The Fremont Frontier: Living at the Margins of Maize Farming

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Draft compiled on 2024-03-19

Abstract

The Fremont provide an important case study for examining the resilience of ancient farmers to climatic downturns, for they lived at the far northern margin of intensive maize agriculture in the American West, where the constraints on maize production are made abundantly clear. Using a tree-ring and simulation-based reconstruction of average annual precipitation and temperature, along with cost-distance to perennial streams, we model spatial variability in Fremont site density in the eastern Great Basin. The results of our analysis have implications for defining the ecological envelope in which farming is a viable strategy across this arid region and can be used to predict where and why maize farming strategies might evolve and eventually collapse as climate changes over time.

Keywords: Ideal Free Distribution, Great Basin, Paleoclimate Reconstruction

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1 Introduction

Archaeological populations of subsistence maize farmers known collectively as "the Fremont" lived at the far northern periphery of maize farming in western North America, in an area encompassing much of the modern state of Utah north of the Virgin and Colorado Rivers, from roughly 2000 to 700 years BP (Madsen 1989; Madsen and Simms 1998). Conditions in this area are extremely harsh and inhospitable to maize farming, so the fact that the Fremont not only pulled it off but also thrived while doing so poses an interesting puzzle. How did they do it? Archaeologists interested in this question have typically focused on strategies directly related to farming and subsistence, like irrigation methods, trade, and seasonal high elevation hunting (e.g., Barlow et al. 2008; Boomgarden et al. 2019; Hart et al. 2021; Janetski 2002; Madsen and Simms 1998; Metcalfe and Larrabee 1985; Morgan et al. 2012; Patterson and Flanigan 2010; Spangler 1993). Here, however, we come at the problem from a slightly different angle. We seek to understand not so much *what* they did to make farming effective, but *where* they chose to do it, and why they chose those places over others (e.g., Bocinsky and Kohler 2014; Thomson and MacDonald 2020). Those are not entirely separate questions, of course, as they trade-off each other, but we think a geographic analysis can actually help illuminate some of the costs and benefits of the other strategies adopted by the Fremont. A geographic approach will also help us to investigate the ways that climate change might have structured those costs and benefits, and by extension the settlement decisions of Fremont farmers.

As a test case, we focus on those Fremont living in the eastern Great Basin of western Utah, which we refer to as the western Fremont (see Figure 1). The extreme desert conditions that the western Fremont adapted to provide a useful backdrop for exploring Fremont settlement, for variation in that environment exhibits abrupt and quite dramatic changes over short distances of space and time, thus heightening the differences between areas the western Fremont did and did not occupy. We explore those differences from a socio-ecological perspective, focusing on dynamic interactions between competing individuals on the one hand and individuals and their environment on the other (Bird and O'Connell 2006; Kennett et al. 2006). This dynamic is captured nicely by the Ideal Free Distribution model from Behavioral Ecology, as it represents individual decisions about where to live as a choice between habitats whose benefits to the individual may be constrained by what other individuals are doing. The technical term for these benefits is 'suitability', which the IFD defines as some function of both the habitat's intrinsic or pristine environmental quality and its current population size (Codding and Bird 2015; Fretwell and Lucas 1969; Winterhalder et al. 2010).

The fundamental assumption underlying the IFD is that individuals will behave optimally, that they will choose to settle the habitat with the highest suitability first, meaning the one that offers them the greatest ratio of benefits to costs relative to the available alternatives. Of course, this comes with the usual caveats. The claim is not that individuals are infallible, that they will always do exactly the right thing, but that their choices will tend to approximate the best strategy given their constraints and trade-offs.

Assuming the western Fremont optimized their agricultural practices, we can use an empirical or inductive species distribution model (SDM, Elith et al. 2006; Elith and Leathwick 2009) of Fremont sites to estimate relative differences in maize suitability across specific environmental gradients and geographic locations (Elith and Leathwick 2009; Jochim 2022; Vernon et al. 2022; Yaworsky et al. 2020). In ecology, you will sometimes hear this approach referred to as "ecological niche modeling" (e.g., Feng et al. 2019; Sillero et al. 2021; Sillero and Barbosa 2021) or even more explicitly as "habitat suitability modeling" (e.g., Bowden et al. 2021; De Kort et al. 2020; Rowden et al. 2017). The basic idea here is that we can look at the distribution of Fremont sites as a reliable indicator of the sorts of available environmental conditions that would best promote maize farming in an arid landscape. To put that in more blatantly economic terms, we are assuming that their environmental preferences are shaped primarily by the constraints of maize farming and revealed in their residential choice behavior. This allows us to build a tentative model of the ecological niche for maize farming and to make some defeasible inferences about its limiting conditions.

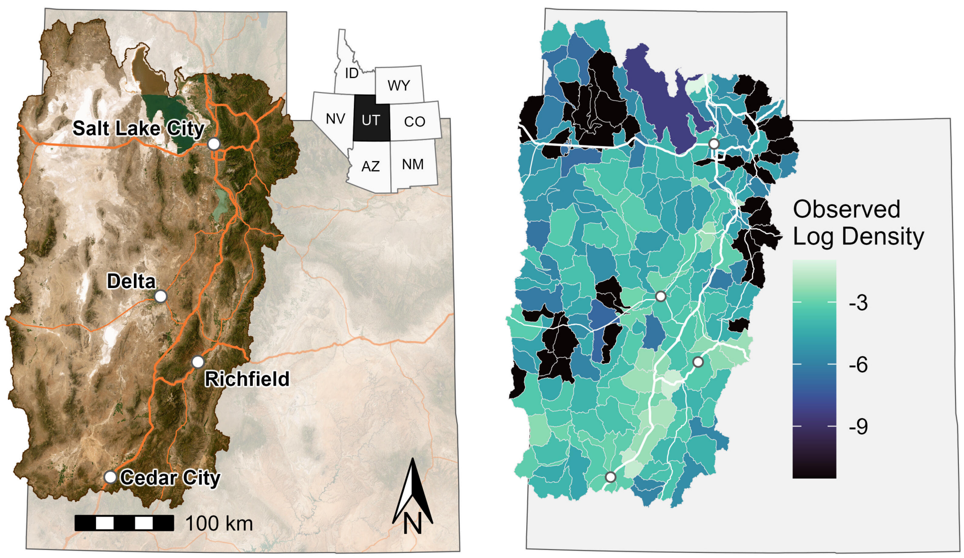

Figure 1. On the left is an overview map showing the project area with modern satellite imagery, so the green areas indicate plant growth, the beige areas, empty desert. The green areas are also the mountainous areas. Thick orange lines are interstate highways. Thin orange lines are major state highways. For visualization purposes, the map on the right shows the log-transformed density of feature-weighted archaeological sites. If no sites have been recorded in a watershed, log(1e-5) is shown.

2 Background

2.1 The Fremont

Archaeologists have nominated a number of artifact types and artifact properties as candidate traits to distinguish the Fremont from their neighbors in space and time, including metates with secondary grinding surfaces, large semi-subterranean pithouses, various clay figurines, trapezoidal rock art, one-rod-and-bundle basketry, painted white and corrugated gray ceramics, and elongated corner-notched arrow points (Madsen and Simms 1998). None of these, however, nor any combination of them, has yet proven up to the task of bringing these diverse people under a single, all-encompassing definition (Madsen and Simms 1998). Nevertheless, the Fremont do stand out, especially at their population apex roughly 1000 years BP.

Around this time, the Fremont likely reached their greatest geographic extent, inhabiting an area that encompassed most of the modern state of Utah (Janetski et al. 2011), with varying levels of support for Fremont foragers in Idaho (Dean 1992) and Wyoming (Hakiel et al. 1987; Smith 1992) and Fremont farmers in Nevada (Cole 2012; Hockett 1998) and Colorado (Baker 1999). These modern political boundaries roughly overlap with the eastern Great Basin and Colorado Plateau physiographic provinces.

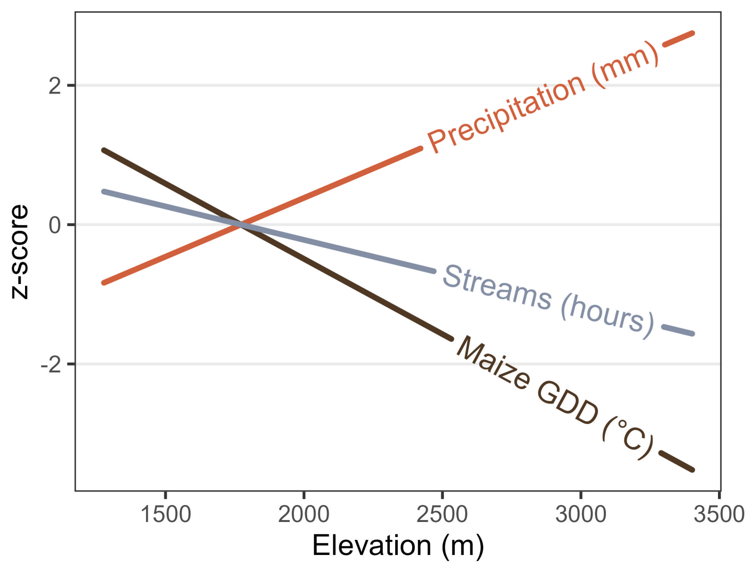

Figure 2. Linear responses of the centered and scaled average water-year precipitation (mm), average growing-season maize gdd (C), and cost-distance to streams (hours) to changes in elevation (m). See methods for how these values were calculated and results for more details.

A basin and range topography dominates the landscape of the Great Basin, with large, dry valleys and endorheic basins punctuated by north-south trending mountain ranges. Changes in elevation in this setting are quite dramatic, on the order of several thousand meters over a short east-west transect. As elevation drives virtually every climatological process in the region, the local ecology is characterized by equally dramatic extremes (Billings 1951; Grayson 2011). As shown in Figure 2, net water-year precipitation in the eastern Great Basin tends to increase with elevation, while maize growing degree days (GDD) over the growing-season tends to decrease. An important trade-off thus exists between temperature and precipitation, with warmer and drier conditions at lower elevations and cooler and wetter conditions at higher elevations.

These are the environments into which the Fremont first emerged in western Utah. Models for describing their origins, while diverse, tend to fall into the familiar categories of migration and diffusion. Where models of the former migration variety insist that Ancestral Puebloan farmers migrated northward from the US Southwest, bringing with them drought-tolerant maize varieties and maize farming (Kidder 1924; Madsen and Berry 1975), models of the latter diffusion variety suggest that the Fremont first emerged within these areas as local Archaic populations transitioned away from mobile foraging, adopting semi-sedentary agricultural practices from the Southwest in a piecemeal fashion over several hundred years (Jennings 1978; Winter and Wylie 1974). While archaeologists have marshaled an impressive array of arguments and counter-arguments for these two classes of models, a general consensus appears to be coalescing around the idea that the truth lies somewhere in between, that the interaction between a lingering Archaic population existing at extremely low population levels and a burgeoning community of migrant Southwest farmers together produced the complex we now call the Fremont (Patterson 2015; Searcy and Talbot 2015; Simms 2008; Spangler 1993, 2000, 2013).

Models that try to explain *why* Fremont maize farmers emerged in the far northern periphery of the US Southwest tend to agree - more or less - that at some point farming became a more economical alternative to foraging in the region. Where they differ, it is in whether things got better for farming starting roughly 2000 years BP (Benson 2011; Coltrain and Leavitt 2002; Matson et al. 1988) or worse for foraging (Barlow 2002; Broughton et al. 2010; Cannon 2000; Cannon 2001). In support of the *farming-got-better* model, archaeologists draw on evidence for a suite of favorable climatic conditions that came together around 1600 years BP, including warmer temperatures and increased precipitation (both winter and summer), as well as the expansion of grasslands (Grayson 2006; Hemphill and Wigand 1995; Madsen 2000). The greatest expansion of the Fremont, in fact, occurred around 1000 years BP, around the time the Medieval Climate Anomaly (MCA) introduced warmer summer temperatures that would have increased the intensity of summer monsoons in the Southwest, pushing them further north into the Great Basin and onto the Colorado Plateau (Grayson 2006), a pattern reflected in numerous tree ring records (e.g., Graybill 1990; Leavitt 1994; Salzer et al. 2014; Stine 1990), though some complications do exist for this suggested pattern (Hart et al. 2021).

In response to these sorts of arguments, those who favor the *foraging-got-worse* model (Barlow 2002; Hart et al. 2021) argue that conditions promoting maize farming would also tend to make foraging a more productive strategy. Plus, farming is an extremely costly endeavor, especially when compared to foraging, including lots of upfront investment of time and energy, so improving conditions favorable to maize agriculture are not by themselves sufficient to explain its origins. To fill that lacuna, archaeologists point to accumulating evidence suggesting that the Fremont transition to agriculture accompanied periods of sustained population growth (Barlow et al. 2008; Codding et al. 2022; Spangler 2013) that likely resulted in the depressed availability of wild resources (Barlow 2002; Janetski 1997; Simms 1986). So, demographic pressure reduced the efficiency of foraging strategies, thus making maize agriculture a more profitable alternative. And that, in turn, led the Fremont to adopt farming as their primary mode of subsistence.

Once they entered the farming niche, the Fremont quickly developed several adaptations for coping with the marginal and stochastic conditions in the eastern Great Basin and the Colorado Plateau, the most important almost certainly being irrigation (for more on this, see the discussion). On the Colorado Plateau, the eastern Fremont settled deep within the steep canyons and washes that flanked the tributaries of major rivers like the Green and Yampa (Yaworsky 2021), in places like Nine Mile Canyon (Spangler 1993) and Range Creek Canyon (Hart et al. 2021). In the eastern Great Basin, the western Fremont chose to settle on open, alluvial fans and stream terraces along the lower slopes of most ranges (Janetski and Talbot 2000; Madsen and Simms 1998; Simms 2008), at places like Nephi Mounds (Sharrock and Marwitt 1967), Pharo Village (Marwitt 1968), Median Village (Marwitt 1970), Evans Mound (Berry 1972; Dodd 1982), and Snake Rock Village (Aikens 1967).

Given the extreme aridity of the west, they were still susceptible to drought, of course, even in those more suitable areas, with a single short growing season making agricultural returns highly variable. To cope with these uncertainties, Fremont farmers may have adopted additional risk-mitigation strategies like spreading farm plots among different micro-environments, a technique otherwise known as plot diversification (Patterson 2015; Spangler 1993, 2013). The Fremont also relied heavily on crop storage both to provide a surplus during the winter season and to make-up for poor yields (Spangler et al. 2019).

3 Materials and Methods

3.1 The Project Area

Because we are focusing on the western Fremont, we constrain the current project area to the eastern Great Basin in western Utah, as shown in Figure 1, where the Great Basin is defined in the hydrologic sense using watershed boundaries (Grayson 2011). On the far eastern edge of this region, a series of north-south ranges, including the Wasatch Mountains in the north and the Sevier Plateau in the south, together stand as the primary physiographic boundaries separating the majority of the Great Basin from the Colorado Plateau. On its far western edge, a series of north-south ranges straddle the Nevada state line or lie just inside it, including the Snake Range where Great Basin National Park is located. Its northern periphery includes the Great Salt Lake (GSL) and the West Desert, its southern boundary the Bull and Pine Valley Mountains that separate the Great Basin from the Virgin River watershed just north of St. George, UT. This is a region approximately 107,000 km^2 in area, encompassing virtually all of the Bonneville Basin in western Utah.

These boundaries also serve as geographic borders between the western Fremont and other contemporaneous populations. Around the GSL and the Utah-Nevada border, Fremont farming gives way to Archaic populations engaged in intensive foraging modes of subsistence. The Wasatch Range and Tushar Mountains separate the western from the eastern Fremont on the Colorado Plateau, and the Pine Valley Mountains serve as a border between the Fremont and the Virgin Ancestral Puebloan to the south (Simms 2008).

3.2 The Unit of Analysis

The unit of analysis for this research is the HUC10 watershed (n = 183), as defined by the Watershed Boundary Dataset (WBD) developed by the US Geological Survey and the Natural Resources Conservation Service within the US Department of Agriculture (USGS and USDA NRCS 2013). These provide a spatially-explicit proxy for specifically human habitats in the proposed study area. There are two reasons for this. First, the topography of the region is such that the cost of travel between watersheds is often quite significant. As a consequence, individuals are expected to spend more time traveling within watersheds than between them, all else being equal. Second, watersheds are by definition water sinks, funneling all available run-off into their respective stream networks. Given the extreme aridity of the proposed project area, this also makes them critical resource sinks, especially for maize farmers, as watersheds determine how much water might accumulate at a location, as well as its potential for irrigation.

While aggregating to the level of the watershed does reduce the spatial resolution of this analysis, depriving our model of a substantial amount of environmental variation, several arguments can be made for the simplification. First, it reduces the computational burdens of this modeling exercise. In particular, it makes paleoclimate reconstructions more tractable, as we are only estimating the means within each watershed through time (see below for details). Second, if there are good theoretical justifications for using certain polygons as spatially explicit habitats (like the ones outlined above), they can be relied upon to identify real, presumably causal, relationships in the data. Third, the aggregated site data can be shared without giving away site locations, making it easier for others to reproduce the analysis. Finally, depending on the question being asked, disaggregated site locations may offer only false precision. This is likely the case for the current analysis as Fremont were opportunistic hunters (Morgan et al. 2012), so many of the sites in our database are likely temporary logistic hunting sites in proximity of their actual residential locations, but crucially the available data make it hard to differentiate these kinds of sites.

3.3 Site Data

To identify Fremont sites in the project area, we rely on site records and cultural resource reports hosted by the cultural resource information systems in Nevada (NVCRIS) and Utah (Sego) with permission from the respective State Historic Preservation Offices. Data collection is part of a larger NSF-funded project (BCS-1921072) that is examining demographic reconstruction in the Bonneville Basin and surrounding areas (see Codding et al. 2022, 2023; Contreras and Codding 2023). Unfortunately, our dataset does not represent all recorded Fremont sites in the study area, as we did not review all site forms in a systematic fashion. Some site forms were chosen at random. Others were selected opportunistically. Still, the resulting dataset contains 2,248 individual Fremont sites, a considerable number representing one of the largest samples used for this sort of analysis to date.

These site data include everything from small ceramic scatters to massive Fremont villages like Five Finger Ridge (Janetski 1998; Janetski and Talbot 2000). For this analysis, we assume that these reflect different levels of population size and settlement intensity. All else being equal, scatters should follow from shorter stays by fewer people, villages from longer stays by more people. This is important because population size correlates with a habitat's suitability according to the IFD model, and our attempts to reconstruct the ecological and geographic borders of the Fremont rely heavily on the idea that more suitable habitats will have larger populations at equilibrium.

To get the architectural feature data, we relied primarily on summaries of well known and named Fremont villages in (Coltrain and Leavitt 2002) and cross-referenced those with original site forms and reports, as well as the work of (Mooney 2014), which attempts to reconstruct poorly reported excavation efforts along the Wasatch Front. Storage features were not included in this count, only residential features described as pitstructures, pueblos, roomblocks, or wickiups. All told, this included 16 Fremont villages and 215 residential features. In several cases, the estimates of the number of features on a site vary wildly, so we erred on the side of taking the most conservative estimates. We then weight the count of sites in each watershed by those estimates. So, a site with no residential features counts as one site, a site consisting of, say, four pithouses counts as four unique sites, and a site containing a roomblock with seven rooms counts as seven sites. This brings the total weighted site count to 2,447, with minimum and maximum values of 0 and 119, respectively.

Figure 1 shows the log density of Fremont sites across watersheds. The log is used mainly for visualization purposes as a number of high density watersheds swamped the variance shown on the untransformed scale. Note that if a watershed has zero sites in it, we used $log(1e-5)$ as $log(0)$ is undefined. It should be emphasized that we do not have an independent estimate of the absolute number of Fremont sites in the area, just an estimate based on a thinned sample, so the map is more appropriately interpreted as showing relative differences in the density of recorded sites across watersheds.

3.4 Environmental Covariates

For this analysis, we use both topographic and climatological covariates. The topographic covariate is cost-distance or travel time to perennial streams (measured in hours). This provides a coarse grained estimate of water availability, as well as the potential costs of irrigation. To calculate this, we first use the R package FedData (Bocinsky 2020) to download perennial stream features from the US National Hydrography Dataset (USGS 2022a) and a digital elevation model (DEM) from the US National Elevation Dataset (USGS 2022b). We then apply Campbell's hiking function (Campbell et al. 2019) to slope estimates derived from the DEM. This allows us to estimate travel time between grid cells in the DEM and then calculate the accumulated cost of travel from each perennial stream to any grid cell within each watershed. We then aggregate these values to the watershed level by taking their mean.

Climate covariates include net water-year precipitation (PPT, in millimeters, mm) from October to September and maize growing degree days (GDD, in Celsius, C) over the growing season from May to September, as these have a large effect on maize productivity, thus providing important constraints on the patterns of settlement for those who relied on maize for subsistence. We caution that GDD is calculated in such a way as to be insensitive to extreme high and low temperatures (extreme heat and frost, in effect). It is also conceptually understood to be a measure of accumulated temperature between the last and first frost-free days, but in our analysis is calculated using hard start and end dates of May 1 and September 30, under the assumption that these dates will roughly coincide with those frost-free days.

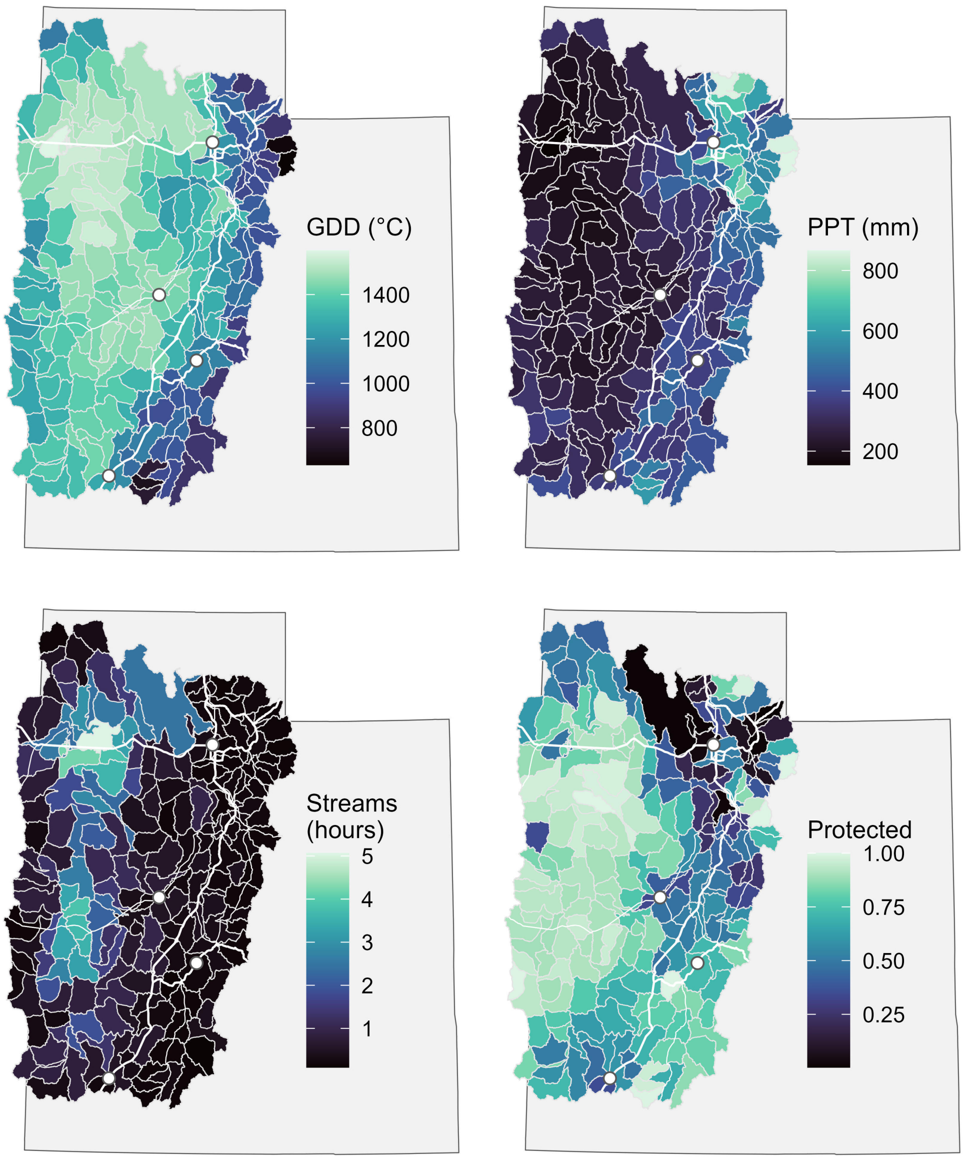

Figure 3. Distribution of covariates across watersheds. These include maize growing degree days (GDD), annual precipitation (precipitation), and cost-distance to streams (Streams). Lighter values represent larger values, darker colors smaller values.

We hindcast these climate covariates for each watershed and year over the Fremont sequence from 1550 to 550 years BP (400 to 1400 CE) using the Correlation Adjusted corRelation (CAR) method implemented in the R package paleocar (Bocinsky 2019). This method, in effect, regresses modern climate data against the width of younger tree rings, then uses older rings to predict past climate trends (Bocinsky et al. 2016; for further details, see Bocinsky and Kohler 2014). In this case, we use interpolated precipitation and temperature estimates from the ~800 m resolution PRISM dataset (PRISM Climate Group 2019) and all tree-ring samples in North America, which were obtained from the International Tree Ring Database using FedData. For each watershed, we took the median values of precipitation and GDD over the Fremont sequence. Although we calculated these results manually, we note that comparable estimates are now more easily obtained through the open, geospatial climate data portal, SKOPE (Bocinsky et al. 2023).

Figure 3 shows the geographic distributions of these covariates over watersheds. Orographic effects (meaning the effects of mountains and elevation) are rampant in these data, so it is reasonable to expect that the covariates will exhibit some multicollinearity. As part of the exploratory phase of this analysis, we, therefore, perform a series of pair-wise tests of correlation measured using Pearson's R. We also regress the scaled and centered values (or z-scores) of maize GDD, precipitation, and cost-distance to streams on elevation using ordinary least squares (OLS). No doubt, this violates many assumptions of OLS, particularly the identity and independence of the errors, but explanation was not our main goal with these simple linear models. We are only trying to get a rough sense of their general response to changes in elevation, which OLS offers (see Figure 2).

Given that our primary covariates all correlate with elevation (reported below), readers may wonder why we do not simply use elevation in our main analysis. The reason for this is two-fold. First, using elevation alone would obscure the trade-off between water availability and temperature. Second, elevation is not explanatory of settlement behavior. A maize farmer does not choose a location for farming *because* it is at, say, 1200 m above sea level. They choose that location *because* it has the right combination of water availability and temperature, that is to say, because conditions there are optimal for maize farming. Were those conditions found at some other elevation, the farmer would be expected to farm there instead.

3.5 Statistical Modeling and Model Evaluation

For this analysis, the outcome of interest is a count N of archaeological sites per watershed i. Here N is assumed to follow a negative binomial distribution:

$$N_i \sim NB\left(\lambda_i, r\right)$$

with r being a dispersion parameter and λ_i the expected number of sites per watershed, $E\left(N_i\right) = \lambda_i$. To estimate λ_i, we model it as a log response to the linear predictor:

$$log(\lambda_i) = \alpha + \sum_{k=1}^{K} s(x_{ik}) + \epsilon_i$$

where α is the intercept, ϵ_i is the error term, and s is a smooth function applied to the K covariates - growing degree days, precipitation, and cost-distance to streams. The smooth is intended to account for potential non-linear responses to the covariates. In our model, ϵ_i incorporates an exponential covariance model to account for spatial autocorrelation in the untransformed residuals. The complete model is fit within a generalized additive mixed model (GAMM) framework using the R package mgcv (Wood 2004).

Importantly, we add to the model specification a constant offset for the log of the area of each watershed, in effect making this a model of population *density*. This is meant to address the idea that larger watersheds will have more sites just as a matter of chance. While our model as currently specified includes the intercept, we caution that such an estimate cannot be interpreted in terms of the abundance of Fremont sites, as that would assume that the absolute site counts can be inferred from this sample, which is implausible. At best, the intercept tells us about the abundance of *recorded* sites when $\sum_{k=1}^{K} f(x_{ik}) = 0$. On that note, we also include a parametric term for the proportion of each watershed classified as federally protected land. This is to account for anthropogenic impacts to archaeological resources that can bias our sample. Notably, for these data, those are almost entirely the result of Euro-American colonization of the area, in particular, the impacts of modern farming techniques and the development of the Wasatch Front as the urban core of the modern state of Utah. This is a coarse metric, but our expectation is that the greater the share of a watershed with federal protections, the smaller the effect of these anthropogenic impacts, the more sites we should observe.

Model evaluation includes checks for concurvity or non-linear correlation in the smooth terms of the GAMM, as well as a Variance Inflation Factor test on the parametric or linear terms. We also test for spatial autocorrelation in the untransformed residuals using Monte Carlo simulations of Moran's I. After fitting the full model, we found that several smooth terms had effective degrees of freedom (EDF) equal to one, suggesting no non-linear response in the data. We, therefore, remove the smooth terms for those covariates in the final model, leaving only precipitation with a potential non-linear effect.

All analyses are conducted in the R programming language and environment (R Core Team 2022). For details of this analysis, please see the Supplement.

Table 1. Model Results

Parametric Terms	**exp (β)**	**std.er**	**t**	**p-value**
Intercept	0.00	1.40	-7.13	<0.001
Maize GDD	1.00	0.001	4.15	<0.001
CD to Streams	0.67	0.156	-2.57	0.011
Protected	4.82	0.497	3.16	0.002

Smooth Terms	**edf**	**ref.df**	**F**	**p-value**
s(Precipitation)	3.25	3.25	11.1	<0.001

4 Results

As shown in Table 1, all linear (or parametric) coefficients are significant in the final model. The intercept ($\exp\beta = 0.00$, $p < 0.001$) is close to zero when transformed back onto the response scale, likely reflecting the large number of watersheds with zero Fremont sites, though as mentioned above, the intercept estimate is only a measure of the recorded site abundance. The proportion of watersheds falling under federal protections ($\exp\beta = 4.82$, $p = 0.002$) has a positive effect on site counts, thus confirming our expectation that more sites occur in watersheds with a larger proportion of federal land. Site counts increase in watersheds with larger GDD values, though the effect is small ($\exp\beta = 1.00$, $p < 0.001$), and site counts decrease with distance from perennial streams, though again the effect is small ($\exp\beta = 0.67$, $p = 0.011$). The only smooth term in the final model is average precipitation over the water-year, which is significant (edf = 3.25, $p < 0.001$). The effective degrees of freedom (EDF) for precipitation suggests a strong non-linear effect of that covariate on site counts, which increases up to about 450 mm and decreases thereafter.

A concurvity test on the final model was not conducted as there was only one smooth term. As expected, a VIF test for linear correlation in the parametric terms of the final model shows some evidence of correlation, particularly for GDD, which was close to 6, but this value is within acceptable limits at a moderate threshold. The Moran's I test suggests that there is no spatial autocorrelation in the untransformed residuals of the final model (I = 0.233, rank = 381, p = 0.476).

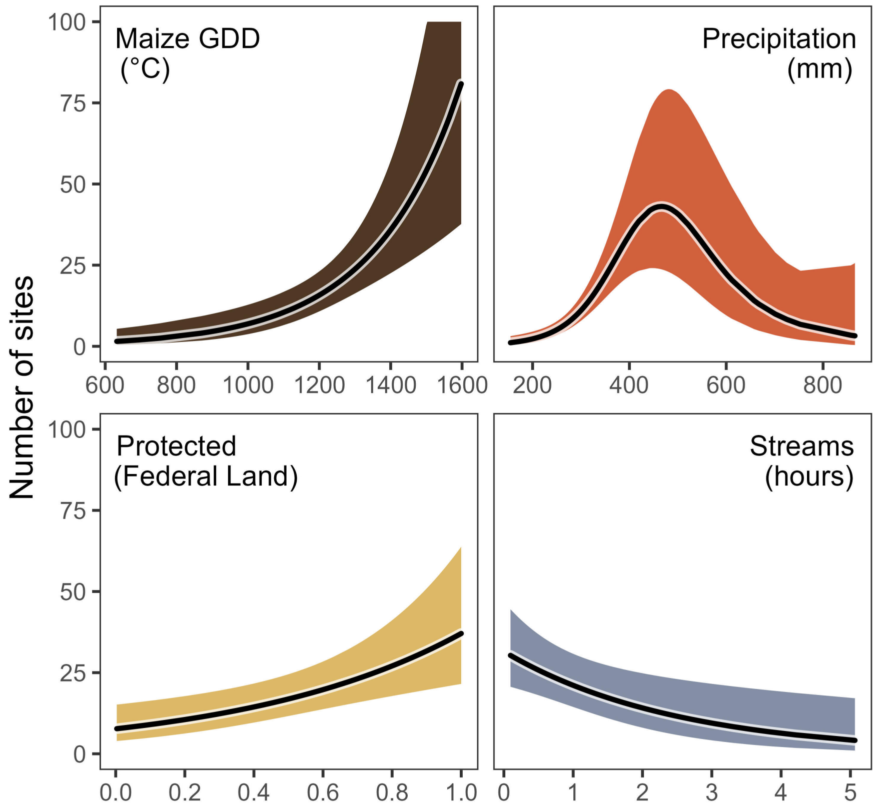

Figure 4. Partial dependence plots. Each plot shows the response of site counts to changes in a target covariate while holding all other variables at their mean.

5 Discussion

With this analysis, we seek to reconstruct the Fremont maize farming niche by estimating relative differences in suitability across watersheds and environmental gradients. Our approach involves the use of a Negative Binomial GAMM model of the feature weighted counts of archaeological sites, under the assumption that more suitable watersheds should have more sites at equilibrium. Results from that model indicate that Fremont maize farmers generally preferred warmer watersheds with longer growing seasons, moderate levels of precipitation (in the range of 400-600 mm), and greater access to perennial streams, as shown by the marginal response plots in Figure 4.

5.1 The Data Quality Problem in Fremont Research

Fremont research focused on individual, well-dated, and excavated sites can and often does describe the processes acting on those sites in great detail, but any attempt to generalize to a whole region runs into a familiar problem, namely that the Fremont sequence suffers from poor chronological resolution due to a paucity of direct dates and a more or less undefined ceramic chronological record. The consequence for this analysis is that we have to use (i) total site counts in each watershed, not the contemporaneous site counts, and (ii) the median values of the climate variables over the entire Fremont sequence rather than over the years that individual Fremont sites were occupied. While there are radiocarbon dates for Fremont sites in the study area, they represent only a small fraction of known Fremont sites, so we can use them to get better chronological control, but only at the expense of losing spatial resolution.

Fortunately, there are good reasons to believe that we have wrestled a meaningful signal from the noise in these temporally unresolved spatial data. For one thing, it is unlikely that inter-watershed variability would have changed substantially over the Fremont sequence. Over the last two thousand years, wetter watersheds would have tended to be wetter than dryer watersheds, and warmer watersheds would have tended to be warmer than colder watersheds. The central tendency of the climate in each watershed also tells us which of them would, in general, have been better for maize farming, even if we cannot yet define diachronic variation in watershed suitability. So, the inference is simply that those typically better watersheds would have attracted maize farmers more often and, over time, would have accumulated a larger archaeological maize farming assemblage, too.

5.2 The Relative Contribution of Foraging to Fremont Diets

Many Fremont scholars are convinced that foraging had to contribute a substantial portion to the diet of Western Fremont populations (Madsen and Simms 1998; Simms 1999). If true, this would pose a substantial obstacle to any inferences about maize suitability based on the distribution of Fremont archaeological materials, as those inferences would conflate settlement patterns owing to constraints on foraging and settlement patterns owing to constraints on farming. This is problematic because it strikes at the heart of the interpretation we propose for our model. In fact, if true, it would basically nullify the whole paper, so it is worth confronting the question head-on: to what extent did foraging contribute to the diet of Fremont maize farming populations in the eastern Great Basin?

Unfortunately, the kinds of observations that might help us arrive at an unequivocal answer to this question are frustratingly few and far between. The most compelling evidence currently available is provided by stable isotope analysis of a small number of Fremont burials (Coltrain 1993; Coltrain and Leavitt 2002). The results of those analyses suggest that the contribution of maize to Fremont diets was on the order of 75 to 80%, a fraction comparable to what one would find in the San Juan Basin, where there is no doubt that maize farming was the primary mode of subsistence during the time period in question. The one exception to this pattern involves individuals from the GSL Wetlands, who were at least part time foragers. But those exceptions are limited to the latter half of the Fremont sequence, after 1100 years BP (850 CE), and they don't show signs of full reliance on foraging until nearly 800 years BP (1150 CE). This is consistent with the suggestion that substantial foraging (and not just opportunistic foraging) would have been relegated mostly to the margins of areas where maize farming occurs (Allison 2008). In the study area, that would include areas surrounding and to the north of the GSL, as well as the West Desert and northern Nevada.

There are two additional things to note here. First, our results have important parallels with the results reported in (Yaworsky et al. 2023), where the Fremont being studied are unambiguous maize farmers. This suggests that we are also modeling maize farming populations. The other point to mention is that our model incorporates an exponential covariance matrix, so if there were any systematic deviations around the north and northwest periphery of the study area, those would at least partially be accounted for in the model. In other words, the primary trend driven by well understood maize farming sites in the core of the study area (following the I-15 corridor south from Salt Lake) should not be noticeably affected by those deviations at the periphery.

5.3 Trade-off Between Precipitation and Temperature

While site counts in our model exhibit a positive linear response to maize GDD, this should not be expected to continue indefinitely for the obvious reason that maize has an upper threshold temperature at which point it no longer grows. Plus, increased temperatures trade-off with precipitation, with warmer conditions being better for plant growth but at the same time increasing water demand on the plant to keep up with growth (Ramankutty et al. 2002). This trade-off probably also explains the curious result that site counts do not increase linearly as a function of precipitation, but instead decline after 500 mm.

Provided that the trade-off between precipitation and temperature is driven largely by elevation in this region, it would seem likely that the western Fremont chose site locations at elevations with the best combination of temperature and precipitation for maize farming in the region, as evidenced by the estimated distribution of sites across watersheds (see Figure 5), though we caution that watersheds are coarse grained units of analysis. Given the topography of the study area, this trade-off would also suggest that areas suitable for maize agriculture take the form of a thin band around the lower slopes of mountain ranges.

It is tempting to think of this elevation band as a Goldilocks Zone for maize agriculture (Yaworsky et al. 2023), but we should take care not to over-interpret this metaphor, for the elevation band is an area of overlap for continuous ecological gradients, not a region demarcated by anything like a perfect line. There is also variation in site density within that band, perhaps suggesting missing covariates in our model. The unaccounted for variation could also be owing to the fact that what matters most for maize agriculture is not necessarily where precipitation falls, but where it accumulates once it enters the stream flow network. Of course, that will largely be a function of elevation in this region, or changes in elevation, so it will still be in proximity to this optimal elevation band, though perhaps not perfectly coincident with it.

At any rate, given these considerations, it would perhaps be more accurate to characterize the trade-off confronting the Fremont as one between what we might call water availability (including general precipitation across the stream flow network, water runoff, proximity to perennial surficial sources, soil moisture, and irrigation potential, among other things) and temperature (including, but not limited to, the length of the growing season and the number of frost-free days).

5.4 Water Management and the Rain-fed Maize Farming Niche

Based on previous research (Adams et al. 2006; Bellorado 2010; Benson 2011), Bocinsky and Kohler (2014) place minimum thresholds for precipitation and maize GDD at 300 mm and 1000°C GDD, respectively. Importantly, these are thresholds for dry-farming, which is typically defined as farming free of irrigation (Benson 2011; Cordell and McBrinn 2012; Varien 1999), so they can be loosely interpreted as minimum temperature and precipitation levels required to grow maize through nothing more than planting and harvesting. The right panel in Figure 5 shows the watersheds whose median values for maize GDD and precipitation over the Fremont sequence are above those values. This is similar to Bocinsky's concept of "refugia," but rather than calculate the proportion of years in niche, we are using median values, so refugia are defined here as watersheds that spend at least half the Fremont sequence in the rain-fed maize farming niche ($\geq$ 500 years, in this case).

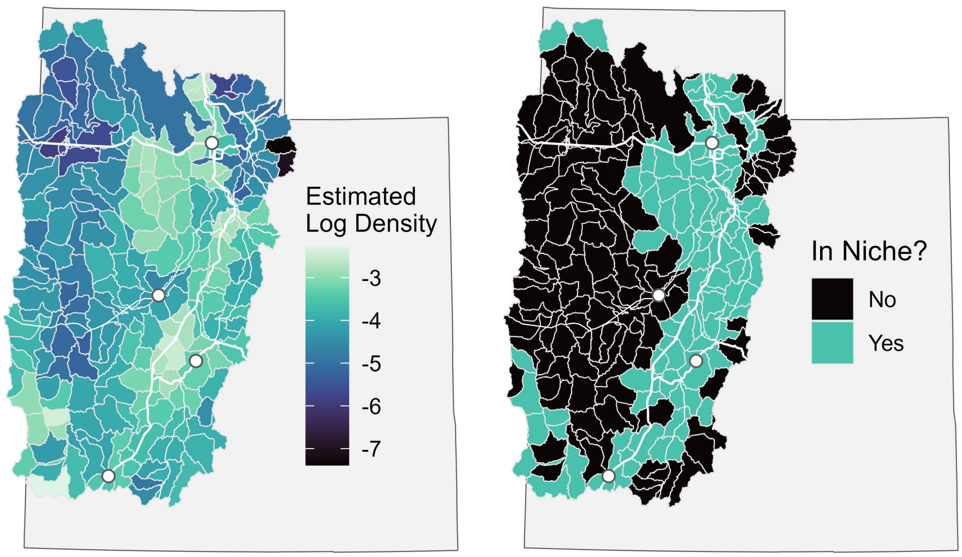

Figure 5. The map on the left shows the log density of feature-weighted site counts as estimated by the model, with lighter colors representing larger relative densities, darker colors representing smaller relative densities. The map on the right shows which watersheds are in the rain-fed maize farming niche for at least half of the Fremont sequence. The light green color indicates those that are in the niche.

It appears that these models tend to agree on the best watersheds for maize farming, though there are some notable exceptions. The western slopes of the Stansbury Range in the north central part of the study area (just west of Salt Lake City) and parts of the Parowan Valley and surrounding areas in the southeast part of the study area (the area roughly midway between Cedar City and Richfield) are estimated by our model to have non-negligible densities, but they fall outside of the niche. Other areas, like much of the Salt Lake valley appear to be in the niche, but are estimated by our model to have relatively low densities. These discrepancies are at least partially explained by limitations of our methodology. For one thing, including the proportion of federal land as a covariate is a very crude way of accounting for sampling bias, so our model might not be picking up on the fact that the Salt Lake valley was actually a highly suitable area for maize agriculture, as evidence to that effect has largely been destroyed. The discrepancy may also be explained by the fact that we have aggregated to the watershed level, thus obscuring important environmental variation across both the landscape in general and site locations in particular. Were we to build a model of the disaggregated data, we would likely find that many agricultural sites do, in fact, fall in the rain-fed maize agricultural niche, even if the watersheds that contain them do not.

But setting aside those methodological issues, some much more interesting explanations may be offered, at least from the perspective of theory. Consider the fact that of the 183 watersheds in the study area, 87% (n=159) have median GDD values greater than 1000°C, but only 54% (n=98) have median precipitation values above 300 mm, and a scant 40% (n=74) meet both requirements. This would suggest that precipitation is the primary limiting factor when it comes to the choice of watersheds in which to dry farm, for there are many more watersheds that meet the minimum GDD requirements than meet the minimum precipitation requirements. One important implication of this is that dry farming would have been very nearly impossible across most of the study area over the Fremont sequence and irrigation or some other form of water management more or less necessary. We note that even within the niche, which we have defined somewhat liberally as those watersheds that are included for at least half the Fremont sequence, water management would almost certainly have been a necessity (Boomgarden et al. 2019; Matson et al. 1990; Spangler et al. 2010). Of course, the type and intensity of water management would probably differ between sites, with more intensive management occurring where there is less precipitation and less intensive management where there is more precipitation, whether that precipitation falls in the watersheds themselves or in the upstream watersheds that feed into them.

5.5 The Spread of Maize Agriculture

Our results comport with previous work suggesting that maize farmers in the eastern Great Basin preferentially targeted a certain elevation band that coincides with alluvial fans, forming a rim around the lower slopes of mountains and ridges on or near important drainages and floodplains. The ruggedness and aridity of this region led to extreme circumscription, with the costs of intensive farming outside these areas being so severe as to render that alternative virtually unsustainable. For maize farmers, the Great Basin should, thus, have the look and feel of an island biogeography, with mountains rising up like islands out of an ocean of desert sand and sagebrush.

To account for the timing and tempo of island colonization among food producers in Oceania, Kennett et al. (2006) offer an extension of the IFD framework that might actually apply to the Great Basin. Their model depends crucially on the potential for farming populations to introduce economies of scale or Allee effects, with suitability increasing with increasing population at low densities. They also assume that individuals will prefer nearer habitats to those that are farther away, under the assumption that greater distances impose greater settlement costs, all else being equal. Together, these assumptions suggest a pulsating pattern of maize spread into the North American Southwest, with maize agriculture growing, then spreading, growing, then spreading, as appears to have happened in Oceania.

This need not be a wholesale movement or adoption of agricultural practices, either. Early on, subsistence would have varied along two dimensions: levels of residential mobility and levels of cultigen adoption. While some individuals would have been more mobile, moving from isolated patch to isolated patch, others would have been more sedentary, typically tethered to a productive wetland or riparian area. As local populations increase, the benefits of increased sedentism and cultigen adoption would slowly begin to outweigh the benefits of a more mobile and foraging-centered diet. According to our model, individuals moving in this direction would tend to concentrate more of their time and energy in the maize farming niche. This would then have the effect of increasing population size within a smaller area, possibly leading to scale effects, which would invite further sedentism from those in the surrounding area. Following this logic, the patchy adoption of agriculture makes more sense. The degree and speed with which it occurs is simply a function of how fast habitat quality declines and how quickly populations grow.

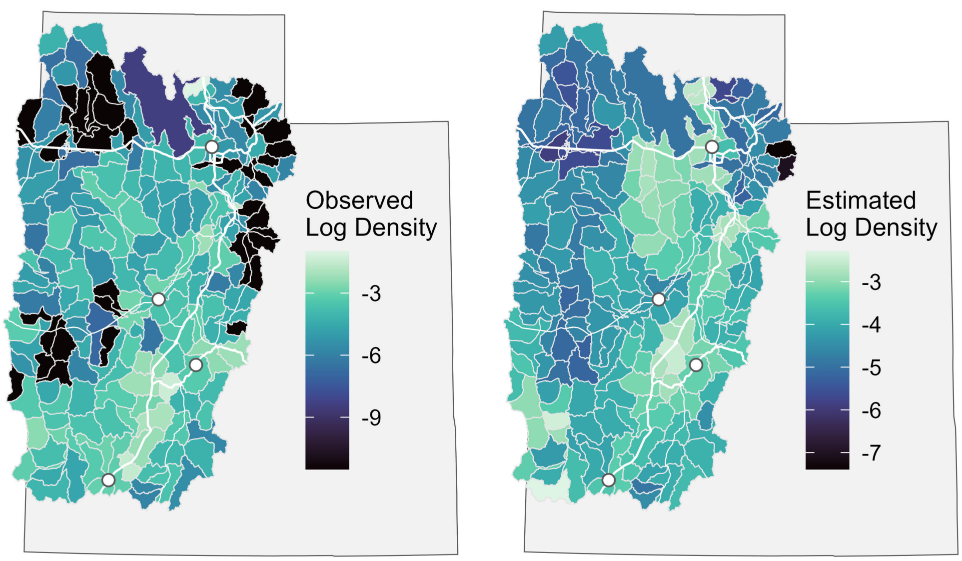

Figure 6. Geographic distribution of Fremont sites across watersheds. The left panel shows the relative density derived from observed site counts, and the right panel shows the relative density from the estimated site counts.

5.6 The Collapse of Maize Agriculture

After farming these regions successfully for over a thousand years, the Fremont began an abrupt process of abandonment starting around 700 years BP. The cause of this event is still a matter of some dispute, though most scholars agree that climate change drove severe reductions in agricultural productivity (Benson et al. 2007; Finley et al. 2020; Spangler et al. 2019; Thomson et al. 2019; Thomson and MacDonald 2020). We follow Lindsay (1986) in thinking this was likely owing to climatic events that, in effect, severed the connection between the optimal temperature and precipitation levels that made maize farming a reliable strategy, pulling higher temperatures further down in elevation and pushing higher precipitation levels further up.

Lindsay suggests that the end of the Medieval Warm Period may have been responsible for the initial coupling of these ecological gradients, as it involved higher temperatures and more growing-season precipitation owing to the northward intrusion of summer monsoons. This period lasted from roughly 1,000 to 600 years BP (Graumlich 1993; Grayson 2011), so it does coincide with the height of the Fremont complex. Given the logic of IFD, this likely led to population spillovers into less suitable habitats (Codding et al. 2022). However, given the extreme circumscription we have highlighted in the Great Basin, the available alternatives would have been limited, potentially leading to increasing population packing across all habitats during this time, thus making the Fremont especially sensitive to climatic downturns.

The well-documented megadrought at the end of the thirteenth century (Cook et al. 2004) would have been catastrophic in this context, reducing precipitation levels across the region (Benson et al. 2007), but also leading to reductions in water accumulation within the streamflow network. So, just as temperatures are beginning to cool, precipitation levels collapse. By extension, this would have decreased overall water availability and, thus, the potential for irrigation. Opportunities for the Fremont to recover from such a drought would have been limited, too, as the end of the Medieval Warm Period was also the beginning of the Little Ice Age, a time during which conditions were generally colder and wetter (Mann et al. 2009), further pulling apart the combination of temperature and precipitation upon which the Fremont so long depended.

6 References Cited

Adams, Karen R, Cathryn M Meegan, Scott G Ortman, R Emerson Howell, Lindsay C Werth, Deborah A Muenchrath, Michael K O'Neill, and Candice AC Gardner

2006 MAIS (Maize of American Indigenous Societies) Southwest: Ear descriptions and traits that distinguish 27 morphologically distinct groups of 123 historic USDA maize (zea mays l. Spp. Mays) accessions and data relevant to archaeological subsistence models. *New Mexico Experimental Grow Out, Farmington, NM.*

Aikens, C. Melvin

1967 *Excavations at Snake Rock Village and the Bear River No. 2 site.* University of Utah Anthropological Papers 87. University of Utah, Salt Lake City, UT.

Allison, James R.

2008 Human ecology and social theory in Utah archaeology. *Utah Archaeology* 21(1):57–88.

Baker, Steven G.

1999 *Fremont archaeology on the Douglas Creek Arch, Rio Blanco County, Colorado; the Sky Aerie Promontory Charnel Site (5RB104). CRI project no. 486.* Centuries Research, Montrose, Colorado.

Barlow, K Renee, Ronald H Towner, and Matthew W Salzer

2008 The Fremont granaries of Range Creek: Defensive maize storage on the northern Colorado Plateau presented at the 31st Great Basin Anthropological Conference, 2008, Portland, OR.

Barlow, K. R.

2002 Predicting maize agriculture among the Fremont: An economic comparison of farming and foraging in the American Southwest. *American Antiquity* 67:65–88.

Bellorado, B. A.

2010 *Animas-La Plata Project, Vol. XII —special studies.* University of Arizona.

Benson, Larry V.

2011 Factors controlling Pre-Columbian and early historic maize productivity in the American Southwest, part 1: The southern Colorado Plateau and Rio Grande regions. *Journal of Archaeological Method and Theory* 18(1):1–60. DOI:10.1007/s10816-010-9082-z.

Benson, Larry, Kenneth Petersen, and John Stein

2007 Anasazi (pre-Columbian Native-American) migrations during the middle-12th and late-13th centuries–Were they drought induced? *Climatic change* 83(1):187–213.

Berry, Michael S.

1972 *The Evans Site.* University of Utah, Salt Lake City, UT.

Billings, W. D.

1951 Vegetation zonation in the Great Basin of western North America. In *Les bases ecolgiques de la regeneration de la regeneration de la vegetation des zones arides*, 9:pp. 101–122. International Union of Biological Sciences Series B Colloquia.

Bird, Douglas W., and James F. O'Connell

2006 Behavioral ecology and archaeology. *Journal of Archaeological Research* 14(2):143–188.

Bocinsky, R. Kyle

2019 *Paleocar: Paleoclimate reconstruction from tree rings using correlation adjusted correlation.*

2020 *Feddata: Functions to automate downloading geospatial data available from several federated data sources.*

Bocinsky, R. Kyle, Andrew Gillreath-Brown, Keith Kintigh, Ann Kinzig, Tim Kohler, Allen Lee, Bertram Ludäscher, and Timothy McPhillips

2023 Synthesizing Knowledge of Past Environments (SKOPE) web application.

Bocinsky, R. Kyle, and Timothy A Kohler

2014 A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest. *Nature Communications* 5:5618.

Bocinsky, R. Kyle, Johnathan Rush, Keith W. Kintigh, and Timothy A. Kohler

2016 Exploration and exploitation in the macrohistory of the pre-Hispanic Pueblo Southwest. *Science Advances* 2(4):e1501532. DOI:10.1126/sciadv.1501532, accessed May 11, 2022.

Boomgarden, Shannon A., Duncan Metcalfe, and Ellyse T. Simons

2019 An optimal irrigation model: Theory, experimental results, and implications for future research. *American Antiquity* 84(2):252–273. DOI:10.1017/aaq.2018.90.

Bowden, David A., Owen F. Anderson, Ashley A. Rowden, Fabrice Stephenson, and Malcolm R. Clark

2021 Assessing habitat suitability models for the deep sea: Is our ability to predict the distributions of seafloor fauna improving? *Frontiers in Marine Science* 8.

Broughton, Jack M., Michael D. Cannon, and Erik J. Bartelink

2010 Evolutionary ecology, resource depression, and niche construction theory: Applications to central California hunter-gatherers and Mimbres-Mogollon agriculturalists. *Journal of Archaeological Method and Theory* 17:371–421.

Campbell, Michael J., Philip E. Dennison, Bret W. Butler, and Wesley G. Page

2019 Using crowdsourced fitness tracker data to model the relationship between slope and travel rates. *Applied Geography* 106:93–107. DOI:10.1016/j.apgeog.2019.03.008.

Cannon, Michael D.

2000 Large mammal relative abundance in pithouse and pueblo period archaeofaunas from southwestern New Mexico: Resource depression among the Mimbres-Mogollon? *Journal of Anthropological Archaeology* 19(3):317–347. DOI:10.1006/jaar.2000.0366.

Cannon, Michael Dale

2001 Large mammal resource depression and agricultural intensification: An empirical test in the Mimbres Valley, New Mexico. University of Washington.

Codding, Brian F, and Douglas W Bird

2015 Behavioral ecology and the future of archaeological science. *Journal of Archaeological Science* 56:9–20.

Codding, Brian F., Joan Brenner Coltrain, Lisbeth Louderback, Kenneth Blake Vernon, Kate E. Magargal, Peter M. Yaworsky, Erick Robinson, Simon C. Brewer, and Jerry D. Spangler

2022 Socioecological dynamics structuring the spread of farming in the North American basin-plateau region. *Environmental Archaeology* 27(4):434–446. DOI:10.1080/14614103.2021.1927480.

Codding, Brian F., Heidi Roberts, William Eckerle, Simon C. Brewer, Ishmael D. Medina, Kenneth B. Vernon, and Jerry S. Spangler

2023 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. *Quaternary International*. DOI:10.1016/j.quaint.2023.06.014.

Cole, Clint

2012 Prehistoric archaeology and the Fremont frontier at North Meadow Valley Wash, eastern Nevada. Unpublished PhD thesis, Department of Anthropology, University of California, Davis.

Coltrain, Joan Brenner

1993 Fremont corn agriculture: A pilot stable carbon isotope study. *Utah Archaeology* 6(1):49–55.

Coltrain, Joan Brenner, and Steven W. Leavitt

2002 Climate and diet in Fremont prehistory: Economic variability and abandonment of maize agriculture in the Great Salt Lake basin. *American Antiquity* 67(3):453–485. DOI:10.2307/1593822.

Contreras, Daniel A., and Brian F. Codding

2023 Landscape Taphonomy Predictably Complicates Demographic Reconstruction. *Journal of Archaeological Method and Theory*. DOI:10.1007/s10816-023-09634-5.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle

2004 Long-term aridity changes in the western United States. *Science* 306:1015–1018.

Cordell, Linda S, and Maxine McBrinn

2012 *Archaeology of the Southwest*. 3rd ed. Routledge.

De Kort, Hanne, Michel Baguette, Jonathan Lenoir, and Virginie M. Stevens

2020 Toward reliable habitat suitability and accessibility models in an era of multiple environmental stressors. *Ecology and Evolution* 10(20):10937–10952. DOI:10.1002/ece3.6753, accessed December 12, 2023.

Dean, Patricia Anne

1992 Prehistoric pottery in the northeastern Great Basin: Problems in the classification and archaeological interpretation of undecorated Fremont and Shoshoni wares. University of Oregon.

Dodd, Walter A. Jr.

1982 *Final year excavations at the Evans Mound site*. University of Utah, Salt Lake City, Utah.

Elith, Jane, Catherine H. Graham, Robert P. Anderson, Miroslav Dudík, Simon Ferrier, Antoine Guisan, Robert J. Hijmans, Falk Huettmann, John R. Leathwick, Anthony Lehmann, Jin Li, Lucia G. Lohmann, Bette A. Loiselle, Glenn Manion, Craig Moritz, Miguel Nakamura, Yoshinori Nakazawa, Jacob McC. M. Overton, A. Townsend Peterson, Steven J. Phillips, Karen Richardson, Ricardo Scachetti-Pereira, Robert E. Schapire, Jorge Soberón, Stephen Williams, Mary S. Wisz, and Niklaus E. Zimmermann

2006 Novel methods improve prediction of species' distributions from occurrence data. *Ecography* 29(2):129–151. DOI:10.1111/j.2006.0906-7590.04596.x.

Elith, Jane, and John R. Leathwick

2009 Species distribution models: Ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* 40(1):677–697. DOI:10.1146/annurev.ecolsys.110308.120159.

Feng, Xiao, Daniel S. Park, Cassondra Walker, A. Townsend Peterson, Cory Merow, and Monica Papeş

2019 A checklist for maximizing reproducibility of ecological niche models. *Nature Ecology & Evolution* 3(10):1382–1395. DOI:10.1038/s41559-019-0972-5.

Finley, Judson Byrd, Erick Robinson, R. Justin DeRose, and Elizabeth Hora

2020 Multidecadal climate variability and the florescence of Fremont societies in eastern Utah. *American Antiquity* 85(1):93–112. DOI:10.1017/aaq.2019.79.

Fretwell, Stephen D., and Henry L. Lucas

1969 On territorial behavior and other factors influencing habitat distribution in birds I. Theoretical development. *Acta Biotheoretica* 19:16–36.

Graumlich, Lisa J.

1993 A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* 39(2):249–255. DOI:10.1006/qres.1993.1029.

Graybill, D

1990 Mammoth Creek, Utah, tree ring record. *International Tree Ring Data Bank. GBP PAGES/World Data Center-A for Paleoclimatology, NOAA/NGDC Paleoclimatology Program, Boulder, CO.*

Grayson, Donald K

2006 Holocene bison in the Great Basin, western USA. *The Holocene* 16(6):913–925.

Grayson, Donald K.

2011 *The Great Basin: A natural prehistory.* University of California Press.

Hakiel, Bridget, Nicholas Hakiel, James C Mackey, Thomas Reust, and Ricky Laurent

1987 The Archery Site (48SW5222): A Uinta Fremont campsite in southwestern Wyoming. *Southwestern Lore* 53(2):1–22.

Hart, Isaac Alfred, Joan Brenner-Coltrain, Shannon Boomgarden, Andrea Brunelle, Larry Coats, Duncan Metcalfe, and Michael Lewis

2021 Evidence for a winter-snowpack derived water source for the Fremont maize farmers of Range Creek Canyon, Utah, USA. *The Holocene* 31(3):446–456. DOI:10.1177/0959683620972767, accessed December 14, 2022.

Hemphill, ML, and Peter E Wigand

1995 *A detailed 2,000-year late Holocene pollen record from Lower Pahranagat Lake, southern Nevada, USA*. Rust Geotech, Inc., Grand Junction, CO (United States).

Hockett, Bryan Scott

1998 Sociopolitical meaning of faunal remains from Baker Village. *American Antiquity* 63(2):289–302. DOI:10.2307/2694699.

Janetski, Joel C

2002 Trade in Fremont society: Contexts and contrasts. *Journal of Anthropological Archaeology* 21(3):344–370. DOI:10.1016/S0278-4165(02)00003-X.

Janetski, Joel C.

1997 Fremont hunting and resource intensification in the eastern Great Basin. *Journal of Archaeological Science* 24(12):1075–1088. DOI:10.1006/jasc.1996.0187.

1998 *Archaeology of Clear Creek Canyon*. Museum of Peoples and Cultures, Brigham Young University, Provo, UT.

Janetski, Joel C., Cady B. Jardine, and Christopher N. Watkins

2011 Interaction and exchange in Fremont society. *Perspectives on Prehistoric Trade and Exchange in California and the Great Basin*:22–54.

Janetski, Joel C, and Richard K Talbot

2000 Fremont social and community organization. *Clear Creek Canyon Archaeological Project: Results and Synthesis*:247–262.

Jennings, Jesse

1978 *Prehistory of Utah and the eastern Great Basin.* University of Utah, Salt Lake City, UT.

Jochim, Michael A.

2022 Dots on the map: Issues in the archaeological analysis of site locations. *Journal of Archaeological Method and Theory.* DOI:10.1007/s10816-022-09580-8.

Kennett, Douglas J., Atholl J. Anderson, and Bruce Winterhalder

2006 The Ideal Free Distribution, food production, and the colonization of Oceania. In *Human Behavioral Ecology and the Origins of Agriculture*, edited by Douglas J. Kennett and Bruce Winterhalder, pp. 265–288. University of California Press, Berkeley.

Kidder, Alfred V.

1924 *An introduction to the study of southwestern archaeology with a preliminary account of the excavations at Pecos.* Yale University Press, New Haven, CT.

Leavitt, Steven W.

1994 Major wet interval in White Mountains Medieval Warm Period evidenced in Δ13c of bristlecone pine tree rings. In *The Medieval Warm Period*, edited by Malcolm K. Hughes and Henry F. Diaz, pp. 299–307. Springer Netherlands, Dordrecht.

Lindsay, LaMar W.

1986 Fremont fragmentation. In *Anthropology of the Desert West: Essays in Honor of Jesse D. Jennings*, pp. 229–251. University of Utah Anthropological Papers 110. Salt Lake City, Utah.

Madsen, D. B.

2000 *Late Quaternary paleoecology in the Bonneville Basin.* Utah Geological Survey Bulletin 130.

Madsen, David B.

1989 *Exploring the Fremont.* University of Utah Press, Salt Lake City, UT.

Madsen, David B., and Michael S. Berry

1975 A reassessment of northeastern Great Basin prehistory. *American Antiquity* 40(4):391–405. DOI:10.2307/279326.

Madsen, David B., and Steven R. Simms

1998 The Fremont Complex: A behavioral perspective. *Journal of World Prehistory* 12(3):255–336. DOI:10.1023/A:1022322619699.

Mann, Michael E., Zhihua Zhang, Scott Rutherford, Raymond S. Bradley, Malcolm K. Hughes, Drew Shindell, Caspar Ammann, Greg Faluvegi, and Fenbiao Ni

2009 Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326(5957):1256–1260. DOI:10.1126/science.1177303.

Marwitt, John P.

1968 *Pharo Village.* University of Utah, Salt Lake City, UT.

1970 *Median Village and Fremont culture regional variation.* University of Utah, Salt Lake City, UT.

Matson, Richard G., William D. Lipe, and William R. IV Haase

1990 *Human adaptations on Cedar Mesa, southeastern Utah.*

Matson, Richard G, William D Lipe, and William R Haase

1988 Adaptational continuities and occupational discontinuities: The Cedar Mesa Anasazi. *Journal of Field Archaeology* 15(3):245–263.

Metcalfe, Duncan, and Lisa V. Larrabee

1985 Fremont irrigation: Evidence from Gooseberry Valley, central Utah. *Journal of California and Great Basin Anthropology* 7(2):244–254. accessed December 14, 2022.

Mooney, Adrien Carole

2014 An analysis of the archaeological work of the Provo River delta, Utah. Unpublished PhD thesis, Department of Anthropology, Brigham Young University.

Morgan, Christopher, Jacob L. Fisher, and Monique Pomerleau

2012 High-altitude intensification and settlement in Utah's Pahvant Range. *Journal of California and Great Basin Anthropology* 32(1):27–45. accessed May 23, 2022.

Patterson, JJ

2015 Maize growing, processing, and storage: Evidence from Nine Mile Canyon. *Arizona. Archaeol. Southwest Mag* 29.

Patterson, JJ, and TH Flanigan

2010 Capacity, distribution, and spatial associations of granaries in Nine Mile Canyon, a historical ecology perspective on arable acreage and mobility presented at the Utah. Paper Presented at the 32nd Great Basin Anthropological Conference., 2010, Layton, UT.

PRISM Climate Group

2019 Parameter-elevation Regressions on Independent Slopes Model (PRISM). Oregon State University. http://prism.oregonstate.edu.

R Core Team

2022 *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Ramankutty, Navin, Jonathan A. Foley, John Norman, and Kevin McSweeney

2002 The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography* 11(5):377–392.

Rowden, Ashley A., Owen F. Anderson, Samuel E. Georgian, David A. Bowden, Malcolm R. Clark, Arne Pallentin, and Andrew Miller

2017 High-resolution habitat suitability models for the conservation and management of vulnerable marine ecosystems on the Louisville Seamount Chain, south Pacific Ocean. *Frontiers in Marine Science* 4.

Salzer, Matthew W., Andrew G. Bunn, Nicholas E. Graham, and Malcolm K. Hughes

2014 Five millennia of paleotemperature from tree-rings in the Great Basin, USA. *Climate Dynamics* 42(5):1517–1526. DOI:10.1007/s00382-013-1911-9.

Searcy, Michael T., and Richard K. Talbot

2015 Late Fremont cultural identities and borderland processes. In *Late Holocene Research on Foragers and Farmers in the Desert West*, pp. 234–264. University of Utah Press, Salt Lake City, UT.

Sharrock, Floyd W., and John P. Marwitt

1967 *Excavations at Nephi, Utah 1965-1966.* University of Utah, Salt Lake City, UT.

Sillero, Neftalí, Salvador Arenas-Castro, Urtzi Enriquez-Urzelai, Cândida Gomes Vale, Diana Sousa-Guedes, Fernando Martínez-Freiría, Raimundo Real, and A.Márcia Barbosa

2021 Want to model a species niche? A step-by-step guideline on correlative ecological niche modelling. *Ecological Modelling* 456:109671. DOI:10.1016/j.ecolmodel.2021.109671.

Sillero, Neftalí, and A. Márcia Barbosa

2021 Common mistakes in ecological niche models. *International Journal of Geographical Information Science* 35(2):213–226. DOI:10.1080/13658816.2020.1798968.

Simms, Steven R.

1986 New evidence for Fremont adaptive diversity. *Journal of California and Great Basin Anthropology* 8(2):204–216. accessed October 25, 2021.

1999 Farmers, foragers, and adaptive diversity: The Great Salt Lake Wetlands Project. In *Prehistoric Lifeways in the Great Basin Wetlands: Bioarchaelogical Reconstruction and Interpretation*, edited by Brian E. Hemphill and Clark S. Larsen, pp. 21–54. University of Utah Press, Salt Lake City, UT.

2008 *Ancient peoples of the Great Basin and the Colorado Plateau.* Left Coast Press, New York, NY.

Smith, Craig S

1992 The Fremont: A view from southwest Wyoming. *Utah Archaeology* 5(1):55–75.

Spangler, Jerry D

1993 Site distribution and settlement patterns in Lower Nine Mile Canyon: The Brigham Young University surveys of 1989-91.

2000 One-pot pithouses and Fremont paradoxes: Formative stage adaptations in the Tavaputs Plateau region of northeastern Utah. *Intermountain Archaeology, Anthropological Papers*(122):25–38.

2013 *Nine Mile Canyon: The archaeological history of an American treasure*. University of Utah Press.

Spangler, Jerry D., Peter M. Yaworsky, Kenneth B. Vernon, and Brian F. Codding

2019 *Hisatsinom of the high plateaus: A Class I overview of prehistoric cultural resources in Grand Staircase-Escalante National Monument*. Bureau of Land Management, Salt Lake City, Utah.

Spangler, Jerry D, Andrew T Yentsch, and Rachelle Green

2010 Farming and foraging on the southwestern frontier: An overview of previous research of the archaeological and historical resources of the great Cedar Mesa area.

Stine, Scott

1990 Late Holocene fluctuations of Mono Lake, eastern California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78(3):333–381. DOI:10.1016/0031-0182(90)90221-R.

Thomson, Marcus J., Juraj Balkovič, Tamás Krisztin, and Glen M. MacDonald

2019 Simulated impact of paleoclimate change on Fremont Native American maize farming in Utah, 850–1449 CE, using crop and climate models. *Holocene Civilization* 507:95–107. DOI:10.1016/j.quaint.2018.09.031.

Thomson, Marcus J, and Glen M MacDonald

2020 Climate and growing season variability impacted the intensity and distribution of Fremont maize farmers during and after the Medieval Climate Anomaly based on a statistically downscaled climate model. *Environmental Research Letters* 15(10):105002. DOI:10.1088/1748-9326/aba57e.

USGS

2022a 3D Elevation Program 1/3 Arc-Second Resolution Digital Elevation Model.

2022b National Hydrography Dataset.

USGS, and USDA NRCS

2013 *Federal Standards and Procedures for the National Watershed Boundary Dataset (WBD) (4 ed.): Techniques and Methods*.

Varien, Mark D.

1999 *Sedentism and mobility in a social landscape: Mesa Verde \& beyond*. University of Arizona Press, Tucson, AZ.

Vernon, Kenneth B., Peter M. Yaworsky, Jerry Spangler, Simon Brewer, and Brian F. Codding

2022 Decomposing habitat suitability across the forager to farmer transition. *Environmental Archaeology* 27(4):420–433. DOI:10.1080/14614103.2020.1746880.

Winter, Joseph C., and Henry G. Wylie

1974 Paleoecology and diet at Clydes Cavern. *American Antiquity* 39:303–315. DOI:10.2307/279590.

Winterhalder, Bruce, Douglas J. Kennett, Mark N. Grote, and Jacob Bartruff

2010 Ideal free settlement of California's Northern Channel Islands. *Journal of Anthropological Archaeology* 29:469–490.

Wood, Simon N

2004 Stable and efficient multiple smoothing parameter estimation for Generalized Additive Models. *Journal of the American Statistical Association* 99(467):673–686. DOI:10.1198/016214504000000980.

Yaworsky, Peter Michael

2021 Prehistoric land use in the Grand Staircase-Escalante National Monument and West Tavaputs Plateau, Utah. ProQuest Dissertations Publishing.

Yaworsky, Peter M., Kenneth B. Vernon, Weston C. McCool, Isaac A. Hart, Jerry Spangler, and Brian F. Codding

2023 The Goldilocks Zone for maize agriculture and the settlement and abandonment of the West Tavaputs Plateau. *Quaternary International*. DOI:10.1016/j.quaint.2023.12.003.

Yaworsky, Peter M., Kenneth B. Vernon, Jerry D. Spangler, Simon C. Brewer, and Brian F. Codding

2020 Advancing predictive modeling in archaeology: An evaluation of regression and machine learning methods on the Grand Staircase-Escalante National Monument. *PLOS ONE* 15(10):e0239424. DOI:10.1371/journal.pone.0239424.