could further help correct for this by applying a variance-reducing scaler or smoother and by calculating bootstrapped confidence intervals to focus interpretation on the highest probability region.
5. One limitation of the volcanic correction is that the calculation implicitly assumes that recent populations are orders of magnitude larger than past ones (see Williams, 2012, 584–586). If they are not, more recent estimates will be downweighted relative to earlier populations, producing population estimates that suggest larger populations in, e.g., the Early Holocene than in 500 BP. We suggest that the best way to handle this is to consider the corrected results *only* for earlier periods, considering instead the *uncorrected* SPD for the recent part of the population distribution. Unfortunately, there is no method, in the abstract, for determining the inflection point — i.e., at what date BP we should stop preferring the corrected results in favor of the original SPD. Some of these issues were recently raised by Bluhm and Surovell (2019).

A Realistic Coso Basin Simulation

In this section, we use the methods detailed above to simulate a realistic scenario based on Eerkens et al.' (2007) study in the Coso Basin. Eerkens and colleagues concluded that the abundance of Early Holocene sites has generally been underestimated due to the extant distribution of landforms of varying ages in the region: the relative scarcity of landforms on which Early Holocene components *could* be present/preserved/found has led to their under-representation in archaeological survey data and consequently to underestimation of their abundance. That, in turn, has led to reconstructions of site and population densities over time that underestimate the Early Holocene component. In fact, Eerkens and colleagues note, "Early Holocene sites are found throughout the study area *wherever older landforms are present at or near the surface*" (2007, p. 107 [our emphasis]). While Eerkens and colleagues focus on site counts, including as a proxy for population, the issues that they highlight are equally applicable to use of ^{14}C dates as a population proxy. They note: "we believe that site density is a fairly reliable indication of population density. This method of estimating population density avoids many of the problems noted by

Surovell and Brantingham (2007), such as tabulating radiocarbon dates" (2007, p. 106).

We draw on the Coso Basin case for (1) frequency distributions of landforms (based on Eerkens et al., 2007: Table 3) and (2) a realistic Holocene population distribution (based on Eerkens et al., 2007: Table 7; we assume for present purposes that Eerkens and colleagues accurately reconstruct Coso Basin populations by accounting for landscape taphonomy). Eerkens et al. (2007) exclude the post-1500 BP period from consideration, but Eerkens and Rosenthal (2002, p. 29) consider Coso Basin population growth post-Newberry unlikely; we here follow this in considering post-Newberry population stable. These estimates of relative populations over time provide a realistic population distribution that we use as the basis for this simulated scenario. The point is not the absolute accuracy of the population distribution itself, but rather how well it can be reconstructed from a simulated assemblage of ^{14}C dates that accounts for landscape taphonomy. In this case, that landscape taphonomy is significant: the Coso Basin landscape is one where ~40% of the extant landforms — Mid–Late Holocene dunes, alluvial fans, and playa deposits — were not available for habitation in the Early Holocene (Table 1).

We simulate an archaeological radiocarbon assemblage as described in the "Developing and Applying a Local Taphonomic Correction Based on Landform Frequencies" section, using landform frequencies and population and population distribution derived from Eerkens et al. (2007) as described above. The resulting assemblage of dates is summarized in an SPD and corrected using both the volcanic correction and a correction derived from the Coso Basin landform frequencies. R code that details this process, like that for the idealized scenarios described in the "Simulating Population Scenarios and Geomorphic Extremes" section, is available in the Supplementary Material.

Accounting for landscape taphonomy in this context can have significant effects: Fig. 4 contrasts an uncorrected SPD of a simulated Coso Basin radiocarbon record (Fig. 4a) with one adjusted using the global volcanic taphonomic correction suggested by Surovell and colleagues (2009) (Fig. 4b) and one adjusted

Table 1 Coso Basin landform frequencies (after Eerkens et al., 2007: Table 3)

Landform	Abbrev	Acreage	Period	Proportion acreage
Pre-Tertiary basement	pTu	1978	Pre- to Early Holocene	0.032
Volcanic rocks	Qv	6530	Pre- to Early Holocene	0.105
Older lakeshore deposits	Qls	34	Pre- to Early Holocene	0.001
Older fan deposits	Qof	22852	Pre- to Early Holocene	0.368
Older lacustrine deposits	Qol	4032	Pre- to Early Holocene	0.065
Older dune sands	Qos	499	Pre- to Early Holocene	0.008
Playa deposits	Qp	2496	Middle to Late Holocene	0.04
Younger fan deposits	Qyf	20989	Middle to Late Holocene	0.338
Dune sands	Qds	2617	Middle to Late Holocene	0.042

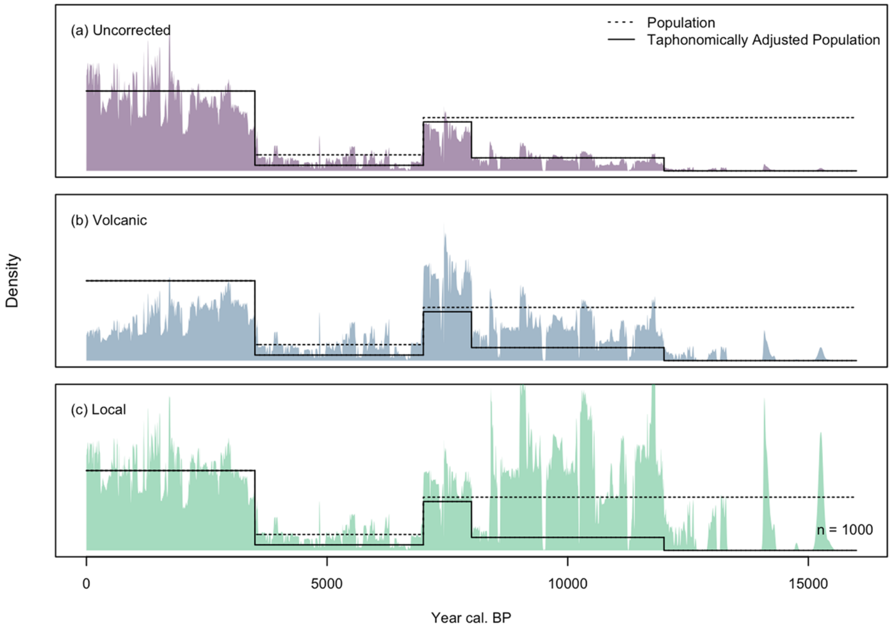

Fig. 4 SPDs derived from a simulated Coso Basin radiocarbon assemblage ($n = 1000$): (**a**) uncorrected summed probability distribution, (**b**) summed probability distribution corrected following the global volcanic taphonomic correction produced by Surovell et al. (2009), and (**c**) summed probability distribution corrected with a local Coso Basin taphonomic correction. Applying a taphonomic correction at all results in a markedly different distribution (compare **a** with **b** or **c**), and which correction is applied also results in significant changes (compare **b** and **c**).The estimated local taphonomic correction employed in **c** is derived from the frequency distribution of landforms of different ages reported by Eerkens et al. (2007, p. Table 7), combined with an approximated low rate of taphonomic decay following the exponential curve suggested by Surovell and Brantingham (2007)

using a taphonomic correction factor estimated based on the frequency distribution of landforms in the Coso Basin (Fig. 4c). Sites that predate 8400 BP cannot be found on Mid–Late Holocene landforms and have been subject to decay processes for longer, making their survival less likely. As a result, the simulated population distribution (dashed line in Fig. 4a, b, and c) — moderate in the late Pleistocene and early Holocene, low in the middle Holocene, and relatively high in the later Holocene — produces a distribution of dateable material (solid line in Fig. 4a, b, and c) that is differentially attenuated over time. Because it is derived from this distribution of surviving material, any radiocarbon-based reconstruction — regardless of the method of summary used — will reflect that pattern, rather than the original population distribution. This is evident in Fig. 4a, where the SPD that summarizes the simulated ^{14}C assemblage (in purple) can be understood as a noisy approximation of the solid line; noise has been introduced by sampling, calibration uncertainty, and summary method.

In fact, the target is the original population distribution, not the distribution of surviving dateable material. In this simulated case study, uncorrected, volcanically/globally corrected, and locally corrected SPDs clearly do not all approximate that original distribution equally well.

The macro-pattern of Coso Basin population — relatively low in the Middle Holocene — is evident in all three results. All three also indicate that the later Early Holocene population was higher than that of the Middle Holocene; the volcanic correction strongly exaggerates this relative high, while the uncorrected SPD slightly underestimates it. The increase in population at the end of the Middle Holocene is apparent in all three results as well, though its magnitude is underestimated by the volcanic correction. As noted above, an unexpected consequence of the volcanic correction is the downward adjustment of the more recent part of a distribution if it is not significantly higher than the earlier portion; in this case, the later Holocene is increasingly underestimated by the uncorrected SPD.

An expected consequence of taphonomic decay is that uncorrected and corrected SPDs vary dramatically in the earlier Early Holocene. The uncorrected SPD approximates the relative quantities of surviving dateable material, and as a result appears to indicate a low population that increased slowly over time even though the initial simulated population was stable. Both corrections alleviate this tendency, but they produce very different results, with the local correction much more strongly correcting the Early Holocene. Because the correction only acts upon positive values in the probability distribution (rather than creating data where probabilities are zero), this strong correction increases the variance in the dataset by further exaggerating the positive values. While the result is that the majority of annual estimates vary around the original population distribution, the increased variance due to sampling also produces a noisier signal. Particularly in the earlier Early Holocene and the Terminal Pleistocene, the result gives the impression of boom-and-bust population cycles. Because the volcanic correction similarly does not attempt to modify probabilities of zero, it also produces a high-variance, noisy pattern of apparent population fluctuation during the same period. Since in this case it is not correcting as strongly, this tendency is less pronounced, but as a result, the volcanic correction, like the uncorrected SPD, gives the impression of incremental population growth rather than of substantial and stable population. In addition, even the corrected versions still suggest a contrast between later Early Holocene and earlier Early Holocene, which is in fact the result of the landform distribution (the recent landforms postdate 8400 BP).

In fact, not only is the Early Holocene population underestimated by an SPD; neither correction does enough to recapture the Early Holocene population. This limitation is empirical rather than methodological — correction cannot address an absence of material available to sample (as addressed by Rhode et al., 2014). This problem might be addressed by using a rolling mean or other smoothing approach to capture the central tendency of the corrected SPD, but such an approach requires the tacit assertion that peaks and troughs in the SPD reflect only noise and not signal (i.e., changes in population). Imputing values in the absence of evidence — asserting that for time periods when no archaeological evidence has been found, that absence is due to taphonomic processes and not an absence of occupation — likely is beyond the threshold of correction with which most archaeologists would be comfortable.

This Coso Basin simulation demonstrates that correcting an SPD is likely to be necessary, particularly earlier in the record, that correction may or may not be

Table 2 Likely inferences about population history of the Coso Basin. Results indicate that local correction would most closely approximate the underlying trends in past populations

Simulated population	• Stable and moderate in scale throughout the Terminal Pleistocene and Early Holocene • Significant Middle Holocene low • Rapid growth to a relatively high and stable Late Holocene population
Population reconstruction	**Likely inference**
Uncorrected SPD	• Consistent population increase throughout the Early Holocene • Probable period of population increase immediately preceding a significant mid-Holocene population low
Volcanic correction	• Early Holocene distinguishable into three stages • Dramatic late Early Holocene population boom preceding a significant Middle Holocene population low • Middle Holocene low is followed by strong but ephemeral population growth in the Late Holocene
Local correction	• Early Holocene boom-and-bust with generally high population • Dramatic Middle Holocene population low • rapid growth to a high and stable Late Holocene population

sufficient to accurately reconstruct a population distribution, and that the choice of correction can significantly affect the results. In this case, archaeologists confronting the distinct population reconstructions would likely infer differing population histories, summarized in Table 2. In the context of Great Basin prehistory, these distinctions have significant interpretive weight. They cast initial colonization and early occupation, responses to mid-Holocene aridity, and Late Holocene re-population in notably different lights and suggest divergent interpretations of such phenomena as risk management in dynamic environments, adaptive responses to resource uncertainty, and population sensitivity to climate change.

Discussion

The simulations detailed in the “Simulating Population Scenarios and Geomorphic Extremes” and “A Realistic Coso Basin Simulation” sections illustrate some key issues in correcting and interpreting SPDs:

- The volcanic correction does not just under-correct or over-correct, but may do one or the other for different spans of time, depending on local landscape taphonomy.
- How much better a local correction approximates the original distribution varies (presumably depending on how much the landform distribution departs from the assumptions of the volcanic correction).
- Further back in time, sparseness of sample leads to underestimates and increased variance with either correction, and neither correction can address an absence of data.
- The volcanic correction down-weights the last 4000 years; this is a mathematical artifact and not an intended effect of the correction.

- One of the problems of any correction that upscales the high values but maintains no-data values (zeroes) is exaggeration of variance, which exacerbates the problem of distinguishing signal from noise.

These issues are fundamental to interpreting assemblages of ^{14}C dates and do not depend on the method used to summarize assemblages of ^{14}C dates. In the terms of the simulations above, methodological improvements focused on improved summary of ^{14}C assemblages (e.g., Bronk Ramsey, 2017; Price et al., 2021) may improve how well a taphonomically adjusted population is reconstructed but remain vulnerable to taphonomic effects. These simulations reveal the significant differences in archaeological interpretation that may result from using different estimates of taphonomic loss (or discounting it) and highlight the importance of selecting the best possible model of taphonomic effects.

The correction suggested by Surovell and colleagues is reasonable and widely employed, but as the Coso Basin simulation demonstrates, it can either over-correct or under-correct, depending on the local landscape history. In the Coso simulation, it over-corrects in the later Early Holocene, but under-corrects in the earlier part of the Early Holocene. These effects result from the relative scarcity of Early Holocene surfaces, which have been buried by later Holocene aeolian, alluvial, and lacustrine deposits. As a result, the volcanic correction, like the uncorrected SPD, underemphasizes the Early Holocene population; for mathematical reasons, it also underestimates the Late Holocene population.

Although neither the volcanic correction nor the local Coso Basin correction produces reconstructions that perfectly approximate the initial population distribution, both outperform the uncorrected SPD and demonstrate the potential significance of taphonomic correction in structuring interpretations of past demography. Although both introduce additional artifacts to data that are already noisy from sampling and calibration effects, the majority of annual estimates from the corrected distributions tend to better approximate initial population distributions. Mismatches between volcanic correction and local landscape history, however, can produce spurious effects, while a local correction — presuming of course that it is accurate — better approximates the initial distribution of dateable material.

Neither method of taphonomic correction is perfect, and neither pretends to address all the potential complications of SPDs. Other systematic biases affecting dated samples — for example, increasing reliance on wood charcoal samples in older contexts where organic preservation can be a significant constraint — can also impact the fidelity with which an SPD reflects population dynamics. A global correction addresses the potentially dramatic underestimation of older dateable material, but its generalized approach risks over- and under-correcting where local landscape taphonomies diverge from the global average. Local correction avoids this problem but depends on accurate estimates of the frequency distributions of landforms of different ages. Neither correction can address the uneven sampling that is common if surviving material is sparse (a pattern which might be generated either by relatively small initial quantities and low probability of survival *or* by especially small initial quantities and intensive research [i.e., search for earliest inhabitants]) or if research intensity is heterogenous for different time periods. The magnification of small early signals exacerbates the problem of distinguishing continuous low-level occupation from sporadic occupation (see Rhode et al., 2014), while the successful identification, and accurate and precise dating, of rapid population changes can be critical to interpretation, for example, of responses to climate change (Codding et al., 2023).

Conclusion

The simulations that we have explored here demonstrate both the potential of summarized radiocarbon data for reconstructing population distributions and the pitfalls of any such approach. It is clear that, as with any archaeological interpretation, biases in the data can significantly structure interpretations, in this case leading to spurious conclusions about past demography. While correcting for taphonomic effects is not a panacea, the structured relationship between frequency distributions of landforms of different ages and distributions of dateable material over time means that biases can be anticipated, described, and accounted for. The results may remain structured by research biases as well as past demography, and the challenge of distinguishing signal from noise will continue to make radiocarbon summaries difficult to interpret (see Fig. 4) — but because the complications introduced by taphonomic effects are predictable, they may be accounted for and one source of inaccuracy minimized.

It is clear that taphonomic factors have the potential to skew dates-as-data results. Moreover, and contrary to the assumptions inherent in a global correction, at least some of the likely taphonomic agents — e.g., sea level change and alluvial deposition and erosion — are likely to have produced taphonomic biases that are heterogeneous both in space and over time. Even within a single study region, a specific taphonomic correction (which no study, so far as we are aware, has attempted to develop) is likely to subsume areas with varying landscape histories, resulting in spatially and temporally distributed over- and under-correction and consequent over- and under-representation of dates and estimation of population. This risk is exacerbated as study regions expand in space and time and more potential diversity is encompassed by an implicit assumption of homogeneity.

As the simulated scenarios discussed here illustrate, without appropriate taphonomic correction, results are likely to be inaccurate, and they are likely to be inaccurate in ways that can meaningfully affect archaeological interpretation. Landscape-scale taphonomic processes are likely to significantly structure the archaeological record, but they are local rather than global. As such, accounting for their effect requires specific attention to local landscape processes. Adjusting summaries of radiocarbon assemblages to account for local/regional frequencies of landforms of varying ages provides an approach that is generalizable to local contexts across the globe. It responds to the as-yet unaddressed appeal that Surovell and colleagues issued when publishing their widely employed global correction: "The ideal approach would be to build local databases of geologic radiocarbon dates that can be used to correct for taphonomic bias, *and to take into account local variation in* *sedimentation and erosion not captured by the global volcanic model*" (Surovell et al., 2009, p. 1723 [our emphasis]).

These simulated cases demonstrate the significant differences in interpretation that may result from using different estimates of taphonomic loss (or discounting it) and highlights the importance of selecting the best possible model of taphonomic effects. Given the potential magnitude of the effects, addressing the differential probabilities of survival of cultural material of different ages is vital to interpretation of regional prehistory and human–environment interactions.

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Data and Code Availability The R code used in this project is available in the included Supplementary Information.

Author Contribution D.C. and B.C. contributed equally to the manuscript.

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Declarations

Competing Interests The authors declare no competing interests.

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