Can we reliably detect adaptive responses of hunter-gatherers to past climate change? Examining the impact of Mid-Holocene drought on Archaic settlement in the Basin-Plateau Region of North America

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Abstract

Climatic change appears to influence major patterns in human history. However, confirming the association between climatic events and adaptive human responses is not straightforward given the potential for spurious correlations and uncertainty in the timing of events. Here we leverage theory from behavioral and population ecology to generate predictions about causal relationships between climate and settlement decisions. We then test those predictions using statistical methods designed to evaluate the likelihood of associations under uncertainty. This allows us to evaluate a comprehensive record of radiocarbon dated archaeological sites in the Basin-Plateau region of North America relative to a record of effective precipitation reconstructed using Macrophysical Climate Models. Consistent with theory, the results show that regional populations declined in the mid-Holocene during a prolonged period of reduced precipitation, leading to the abandonment of many major rockshelter sites. Remaining populations concentrated at open-air sites around well-watered sand dune localities where they constructed pithouses and adopted more intensive subsistence practices. These findings illustrate an adaptive response of hunter-gatherer populations to past climate change that supports theoretical predictions and is unlikely to result from spurious correlations or uncertainties in the timing of events.

Keywords: Behavioral ecology; Climate change resilience; Environmental archaeology; dates as data

1. Introduction

Climate change is proposed to be a major driver of patterns in human history (e.g., DeMenocal 2001). Recent archaeological research in the Americas suggest that climatic variation influences resource availability (e.g., Broughton et al. 2008; Broughton et al. 2022; Jones et al. 2021), diet (e.g., Ebert et al. 2019; Wilson et al. 2022), settlement (e.g., Azevado et al. 2019; Polyak et al. 2022; Sandweiss and Maasch 2022; Yaworsky et al. this issue), demography (e.g., Kelly et al. 2013; Riris and Arroyo-Kalin 2019), health (e.g., McCool et al., this issue), and conflict (e.g., Kennett et al. 2012; McCool et al. 2022; Schwindt et al. 2016). Climate continues to influence many of these factors today, and may contribute to societal collapse in the future (Bradshaw et al. 2021; Gowdy 2020; Kemp et al. 2022; Lyon et al. 2022; Richards et al. 2021; Xu et al. 2020). Elucidating past responses to climate change is important for understanding human adaptation (e.g., Davis 2020) and because it provides a greater range of variation, including greater cultural diversity (Burke et al. 2021), which may help identify factors that facilitate future adaptation (Rick and Sandweiss 2020). However, quantifying past adaptive responses to climate change is not always straightforward, and proposed trends are often hotly debated (e.g., Jones et al. 1999; Kintigh and Ingram 2018).

In one such debated case, archaeologists have argued over evidence of hunter-gatherer response to climatic conditions during the Middle Holocene in western North America (e.g., Baumhoff and Heizer 1965; Madsen and Berry 1975; Aikens 1976; Weide 1976; Elston 1976; Byrn et al. 1979; O'Connell et al. 1982). Originally referred to as the "Altithermal" period from 7,500 to 4,500 years ago (Antevs 1948, 1955), paleoclimatic evidence from in the Basin-Plateau region suggests warmer and drier conditions, though perhaps colder winters (Lachniet et al. 2017), emerged around 8,300 years ago, roughly concordant with the 8.2 ka climate event (Dean et al. 2015; Lachniet et al. 2017), and persisted until about 5,500 years ago (e.g., Louderback and Rhode 2009; Steponaitis et al. 2015; Theissen et al. 2019), leading to changes in faunal composition (Grayson 2000) and region-wide declines in the frequency of radiocarbon-dated archaeological sites (Louderback et al. 2011). In southwestern Utah, this period of reduced precipitation coincides with the archaeologically-defined "Middle Archaic Period" (ca. 7,500 to 4,800 cal BP.; Spangler et al. 2019; Spangler and Zweifel 2020), during which time some of the largest and longest occupied rockshelters were abandoned, such as Cowboy (Jennings 1980), Sand Dune (Lindsay et al. 1968), and Dust Devil Caves (Ambler 1996), and possibly North Creek Shelter (Janetski et al. 2012; Louderback et al. 2020), while others such as Sudden and O'Malley Shelters were occupied at a lower level of intensity (Fowler et al. 1973; Jennings et al. 1980). This has led to a general narrative that people were responding to poor environmental conditions by abandoning the region.

However, recent archaeological excavations at open-air sites complicate this picture, revealing a robust record of long-term occupations during the mid-Holocene evidenced by activity surfaces, thermal features, pithouses, and brush shelters (Nash and Roberts 2018; Roberts 2018; Roberts and Ahlstrom 2003, 2018; Roberts and Eskenazi 2006; Roberts and Hardin 2019, 2020; Roberts and Lyon 2012; Roberts et al. 2017, 2018). This shows that Archaic Period foragers did not abandon the region, but does this mean they were not impacted by drought, or did they respond with more nuanced adaptations to climatic change?

Answering this question is not straightforward. As with all studies seeking to evaluate past responses to climate change, there are at least two fundamental issues. The first involves doubts about the causal relationships between variables (e.g., Contreras 2016), which may lead to spurious associations. The second is the uncertainty in the timing of change, whether discrete events such as the beginning or end of cultural periods (e.g., Kintigh and Ingram 2018) or continuous responses such as inferred demographic trends (e.g., Brown 2015; Carleton and Groucutt 2021). To help overcome these limitations, we approach this research question with two complementary strategies.

(1) We leverage theoretical predictions from behavioral and population ecology (e.g., Fretwell and Lucas 1969) to generate expectations about how individuals should respond to specific climatic variables proposed to influence subsistence. Specifically, following the ideal free distribution model from Fretwell and Lucas (1969; see also Green and Stamps 2001), we propose that lower precipitation in this arid to semi-arid region reduces the intrinsic suitability (i.e., baseline resource potential if the habitat were unoccupied) of habitats by limiting resource availability. If this is true, then individuals should redistribute themselves in response to drought so that archaeologically we see (i) lower regional population size overall, but (ii) relatively high densities in the most suitable habitats relative to lower suitability habitats. While we cannot observe this behavior directly, these predictions are testable archaeologically using material proxies of past settlement behavior (O'Connell et al. 1982; O'Connell 1995; Bird and O'Connell 2006; Codding and Bird 2015; Weitzel and Codding 2022).
(2) We evaluate these theoretical predictions using Monte Carlo simulations to randomly resample possible settlement and climate scenarios to assess uncertainty in the relationships between a comprehensive archaeological radiocarbon record of human settlement and Macrophysical Climate Model-based reconstruction of past effective precipitation. Following insights from causal reasoning (Lewis, 1973), we also introduce counterfactuals by randomly permuting exogenous climate variables to assess the potential for false associations.

Combined, these strategies help us understand the resilience – societal persistence to perturbations, or the inverse of vulnerability (Brewer and Riede 2018) – of past populations and unpack the details of their adaptive responses to drought. Before turning to the analysis, we briefly review the Archaic Period and the emerging record of open-air sites. This background establishes a critical foundation for interpreting the results in the discussion.

2. Regional Setting

The project area is focused on the archaeological record of southern Utah and northern Arizona north of the Colorado River (referred to as the "Arizona Strip"; see Figure 1). The archaeological record of this arid to semi-arid region includes many major rockshelter investigations, and growing evidence from open-air excavations.

2.1 The Archaic Period

The Archaic Period represents populations living after the Paleoindian period (older than 9,000 cal BP) and before the adoption of farming (circa 3,000 years ago), though the timing of the onset of farming varies across the region (e.g., Codding et al. 2022). Following Spangler et al. (2019; Spangler and Zweifel 2020) we divide the Archaic period in the region into three sub-periods. The Early Archaic period (9,000-7500 cal BP) is associated with several diagnostic artifacts, including open-twined sandals, plus Pinto and Humboldt projectile points. During the beginning of the Middle Archaic period (7500-4800 cal BP) plain-weave sandals replaced twined types and coiled basketry was favored over twining. Middle Archaic diagnostic projectile points are rare in dated contexts, but when present they typically include large side-notched points such as Sudden Side-notched and Northern Side-notched types. During the Late Archaic (4800-3200 cal BP) period, point types shifted to Gypsum, Lanceolate points, and possibly Elko Eared points. While much attention to this record focuses on robust assemblages from rockshelter deposits (Ambler 1996; Fowler et al. 1973; Jennings 1980; Jennings et al. 1980; Janetski et al. 2012; Louderback et al. 2020; Lindsay et al. 1968), there is also an emerging record of substantial open-air sites that complicate longstanding narratives.

2.2 Recent Open-Air Investigations

Roberts et al. (2017) provide a recent synthesis of Archaic Period archaeology in the region (see also Landon and Roberts 2018; Roberts et al. 2022). Most of these recent studies are conducted through cultural resource management firms and focus on drainages to clear land for reservoirs, and sand dunes or sheets for housing or resort developments. These previously under-investigated landscapes provide a new picture of Archaic settlement and subsistence.

Early Archaic open-air sites provide a robust record of thermal features, primarily hearths, roasting pits, and lenses or dispersed charcoal (Talbot and Richens 2009). Structures appear ephemeral and artifacts include grinding slabs, manos, biface production detritus, and large side-notched points. Subsistence remains include bones from small mammals; plant remains are limited likely due to preservation. For example, the oldest site excavated during the Coral Canyon project north of St. George, Utah consisted of a thin scatter charcoal and ash with a small artifact assemblage (Roberts and Ahlstrom 2003; Roberts and Eskenazi 2006).

This pattern changes around 7600 cal BP when the first pithouse was built at the Dune Site in Sand Hollow in the St. George Basin (Talbot and Richens 2009). This may indicate the first response to mid-Holocene climate change. After 6000 BP a new type of feature, identified as a use surface, activity area, or midden appears regularly in the archaeological record. After 5500 cal BP, pithouse use increased. These were small, round, shallow structures, most of which contained one or more shallow interior hearths or clusters of fire cracked rock. Postholes were rare and when preserved they often were found around the structure’s perimeter, and sometimes slanted indicating they were likely connected in the center of the structure. The increased use of subterranean structures may indicate greater permanence in occupational duration. The Late Archaic shows an increased use of more ephemeral surface brush shelters. The majority were oval, or irregularly shaped, with small diameter poles placed around the perimeter. Often, hearths are present, and many are off center. Artifact assemblages collected from within the structures are typically small. This may indicate a return to more mobile activities as conditions ameliorated.

2.2.1 Jackson Flat Reservoir Project

Results from the Jackson Flat Reservoir project in Kanab, Utah, provide a robust example of Archaic settlement in the region (Roberts et al. 2017, 2018; Roberts et al. 2022). Extensive aeolian sand sheets and slopewash-redeposited aeolian sand (Finley et al. 2008) contain four sites that date to the Middle through Late Archaic period. The oldest site, Rodent Ridge (42KA6164, Locus 1), contained two sequential occupations of two habitation features (Roberts and Ahlstrom 2018). The first two structures built at the site were shallow, basin pithouses that measured 3 m in diameter and were built 10-30 cm below the prehistoric surface. Roasting pits filled with fire cracked rock were built between the structures. After it was abandoned, an oval surface structure was built directly over it along with a second one built several meters to the west, measured 5 m by 3.5 m. Both structures were constructed with small diameter poles placed around the perimeter, and each contained multiple hearths or warming pits built within their interiors. There was also an extramural hearth built between the two surface structures. Although the artifact assemblage from the site was small it was consistent with other Archaic habitations and included a single side-notched projectile point, two grinding slab fragments, a chopper, a utilized flake, one single hand mano, and debitage. The faunal assemblage, although also small, was dominated by rabbits. Evidence for plant processing included a few cheno-am seeds and juniper berries.

After Rodent Ridge was abandoned three other sites in the project area were occupied intermittently between the Middle and Late Archaic periods. These sites contained thermal pits within midden-like deposits that were likely heavily bioturbated activity surfaces with hearths and roasting pits. The Black Stain Midden site (42KA6167, Locus 2), named for the site's dark black midden deposit, was occupied soon after Rodent Ridge was abandoned (Roberts 2018). It consisted of a single charcoal-stained midden deposit with lightly used ground stone and a small assemblage of debitage. A nearby site, known as Jackrabbit Roast Midden, also consisted of a charcoal-stained midden deposit that was used intermittently into the Late Archaic period (Roberts et al. 2018). The lightly stained midden deposit contained several hearths and roasting pits, plus a small assemblage of ground stone, debitage, and these projectile points. The large, shallow roasting pit was discovered near the base of the midden and was associated with one of two lanceolate style projectile points.

The excavators hypothesized that after the initial occupation at Rodent Ridge Jackson Flat's subsequent Archaic inhabitants used the area periodically to hunt jackrabbits with nets and process the animals at the repeatedly used campsites (Nash and Roberts 2018). The rabbits were then skinned, cooked in roasting pits, and their skeletal remains were ground for marrow. Communal hunts were carried out in the approximate location of the Jackson Flat project area by Southern Paiute people during the historic period (Kelly 1976).

3 Materials and Methods

3.1 Radiocarbon Dates from Archaeological Sites

We model settlement patterns using a comprehensive record of radiocarbon dated archaeological sites in the state of Utah and the Arizona Strip compiled by JDS (Figure 1). These dates are also part of a national-level effort recently published by Kelly et al. (2022). We have previously drawn on these data to evaluate the onset of farming adaptations (Codding et al. 2022) and the influence of past populations on wildfire activity (Carter et al. 2021). All dates are available to permitted researchers through the Canadian Archaeological Radiocarbon Database (https://www.canadianarchaeology.ca/).

3.2 Macrophysical Climate Models and Modern Climate

We construct past climate using Macrophysical Climate Models (MCMs) following Bryson and colleagues (Bryson and Bryson 2000; Bryson 2005; Bryson and McEnaney 2006). MCMs are made up of a series of modules that estimate horizontal and vertical temperature gradients from variation in solar energy from orbital forcing and volcanic aerosols (Bryson and McEnaney 2006). These modules estimate variation in heat energy over the earth surface and within the atmosphere, which controls atmospheric circulation and determines the position of major circulation features. We apply these methods informed by the instrumental record from the Saint George weather station. We calculate a rough measure of effective precipitation by subtracting pan evaporation (E) from precipitation (P). P minus E (P-E) values were then normalized on a scale of 0 (dry conditions) to 1 (wet conditions). These values are shown in Figure 2.

In order to evaluate spatial variation in precipitation, we also rely on reconstructions of modern climate. Specifically, we take average annual precipitation values from the PRISM Climate Group (PRISM 2021) calculated over the preceding 30 years. The current set of 30-year normals covers the period 1991-2020. While the modern record does not reflect past variation, it is a more fine-grained spatial record which should represent relative differences across space, likely driven by elevation.

3.3 Statistical Analysis

We model relative population size or settlement frequency with counts of radiocarbon-dated archaeological sites (e.g., Rick 1987; Louderback et al. 2011; Riris 2018; Crema and Shoda 2021). However, we acknowledge there are several issues with this approach (see Contreras and Meadows 2014; Brown 2015; Crema 2022). One major concern stems from the uncertainty in the actual date of the event: because a calibrated radiocarbon date is represented by a probability distribution describing the potential ages of when a discrete event (the death of the organism being dated) occurred, summing those distributions are thought to integrate this uncertainty. However, as Carleton and Groucutt (2021) recently reviewed, most methods focused on generating and analyzing the summed probability distribution (SPD) of radiocarbon-dated archaeological events target uncertainty in the dates themselves, rather than uncertainty in the resulting height of the SPD. Methods that include estimates of uncertainty in the height of aggregated dates include Monte Carlo simulations (i.e., randomly resampling ages from calibrated probability distributions) to generate confidence intervals around SPDs (e.g., Brown 2015; Weitzel and Codding 2016). Though we suggest this still does not go far enough to understand past responses to climate change, as what researchers actually care about is uncertainty in the *relationships* between environmental and demographic or social variables (see, e.g., Wilson et al. 2021).

Here we implement this by incorporating uncertainty in the date of events, the aggregate height of resulting frequency, and in the relationship of that frequency to theoretically-derived predictor variables. We propose a simple approach to analyzing variation in radiocarbon dated site frequency as a function of environmental predictors that relies on Monte Carlo simulation to assess the strengths of relationships. This is conceptually similar to more complex approaches recently proposed to assess associations between radiocarbon dates and paleoclimate events (e.g., Carleton 2021). We focus on unique dated site counts per century, which has the limitation of relying on binned counts, but benefits from keeping the response variable as close as possible to the empirical unit of interest: an occupied archaeological site. This approach also benefits from being able to rely on standard count regression through generalized linear models (GLMs).

To incorporate estimates of uncertainty, we follow a seven-step process implemented in the R environment for statistical computing (R Core Team 2022).

1. Calibrate ages. Calibrate each date using the appropriate curve and store the resulting calibrated probability distribution. We calibrate ages using the intcal20 curve (Reimer et al. 2020) in the Bchron library (Haslett and Parnell 2008; Parnell et al. 2021).
2. Sample ages. Randomly sample one year from each unique calibrated probability distribution. Here this is done by replicating a for loop that samples one year from each of calibrated probability densities. This could also use the `sampleAges` function in Bchron.
3. Bin samples. Assign each sampled year to a bin or window of time. Consider selecting a temporal bin size relative to the precision of the radiocarbon date sample. A reasonable bin will likely be around 100 years given the limit of dating precision and error introduced through calibration. Also consider the precision and uncertainty in the predictor variable as it will need to be aggregated over the same temporal window. Through resampling, ages near the edges of bins will be reassigned to incorporate uncertainty. Additional runs could include sensitivity analyses by varying the aggregating window across iterations to examine how binning decisions influence results.
4. Thin samples. If there are multiple years in the same bin from the same provenience, randomly select one sampled year from each relevant unit (e.g., one year per site for regional analysis, one year per feature for within site analysis). This avoids double-counting sites or features that occur in the same bin, which may result from mixed sampling intensity or research bias.
5. Sum samples. Sum the number of resulting years per bin, which produces an estimate of the number of unique dated events that occurred within each temporal window. An example of one iteration up to this step is shown in Figure 2b.
6. Sample predictors. Extract predictor (i.e., climate) variable(s) for each bin, in this case each century (see Figure 2a). An alternate approach is to construct a counterfactual by randomly permuting the predictor(s) so as to examine the possibility of spurious correlations.
7. Fit regression model. We model the frequency (count) of dated events using count regression through generalized models with a Poisson or negative binomial distribution. The type of model should be selected depending on the hypothesized response (e.g., should dated events increase linearly or nonlinearly as a function of the predictor) and whether there are other confounds or complications that need to be accounted for such as additional

variables, interaction terms, mixed effects, or correlation structure. For each iteration, we save model coefficients for evaluation.

We begin by analyzing one iteration of the above steps with a Poisson GLM to assess diagnostics for overdispersion and zero-inflation. If present, we re-fit with a negative binomial GLM (Venables and Ripley 2002). We then check other diagnostics including the residuals vs. fitted values, and temporal autocorrelation. We assess model fit with an examination of the coefficients (log odds) and the likelihood r-squared value (r_l^2).

We then iterate steps 2-7 above 10,000 times both with the reconstructed climate data and with randomly permuted climate data. We refer to the model examining the response of dated settlement count to reconstructed effective precipitation as the “empirical model”. We refer to the model with randomly permuted effective precipitation data as the “permuted model”. We report the quantiles of all empirical model coefficients, plot the predicted model fits, and compare the distribution of coefficients between the empirical and permuted models. With count regression, the model coefficients represent the log-odds that the number of occupied sites changes with each unit of change in the predictor (effective precipitation). Values around zero indicate no change in the response as a function of the predictor. We consider the model “significant” at an alpha level of $p < 0.05$, though interpretation focuses on model coefficients.

In addition to modeling the response of settlement density to climate change, we also model the relative suitability of each site location over time using the contemporary precipitation data. Given that we expect a potential non-linear response of settlement to variation in climate over time, we specifically evaluate the average annual precipitation at occupied archaeological sites through time using a generalized additive model (GAM; Wood 2011, 2017) with a Gaussian distribution. We also assess temporal trends in the proportion of open-air relative to sheltered sites using a GAM with a binomial distribution and quasi-likelihood estimation.

All code required to replicate this analysis is provided as a supplement. We omit site locations as these are protected by federal law. Permitted researchers may obtain location data from the relevant State Historic Preservation Offices (SHPO).

4. Results

As shown in Figure 2, the Middle Archaic Period corresponds to a time of reduced dated site frequency, especially fewer sheltered sites. This period also seems to coincide with a prolonged period of reduced effective precipitation, though there are periods of relative dryness before the Middle Archaic, and periods of relative witness during the Middle Archaic. To investigate this relationship further, we perform the modeling approach described above examining continuous variation through time.

The empirical model shows that regional settlement frequency increases significantly with effective precipitation across all 10,000 model runs (Figure 3a; Table 1). As shown in Figure 3a, predicted site counts tend to increase from about 2-3 to 7-12 across the range of effective precipitation. More precisely, the median (50%) of model coefficients (see Table 1) suggests that site counts increase by the exponent of 4.06 ($\pm$1.27) with a unit increase in effective precipitation from 0 to 1, or from around 3 sites at the driest conditions (reported by the intercept) to near 60 sites under the wettest conditions (effective precipitation of one, not observed in this sample).

Models fit with randomly permuted effective precipitation show a very low incidence of false positives, and even those have a small slope that can be either positive or negative depending on the iteration, indicating no consistent meaningful relationship between site counts and randomly permuted climate data (Figure 3b).

Figure 4 shows a comparison of coefficients between the empirical and permuted models, confirming that they meaningfully differ: the empirical model coefficients are all positive, centered on 4, and do not overlap with zero or the distribution of coefficients from the permuted model. The permuted model coefficients are centered on zero, indicating no meaningful relationship between dated site count and random climate data (Figure 4). This trend holds when modeling only open-air locations (see Supplementary Information).

Examining one of the empirical model fits in more detail (see the time series of this iteration in Figure 2) reveals that effective precipitation accounts for about 14% of the variation in settlement count ($p = 0.0012$). Model residuals do not retain residual temporal autocorrelation (see Supplementary Information), nor is there meaningful overdispersion (overdispersion parameter = 1.12). The distribution of model residuals is centered on zero across the range of fitted values with little patterning, indicating strong model performance (see Supplementary Information).

Coincident with the regional decline in occupied sites during the dryer Middle Archaic period, the settlements that remain occupied are increasingly biased toward wetter locations (Figure 5). Though time only accounts for about 7% of the variation in occupied precipitation ($p = 0.0001$; see Supplementary Information). Comparing the quantiles of precipitation at open-air vs. rockshelter sites shows that open-air sites are located in wetter areas (Figure 5b). The proportion of open-air sites relative to open-air and sheltered sites varies significantly over time ($p < 0.0001$), and peaks during the Middle Archaic period (Figure 5c), with time accounting for approximately 38% of the variation in the proportion of site type occupied. This suggests that the increase in occupied precipitation during the Middle Archaic period is the result of individuals preferentially settling in open-air locations during the mid-Holocene.

5. Discussion

Our analysis suggests that populations in the Basin-Plateau region of southern Utah and the Arizona strip responded to aridity by living at lower densities overall, but concentrated in well-watered localities. As illustrated in Figure 3a, populations are significantly lower during periods of low effective precipitation, a pattern not produced by chance correlations with climate (Figure 3b). As shown in Figure 4, the relationship is robust across all 10,000 model runs, suggesting that this patterning is not sensitive to uncertainty in the timing of dated occupation events.

Figure 5a shows that individuals who remained in the region during this arid period may have adaptively responded by moving to more well-watered locations. This strategy seemed to prioritize open-air settlements, which tend to occur in higher precipitation locations (Figure 5b), as illustrated by the increase in the proportion of open-air sites relative to sheltered sites which peaked during the Middle Archaic (Figure 5c).

The results have several implications for local and regional archaeology, and for the application of theoretically-informed predictions on climate change adaptation.

5.1 Drought-Induced Subsistence Change

While the focus of this paper is on changes in settlement patterns as a function of climatic change, we can further contextualize the adaptive response of hunter-gatherers to drought through the subsistence and technological remains recovered from these sites.

The combined evidence from rockshelter excavations shows that those which remained occupied during the Middle Archaic period, albeit at lower intensity, such as Sudden Shelter and O'Malley Rockshelter reveal shifting focal resources from larger game to rabbits and to higher cost plants such as grass and other small seeds (Fowler et al. 1973; Jennings et al. 1980). These upland areas likely remained important places for hunting and pine nut collecting in the late summer and fall, and for acquiring Modena obsidian, which was a favored raw tool source located just north of O'Malley Shelter (Roberts and Hardin 2019; Shott 2021).

Evidence from the open-air sites reveals a similar set of subsistence shifts. Many of these sites are situated within a short walking distance to permanent water sources such as the Virgin and Santa Clara rivers, and a few were tethered to springs. Middle and Late Archaic sites were likely occupied in the spring and the focus of procurement activities was tansymustard seeds and small game, particularly rabbits (Landon and Roberts 2018). Flotation samples processed from the two large Sand Hollow Reservoir projects (Talbot and Richens 2009; Winslow 2011) contained burnt seeds, and the pollen and starch records indicate the use of grass seeds, cheno-ams, tansymustard, cactus, wild buckwheat, and Mariposa lilies. The robust ground stone assemblages from these sites support this interpretation.

Mesquite wood charcoal was present in the Coral Canyon by 6500 cal BP and honey and screwbean mesquite pods were likely attractive resources that flourished along the region's major drainages and springs (Ahlstrom and Roberts 2003; Roberts and Ahlstrom 2006). Remnant stands remain today in southwestern Utah, and in southern Nevada mesquite thickets flourished along the Muddy and Virgin rivers and in well-watered segments of Las Vegas Wash, Duck Creek drainage, and springs. The first Euro-Americans who settled Las Vegas drew maps showing a mesquite bosque that extended along the length of Las Vegas Wash (Warren and Eskenazi 2007:11).

In addition to mesquite, cactus and other desert species, such as Banana yucca, and agave produce highly nutritious fruit and flesh in the desert environment. Sand dunes act as sponges to store winter rains and grasses such as the aeolian sand-endemic species. Indian ricegrass as well as the somewhat deeper-rooted sand dropseed grow there in the early summer. A model of winter versus summer precipitation by Bryson and Bryson (2009) for the Sand Hollow project suggests that winter rains, which favor spring and early summer plants, may have been more reliable over time than summer rains.

The faunal record from St. George's Archaic sites indicates that deer were more common in the Early and Late Archaic faunal records than during the Middle Archaic period. Virtually none of the Middle Archaic sites excavated in the St. George area are associated with projectile points. This is true for the Middle Archaic components that were excavated during the Sand Hollow (Talbot and Richens 2009; Winslow 2011), Coral Canyon (Roberts and Ahlstrom 2003; Roberts and Eskenazi 2006), Warm Springs (Eskenazi and Roberts 2008; Landon and Roberts 2018), and Kayenta (Roberts and Hardin 2020) projects. This lends support to the faunal evidence, which favors rabbits and other small mammals during the Middle Archaic. The paucity of diagnostic projectile points at Middle Archaic components renders these sites virtually impossible to identify from surface evidence alone.

In summary, Archaic period foragers adjusted to the warmer and drier climate of the middle Holocene by shifting their focus from large game to lower return resources such as small mammals. This shift may result from reduced large game abundance due to climate change (e.g., Broughton et a. 2008), or the result of increased local hunting pressure by less-mobile, more tethered populations (e.g., Broughton et al. 2010). They also intensified their use of less profitable plants, including grass seeds, and focused on reliable desert plants, particularly mesquite pods, yucca fruit, agave, and cactus species. They also tethered their primary camps to permanent water sources located near sand dunes where these plant species thrived.

5.2 General Trends in Basin-Plateau Adaptations to Climatic Change

The pattern we describe above may be common throughout the broader region. In southern Nevada, Middle Archaic sites show a focus on locations with reliable water and abundant resources, including potentially mesquite (Roberts and Lyon 2012; Roth 2012). In Surprise Valley, California, Middle Archaic sites reveal semi-subterranean houses, which likely indicated denser and more permanent local populations during the Altithermal (O'Connell 1975), presumably in more well-watered locations as seen in this study. In Wyoming, Smith (2003) also reports increased sedentism during this time. Meltzer (1999) reports reduced regional population size and intensified subsistence occurs in the Great Plains as well.

Climate-driven population change may also influence human impacts on local ecosystems. Carter et al. (2021) recently showed that ancient wildfire activity increased on the Fish Lake Plateau in Sevier County, Utah coincident with an increase in farming populations, though climate itself did not have a meaningful impact on fire regimes. If climate change was a partial driver of this increase in human populations, then this period of more fire activity may have been influenced by climate indirectly, only as mediated by changes in population density. If these dynamics are generalizable, that suggests that Middle Archaic populations may have had a reduced impact on regional environments, though perhaps a more concentrated impact around the well-watered open-air sites where populations concentrated.

5.3 Ideal Free Settlement During Drought

While it may seem counterintuitive that a prolonged period of reduced effective precipitation led to reduced mobility and intensified subsistence, these findings are consistent with theoretical frameworks derived from ideal distribution models (Fretwell and Lucas 1969; Weitzel and Codding

2022). Within this framework, climate change-induced drought can be seen as reducing the intrinsic suitability of foraging habitats throughout the region, thereby restructuring the optimal population densities at which individuals maximize their foraging returns. This would encourage some individuals to seek better alternative settlements elsewhere, evidenced archaeologically by regional population decline. Those who remained lived at a new population-resource equilibrium, with individuals concentrating in relatively higher suitability locations where water and food resources were more available. These locations are analogous to resource islands surrounded by tracks of land that may have such low suitability so as to make settlement unprofitable, or near impossible.

To make a living under these new circumstances of lower population density and lower suitability in a heterogeneous environment, Middle Archaic people responded by intensifying their subsistence resulting in expanded diets, increased technological investment, and reduced mobility. As other studies in the region have outlined, in heterogeneous environments, more intensive economies (*sensu stricto*; Morgan 2015) may be more likely to occur in areas of relatively higher suitability (e.g., Codding and Jones 2013; Parker et al. 2019), as a dynamic result of more people working harder in high suitability locations to get more resources out of the same area, which leads to smaller resource catchments, more time spent handling resources (particularly in processing), lower residential mobility, and higher payoffs to technological investment.

When conditions improved, populations again expanded relative to the new equilibrium. Empirically such a pattern may appear as logistic growth, but should be considered as possibly "false" signal of true logistic growth (e.g., Manninen et al. 2023) as populations settle at the new equilibrium under a new carrying capacity through a combination of higher fertility, lower mortality, and in-migration from surrounding areas. Individual responses to changes in environmentally factors may be occurring on the ground in much more subtle ways that are un-detectable at this course scale.

5.4. Adaptive Decisions in Changing Climates

Throughout the paper we focus on "adaptive" decisions resulting from climate change. Specifically, we are referring to adaptive behaviors as result from decisions that are in an individual's best interest given their local ecology (e.g., Bird and O'Connell 2006; Codding and Bird 2015; Ready and Price 2021). Thus, regional abandonment and migration may not be what people necessarily want to do, but it may be the best decision in a bad situation. Halstead and O'Shea (1989) describe adaptive practices of hunter-gatherers as mechanisms to buffer variability, including mobility, resource diversification, storage, and exchange (see also Reide et al. 2017). However, other responses such as regional de-population due to mortality, should not be viewed as adaptations, but impacts of climate change. Though not all responses to climate change are clearly assigned to such categories. For example, life history strategies that include reduced parental investment and increased fertility during times of drought may be seen as adaptations, but can lead to runaway population growth as climate conditions improve (Greenwald et al. 2016; Greenwald 2017). Such unintended consequences may be a general outcome of adaptations that promote climate change resilience.

5.5 Future Work

Future work leveraging these strategies could explore additional adaptive responses to climate change. These include even more substantial abandonments that are debated in the region, including the response of Ancestral Puebloan farmers to mega-droughts in the last thousand years (e.g., Cook et al. 2007; Benson and Berry 2009; Kintigh and Ingram 2018; Thomson et al. 2019; Thomson and MacDonald 2020; Polyak et al. 2022). As recent work has shown, it is critical to account of subsistence adaptations when modeling site settlement (e.g., Vernon et al. 2022). As such, the factors that influence forager site count may not impact the decisions of farmers. By generating specific predictions about how farmers should respond to drought, and testing those predictions in a similar framework, we may be able to understand general patterns of climate change adaptation (see Yaworsky et al., this issue).

6. Conclusion

Here we review this emerging record of open-air Middle Archaic settlements and evaluate these trends within the context of a comprehensive record of radiocarbon-dated archaeological sites relative to MCM-reconstructed effective precipitation. Evidence supports our predictions showing that populations declined throughout the region, and those who remained concentrated in more well-watered areas, likely trying to maximize suitability under a new population equilibrium. Subsistence evidence confirms a more intensive diet and increased investment in residential features suggests that populations were less mobile. These dynamics represent an adaptive response of hunter-gatherers to novel climate conditions which allowed them to persist in the region through a prolonged period of aridity. Understanding how generalizable these trends are in other regions may help elucidate common adaptive strategies that contribute to climate change resilience.

Author contributions

Brian F. Codding: Conceptualization, Funding acquisition, Methodology, Formal analysis, Project administration, Supervision, Visualization, Writing - original draft. **Heidi Roberts**: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing - original draft. **William Eckerle**: Data curation, Methodology, Investigation, Formal analysis, Writing - review & editing. **Simon C. Brewer**: Methodology, Formal analysis, Writing - review & editing. **Ishmael Medina**: Visualization, Data curation, Writing - review & editing. **Kenneth Blake Vernon**: Conceptualization, Data curation, Writing - review & editing. **Jerry S. Spangler**: Conceptualization, Data curation, Investigation, Project administration, Writing - review & editing.

Data availability

All data and code required to replicate this analysis is provided as a supplement. We omit site locations as these are protected by federal law. Permitted researchers may obtain location data from the relevant State Historic Preservation Offices (SHPO).

Declaration of competing interest

None.

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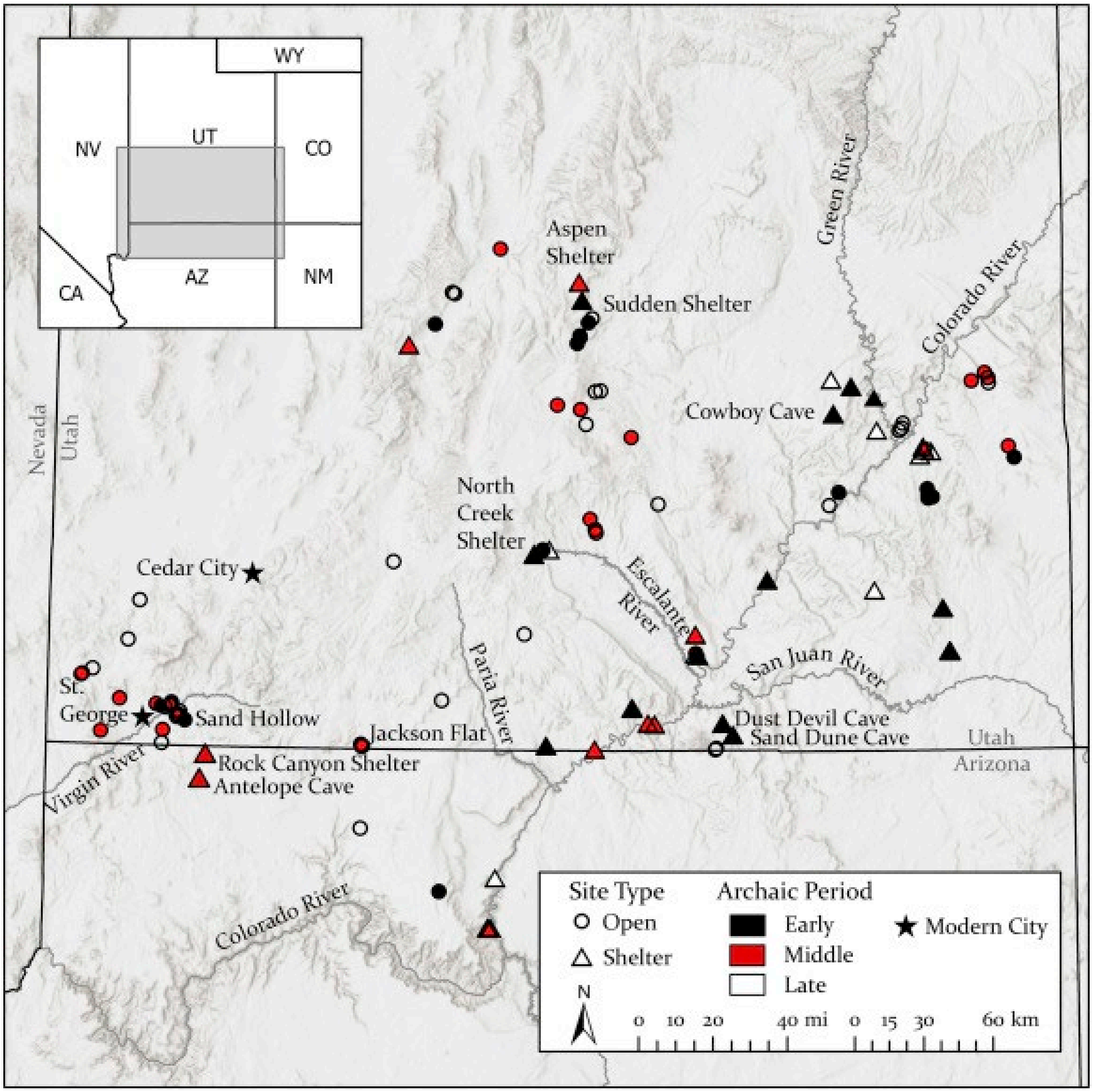

Figure 1. Map of the study area showing the distribution of radiocarbon-dated archaeological sites and major rockshelter sites.

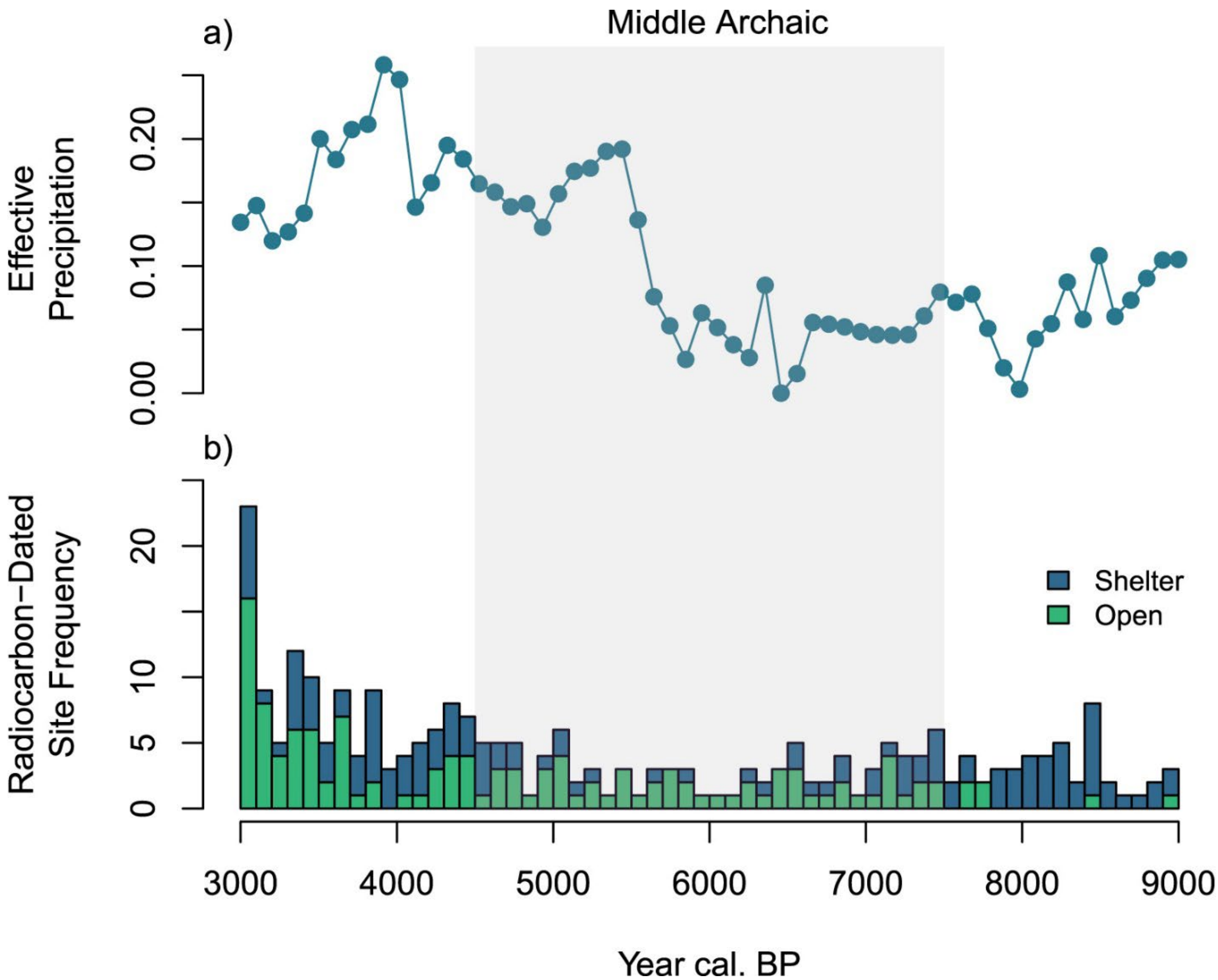

Figure 2. Time series showing a) effective precipitation estimated from a Macrophysical Climate Model (MCM) centered on St. George, Utah, USA (see Figure 1), and b) counts of unique radiocarbon-dated sites per century in the study area from 9000 to 3000 calendar years before present (cal BP). The lower bars indicate counts of open-air sites. Upper bars indicate sheltered sites. The absolute height of the bars shows the combined count of open-air and sheltered sites.

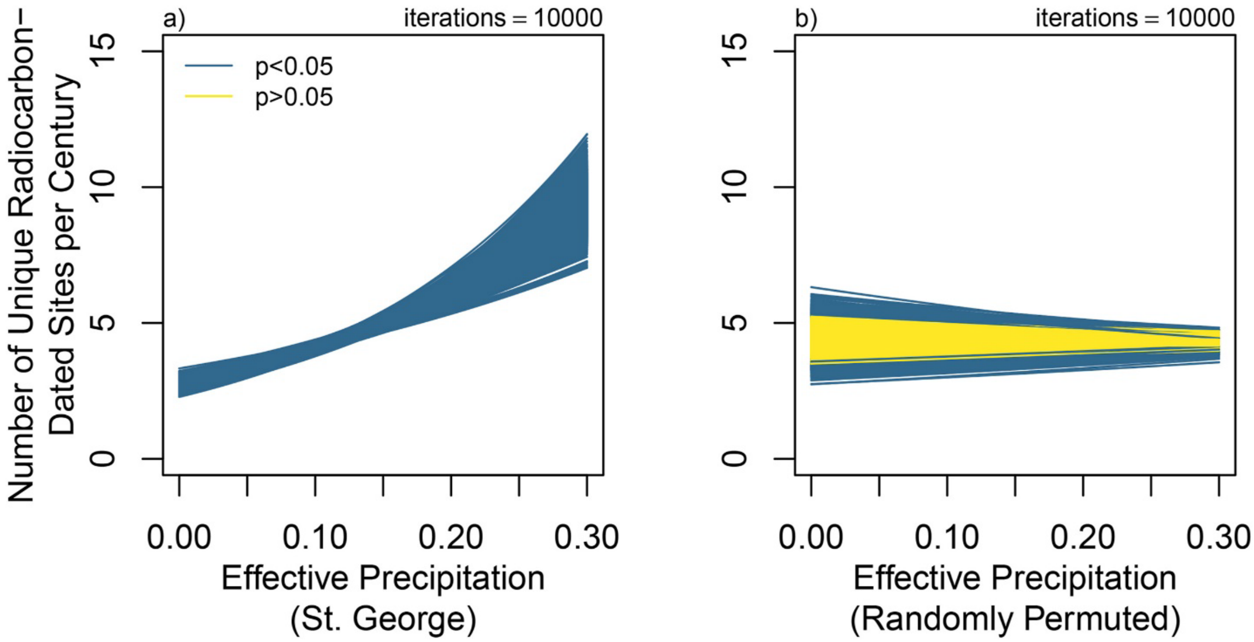

Figure 3. Predicted response of site counts per century as a function of (a) the empirical reconstruction of effective precipitation, and of (b) randomly permuted effective precipitation for each of the 10,000 iterations. Model fits are color-coded to indicate whether the model run is significant at the 0.05 level.

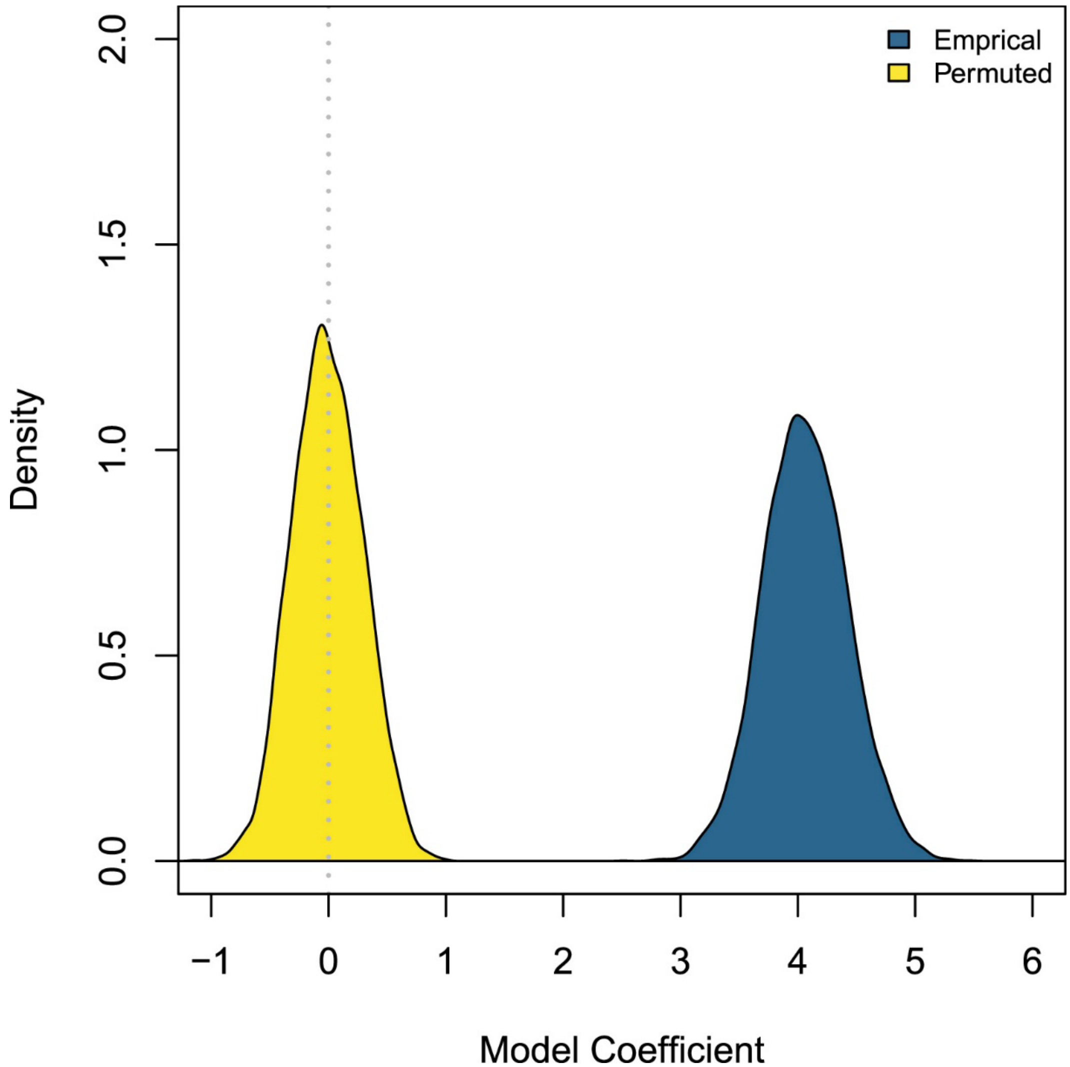

Figure 4. Distribution (kernel density) of model coefficients (log-odds) for all 10,000 iterations sampling the reconstructed estimates of effective precipitation (the empirical model) and all 10,000 iterations sampling the randomly permuted effective precipitation data (the permuted model). The quantiles of the empirical model coefficients are shown in Table 1.

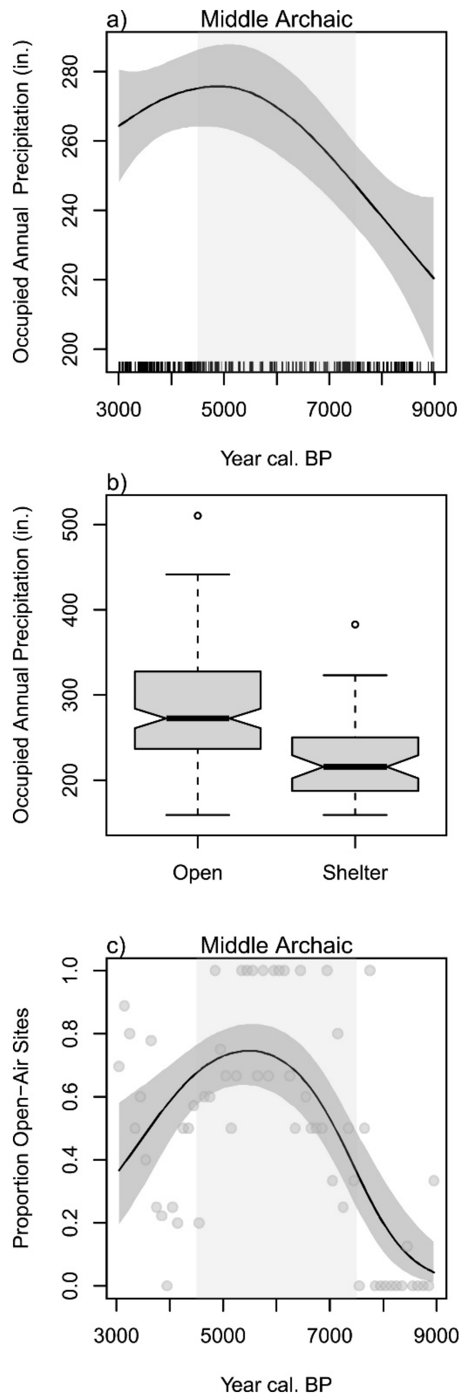

Figure 5. Occupied annual precipitation showing (a) the annual precipitation around dated settlements through time fit with a generalized additive model, (b) annual precipitation at open-air vs. sheltered sites throughout the study area for all time periods (note: one additional open-air site is an outlier outside of the plot area between 700-800 mm), and (c) the proportion of open-air sites occupied through time for the sample iteration shown in Figure 2 fit with a generalized additive model. The precipitation data represents the most recent 30-year normals provided by PRISM. Predicted model fits for panel a and c include 95% confidence intervals shaded in grey.

Table 1. Quantiles of empirical model coefficients across all 10,000 runs sampling the influence of empirically reconstructed effective precipitation for the St. George area on the frequency of radiocarbon dated archaeological sites. Estimates are logged so need to be exponentiated to assess the change in site counts as a function of a per unit (zero to one) increase in effective precipitation.

	Estimate	Std. Error	z value	Pr(>|z|)
Intercept				
0%	0.82	0.14	4.32	<0.0001
25%	0.97	0.16	5.67	<0.0001
50%	1.01	0.17	5.95	<0.0001
75%	1.04	0.17	6.22	<0.0001
100%	1.20	0.20	7.61	<0.0001
Effective Precipitation				
0%	2.51	1.02	2.00	<0.0001
25%	3.82	1.23	2.98	0.0007
50%	4.06	1.27	3.19	0.0014
75%	4.31	1.32	3.41	0.0029
100%	5.48	1.58	4.47	0.0456