The Fremont Frontier: Living at the Margins of Maize Farming

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Abstract

The Fremont provide an important case study to examine 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 maize growing degree days, 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

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 & Simms, 1998). That the Fremont managed to thrive for as long as they did in this part of the world poses an interesting question, for conditions there are extremely harsh and inhospitable for maize farming. Archaeologists interested in that 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 & Simms, 1998; Metcalfe & Larrabee, 1985; Morgan et al., 2012; Patterson & 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., R. K. Bocinsky & Kohler, 2014; Thomson & 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 or spatial model 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, which we consider a long-term record of human adaptation to climate change.

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 & O'Connell, 2006; Kennett & Winterhalder, 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 & Bird, 2015; Fretwell & 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.

Assuming that western Fremont individuals were adept at responding to variation in their local ecology, in particular, that they optimized their choice of habitats, we can use an empirical or inductive species distribution model of Fremont sites to reconstruct the ecological niche for maize farming (Elith & Leathwick, 2009; Vernon et al., 2021; Yaworsky et al., 2020). This is sometimes referred to as ecological niche modeling. 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. In effect, we are helping ourselves to a little reverse engineering of the archaeological record (Dennett, 1995). We are assuming that whatever strategy - whatever habitat - the Fremont chose was the best alternative available to them, not in any absolute sense, of course, just the best given the constraints and trade-offs Fremont farmers faced in those environments (Jochim, 2022). In other words, we are treating their settlement decisions themselves as maize farming adaptations.

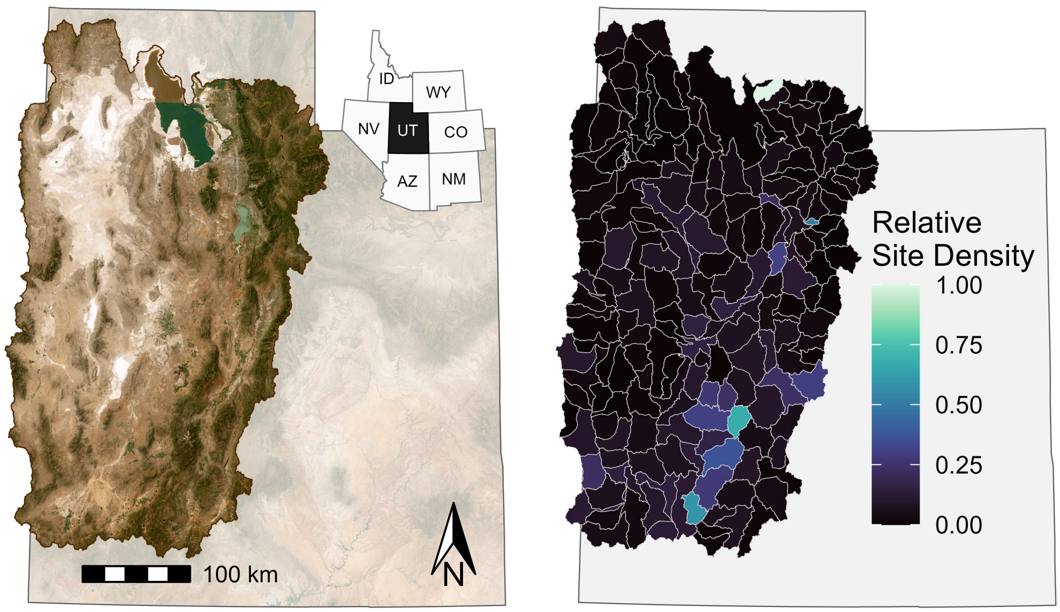

Figure 1. On the left is an overview map showing the project area with modern satellite imagery. Dark green colors represent high elevation, high precipitation areas. The large beige area in the northwest is the Bonneville Basin. What remains of the Great Salt Lake can be seen just west of Salt Lake City. For visualization purposes, the map on the right shows the relative density of archaeological sites (see the section on site data below for details on how we calculate relative density). Please note that although the map appears to show many empty watersheds, most do in fact contain archaeological sites, just at extremely low densities.

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 & 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 & 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 occupations in Idaho (Dean, 1992), Nevada (Hockett, 1998), Colorado (Baker, 1999), and Wyoming (Hakiel et al., 1987; Smith, 1992). These modern political boundaries roughly overlap with the eastern Great Basin and Colorado Plateau physiographic provinces.

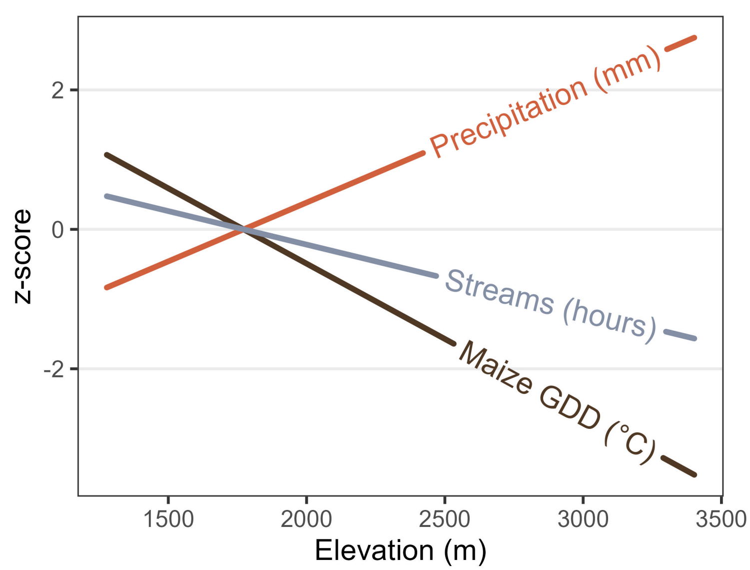

Figure 2. Linear responses of average water-year precipitation (mm), average growing-season maize gdd (C), and cost-distance to streams (hours) to changes in elevation (m). See methods for how these values were calculated and results for more details.

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 & 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 & 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 nascent Archaic population existing at extremely low population levels and a burgeoning community of migrant farmers together produced the complex we now call the Fremont (Patterson, 2015; Simms, 1986; 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 (L. V. Benson, 2011; Coltrain & Leavitt, 2002; R. G. Matson et al., 1988) or worse for foraging (Barlow, 2002; Broughton et al., 2010; Cannon, 2000; Cannon, 2001). In support of the *farming-more-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 & Wigand, 1995; Rhode & 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-more-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., 2021; 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 the optimal strategy. 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); see also, Yaworsky this issue], 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 & Talbot, 2000; Madsen & Simms, 1998; Simms, 2008), at places like Nephi Mounds (Sharrock & 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).

2.2 The Ideal Free Distribution

In population ecology, settlement decisions are represented as a choice between habitats, where each habitat i has some net biological value or benefit, known as its suitability (S_i).

Typically, though not always, this value exhibits negative density dependence, declining as a function of population size (N_i), perhaps owing to increased competition or resource depression. When N_i is very small, the suitability of a habitat approaches its pristine or intrinsic quality (Q_i), or its gross value independent of all settlement costs (Greene & Stamps, 2001). Together, these parameters suggest a very simple model of habitat suitability:

$$S_i = Q_i - f(N_i)$$

This is known as the Ideal Free Distribution (IFD) model (Fretwell & Lucas, 1969). The IFD model assumes that individuals will choose habitats that maximize S_i, settling the most suitable habitat first then shifting to the next most suitable habitat when those become equal, and thereafter infilling each at an equal rate. The aggregate effect is a population distributed at equilibrium, meaning suitability is equal for all habitats. When conditions are ideal (individuals have perfect knowledge) and free (individuals face no additional costs to settlement), this distribution will also satisfy the "input matching" rule, with populations occurring at larger numbers in habitats with greater intrinsic value (Parker, 1978).

Two circumstances provide important exceptions to this simple model. The first concerns economies of scale, or situations in which S_i exhibits positive density dependence. In ecology, these are known as Allee effects, and they are assumed to occur at low density (Allee et al., 1949; Fretwell & Lucas, 1969). The second concerns additional settlement costs, or costs associated with moving from one habitat to another. This is a violation of the free element of the IFD. When it occurs, the result is an ideal despotic distribution (IDD) (Fretwell & Lucas, 1969). This has the consequence of reducing the total population in the more suitable habitat at equilibrium.

Many social and ecological variables may be relevant to defining a general measure of S_i, but here we are focusing on ecological determinants of intrinsic habitat quality, Q_i, that are specific to maize farmers. Our reasoning here is fairly straightforward. If we assume that the distribution of Fremont populations across habitats is at equilibrium, then we can combine this concept of maize-specific suitability with the input matching rule to reconstruct the ranking of habitats on the basis of ecologically-relevant parameters. In other words, it follows from their being at equilibrium that any observed differences in population size, N_i, must be the result of differences in Q_i. So, if we have some proxy for N_i, like the distribution of Fremont sites across habitats, we can model that value as a function of ecological covariates, X_i, then use the resulting model to reconstruct $Q_i \sim f(X_i)$, giving us the maize niche for Fremont farmers, both in geographic and ecological space.

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, Pahvant, and Tushar Mountains, together stand as the primary physiographic boundaries separating 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 is the Great Salt Lake and the West Desert, its southern boundary the 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 Great Salt Lake 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 & 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.

Aggregating to the level of the watershed also 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).

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. The Sego system also includes an attribute table with affiliation data that we use to filter Fremont sites where possible. For a previous project, we also performed a stratified random sample of all archaeological sites by county in western Utah and recorded affiliation and other attribute data from their site forms. For this analysis, we compare the results of that previous effort with the sites identified by filtering the Sego system as a form of quality control. The resulting dataset contains 2,248 individual Fremont sites.

These site data include everything from small ceramic scatters to massive Fremont villages like Five Finger Ridge (Janetski, 1998; Janetski & 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 total suitability according to the IFD model, and our attempts to reconstruct the ecological and geographic borders of the Fremont rely heavily on the input-matching rule, or the idea that habitats with greater intrinsic quality will have larger populations at equilibrium. We, therefore, weight the count of sites in each watershed by the total number of residential features that they contain (+1 for sites with no features). 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 relative density of Fremont sites across watersheds. The *relative* density refers to the density of feature-weighted sites ($D_i = N_i/area_i$) divided by the maximum density ($max\ D$) across all watersheds, thus scaling the density estimates to the unit interval [0,1]. Using the relative density is just a visual tool to help avoid any implication that we have an independent estimate of the absolute number of Fremont sites in the area, and not just an estimate based on a thinned sample.

3.4 Environmental Covariates

For this analysis, we use both topographic and climatological covariates. The topographic covariate is cost-distance 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 (R. K. Bocinsky, 2020) to download perennial stream features from the US National Hydrography Dataset (USGS, 2022b) and a digital elevation model (DEM) from the US National Elevation Dataset (USGS, 2022a). We then apply Campbell's hiking function (Campbell et al., 2019) to slope estimates derived from the DEM using the R package hiker (Vernon, 2021). This allows us to generate estimates of 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 (precipitation, 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.

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 (R. K. 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 (for further details, see K. R. Bocinsky et al., 2016; R. K. Bocinsky & Kohler, 2014). In this case, we use interpolated precipitation and temperature estimates from the ~800 m resolution PRISM dataset (PRISM Climate Group, 2014) 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.

Figure 3 shows the geographic distributions of these covariates over watersheds. As these are all in one way or another driven by elevation, it is reasonable to expect that they will correlate. 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

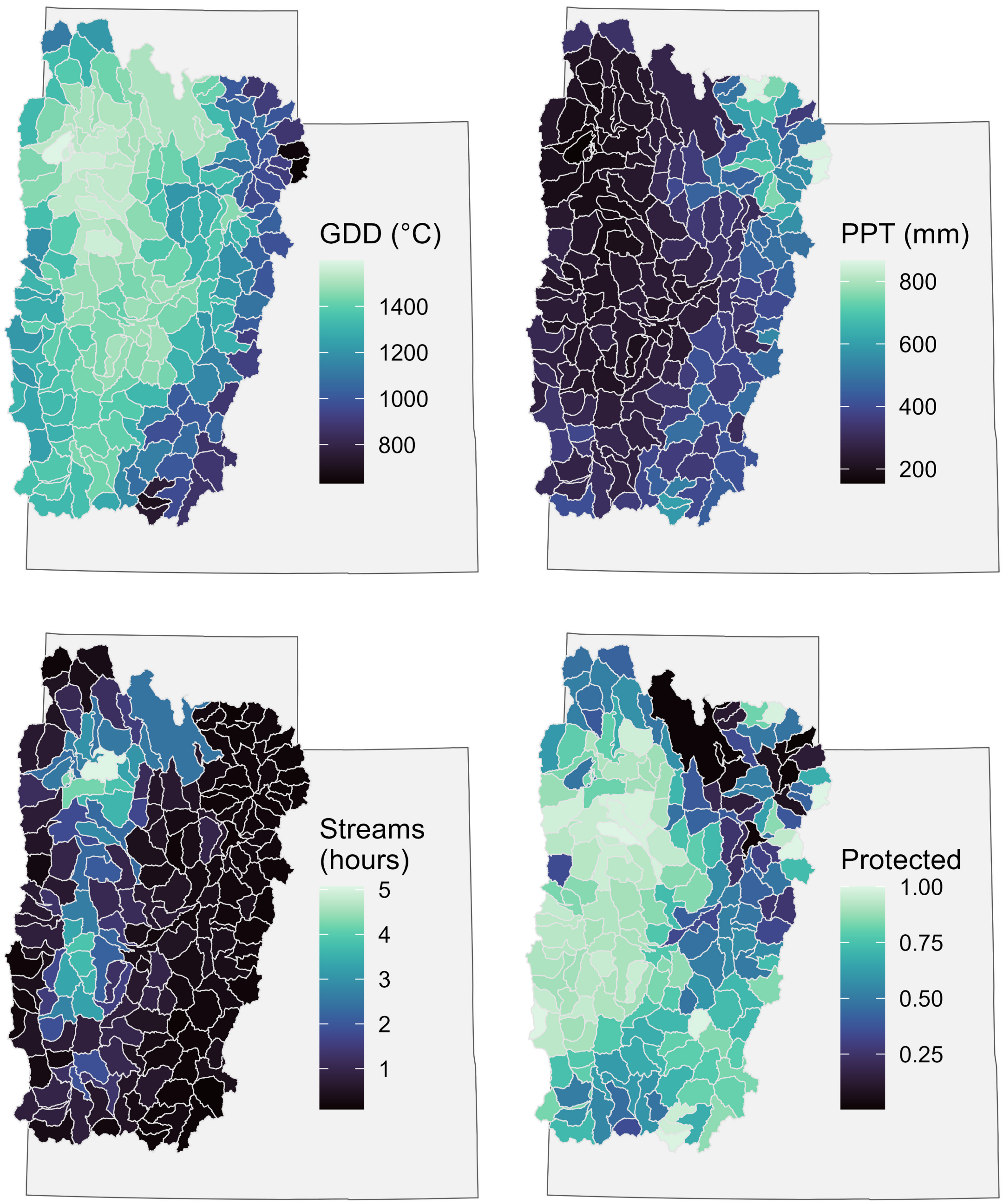

Figure 3. Distribution of covariates across watersheds. These include maize growing degree days (GDD), annual precipitation (precipitation), and cost-distance to streams (Streams).

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.

3.5 Statistical Modeling and Model Evaluation

The response variable is a count N of sites per watershed i, so it should arise as the result of a Poisson process. Given the trade-offs outlined above, we also expect it to exhibit a non-linear response to precipitation, GDD, and cost-distance to streams, so we fit a generalized additive model (GAM) with a log-link to the data using the R package mgcv (Wood, 2004). Although we expect the outcome to be Poisson distributed, we use a negative binomial distribution here, as this includes a parameter, r, that can account for potential dispersion without giving up the inferential benefits of maximum likelihood.

$$
\begin{aligned}
N_i &\sim NB\left(\lambda, r\right) \\
E\left(N_i\right) &= \lambda_i \\
log\left(\lambda_i\right) &= log\left(area_i\right) + s(precipitation_i) + streams_i + gdd_i + protected_i
\end{aligned}
$$

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 is not strictly meaningful for this kind of data, as it assumes that the absolute site counts can be inferred from the sample, which requires that the sample be unbiased - an implausible condition to meet. On that note, we also include a parametric term for the proportion of each watershed classified as federally protected land. This is meant to address potential sampling biases owing to taphonomic processes operating on the archaeological record. 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 GAM, 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 and incorporate an exponential covariance matrix to remove that residual autocorrelation. 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, as expressed in the formula above.

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

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 not strictly meaningful for these data.

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

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).

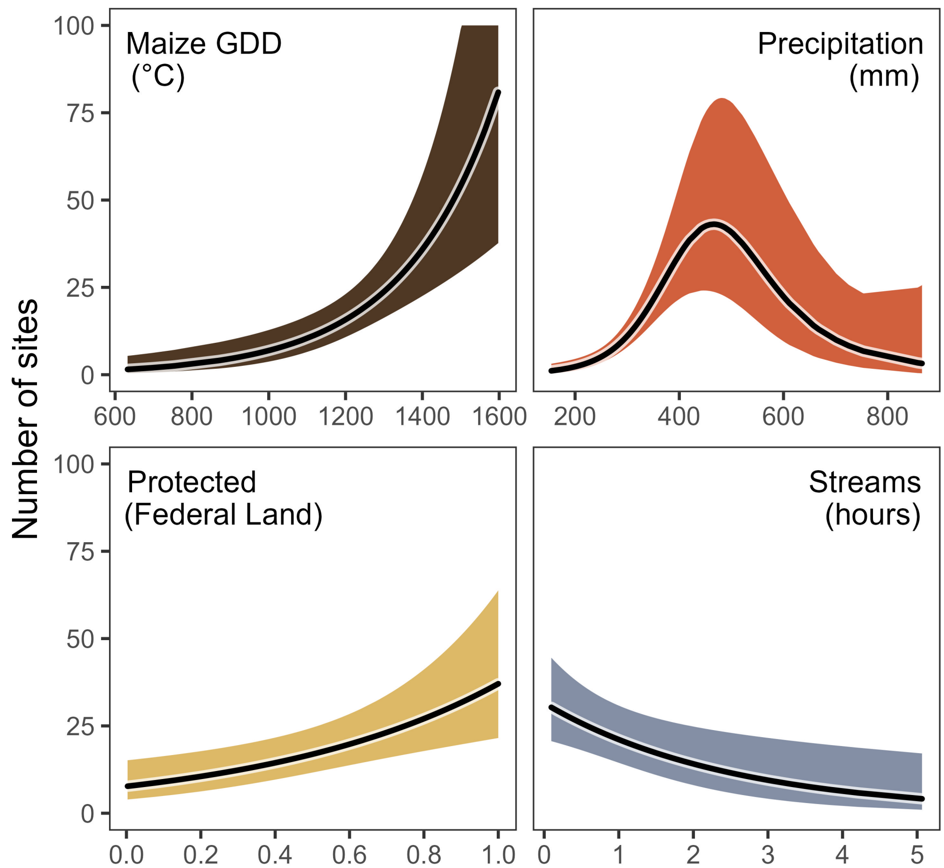

Figure 4. Marginal response plots. Each plot shows the response of site counts to changes in a target covariate while holding all other variables at their mean.

5 Discussion

Our results 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 Fig. 3. While site counts exhibit a positive linear response to maize GDD in our model, 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 water availability, 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). The linear relationship between site counts and maize GDD is, thus, relative to the observed distribution of that variable within the study area and should not be used to generalize outside of that distribution.

Another curious result of our analysis is that site counts do not increase linearly as a function of precipitation, but instead decline after 500 mm. We believe this is likely an artifact of trade-offs related to elevation, specifically the trade-off between precipitation and temperature. We discuss this more below, along with other important implications our results have for the regional prehistory of the eastern Great Basin, particularly for the spread and eventual collapse of maize agriculture.

5.1 A Goldilocks Zone?

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 that maximized agricultural suitability, as evidenced by the estimated distribution of sites across watersheds (see Fig. 4), 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 (or lower canyons in the Uintas). Such a band would be akin to a Goldilocks zone for maize agriculture (Yaworsky et al, in press), a place where the optima for GDD and precipitation overlap.

We should take care not to over-interpret this idea, however, for it is an area of overlap for continuous ecological gradients, not a region demarcated by anything like a perfect line. It should also be emphasized 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 the Goldilocks zone, 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, 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).

5.2 Irrigation and the Maize Farming Niche

Based on previous research (Adams et al., 2006; Bellorado, 2010; L. V. Benson, 2011), Bocinsky and Kohler (R. K. Bocinsky & 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 (L. V. Benson, 2011; Cordell & 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).

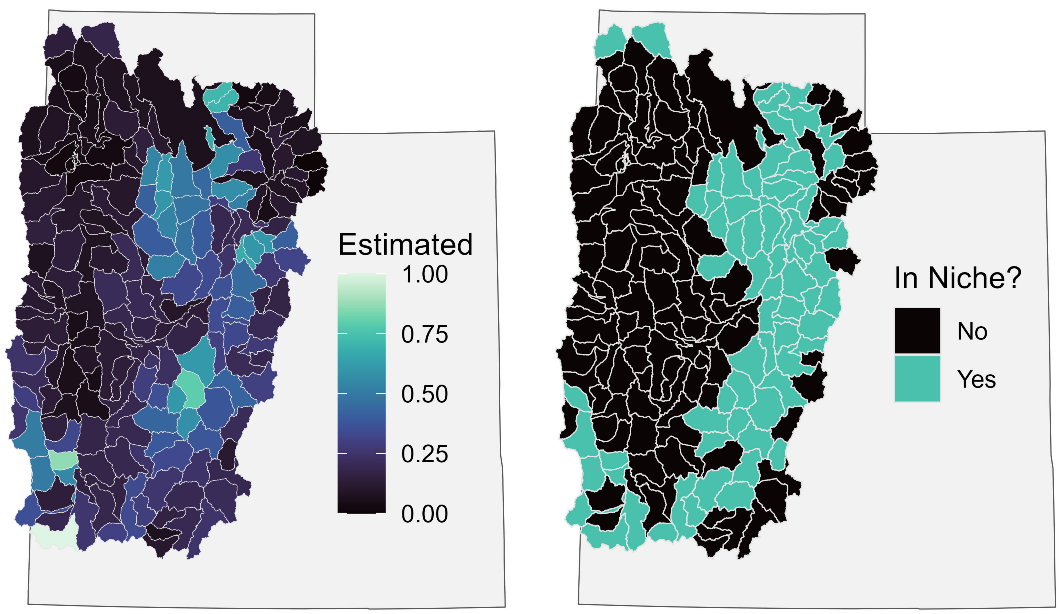

Figure 5. The map on the left shows the relative density of feature-weighted site counts as estimated by the model, with lighter colors representing larger relative densities, darker colors representing smaller relative densities. The map on the right shows which watersheds are in the rain-fed maize 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 and parts of the Parowan Valley and surrounding areas in the southeast part of the study area are estimated by our model to have non-negligible relative 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. In particular, the spatial covariance structure in our model may be picking up on the structure of the stream flow network, specifically the accumulation of water run-off as a function of slope. This would suggest that if there are more people in one watershed, there should be more more people in the downstream watershed, too, at least relative to other watersheds with similar precipitation and GDD values. In the language of the IFD model, the suitability of the watershed habitat should propagate through the stream flow network. Exploring that intuition in a more systematic way, however, would require much more careful consideration of stream flow. Unfortunately, that is well beyond the scope of the current paper.

Still, the distribution of the rain-fed niche may offer additional insights. 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 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, irrigation would almost certainly have been a necessity (Boomgarden et al., 2019; R. Matson et al., 1990; Spangler et al., 2010). Of course, the type and intensity of irrigation would probably differ between sites, with more intensive irrigation occurring where there is less precipitation and less intensive irrigation where there is more precipitation, whether that precipitation falls in the watersheds themselves or in the upstream watersheds that feed into them.

5.3 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. Madsen and Simms (1998) argue that Fremont subsistence largely varies along two dimensions: levels of residential mobility and levels of cultigen adoption. While some were more mobile, moving from isolated patch to isolated patch, others were 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 Allee 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.

5.4 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 a growing consensus appears to be coalescing around climatic changes driving severe reductions in agricultural productivity (L. Benson et al.,

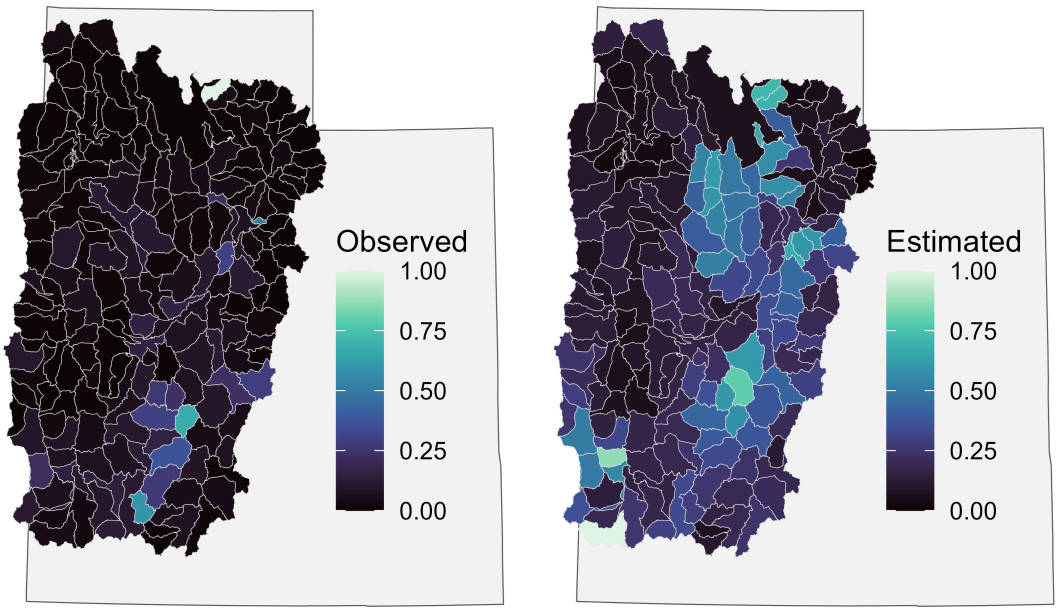

Figure 6. Geographic distribution of Fremont sites across watersheds. The left panel shows the relative density derived from observed site counts, and the right panel shows the relative density from the estimated site counts.

2007; Finley et al., 2020; Spangler et al., 2019; Thomson & MacDonald, 2020; Thomson et al., 2019). We follow Lindsay (1986) in thinking this was likely owing to climatic events that, in effect, tore the Goldilocks zone apart, 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 this decoupling, 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., 2021). 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 (L. 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 Goldilocks zone upon which the Fremont so long depended.

References

Adams, K. R., Meegan, C. M., Ortman, S. G., Howell, R. E., Werth, L. C., Muenchrath, D. A., O'Neill, M. K., & Gardner, C. A. (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. M. (1967). *Excavations at snake rock village and the bear river no. 2 site*. University of Utah.

Allee, W. C., Park, O., Emerson, A. E., Park, T., & Schmidt, K. P. (1949). *Principles of animal ecology*. W.B. Saunders Company.

Baker, S. G. (1999). *Fremont archaeology on the douglas creek arch, rio blanco county, colorado; the sky aerie promontory charnel site (5rb104). cri project no. 486.* (tech. rep.). Montrose, Colorado.

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.

Barlow, K. R., Towner, R. H., & Salzer, M. W. (2008). 31st great basin anthropological conference, portland, oregon.

Bellorado, B. (2010). *Animas-la plata project, vol. xiii—special studies* (tech. rep.).

Benson, L., Petersen, K., & Stein, J. (2007). Anasazi (pre-columbian native-american) migrations during the middle-12th and late-13th centuries–were they drought induced? [Publisher: Springer]. *Climatic change*, *83*(1), 187–213.

Benson, L. 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. https://doi.org/10.1007/s10816-010-9082-z

Berry, M. S. (1972). *The evans site* (tech. rep.). Salt Lake City, UT.

Billings, W. (1951). Vegetation zonation in the great basin of western north america. International Union of Biological Sciences Series B Colloquia.

Bird, D. W., & O'Connell, J. F. (2006). Behavioral ecology and archaeology [Publisher: Springer Netherlands]. *Journal of Archaeological Research*, *14*(2), 143–188.

Bocinsky, K. R., Rush, J., Kintigh, K. W., & Kohler, T. A. (2016). Exploration and exploitation in the macrohistory of the pre-hispanic pueblo southwest [Publisher: American Association for the Advancement of Science]. *Science Advances*, *2*(4), e1501532. https://doi.org/10.1126/sciadv.1501532

Bocinsky, R. K. (2019). *Paleocar: Paleoclimate reconstruction from tree rings using correlation adjusted correlation* (tech. rep.).

Bocinsky, R. K. (2020). *Feddata: Functions to automate downloading geospatial data available from several federated data sources* (tech. rep.). https://CRAN.R-project.org/package=FedData

Bocinsky, R. K., & Kohler, T. A. (2014). A 2,000-year reconstruction of the rain-fed maize agricultural niche in the us southwest [Publisher: Nature Publishing Group]. *Nature Communications*, *5*, 5618.

Boomgarden, S. A., Metcalfe, D., & Simons, E. T. (2019). An optimal irrigation model: Theory, experimental results, and implications for future research [Edition: 2019/04/29 Publisher: Cambridge University Press]. *American Antiquity*, *84*(2), 252–273. https://doi.org/10.1017/aaq.2018.90

Broughton, J. M., Cannon, M. D., & Bartelink, E. J. (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, M. J., Dennison, P. E., Butler, B. W., & Page, W. G. (2019). Using crowdsourced fitness tracker data to model the relationship between slope and travel rates. *Applied Geography*, *106*, 93–107. https://doi.org/https://doi.org/10.1016/j.apgeog.2019.03.008

Cannon, M. 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. https://doi.org/10.1006/jaar.2000.0366

Cannon, M. D. (2001). *Large mammal resource depression and agricultural intensification: An empirical test in the mimbres valley, new mexico* [Doctoral dissertation].

Codding, B. F., & Bird, D. W. (2015). Behavioral ecology and the future of archaeological science [Publisher: Elsevier]. *Journal of Archaeological Science*, *56*, 9–20.

Codding, B. F., Brenner Coltrain, J., Louderback, L., Vernon, K. B., Magargal, K. E., Yaworsky, P. M., Robinson, E., Brewer, S. C., & Spangler, J. D. (2021). Socioecological dynamics structuring the spread of farming in the north american basin-plateau region [Publisher: Routledge]. *Environmental Archaeology*, 1–13. https://doi.org/10.1080/14614103.2021.1927480

Coltrain, J. B., & Leavitt, S. W. (2002). Climate and diet in fremont prehistory: Economic variability and abandonment of maize agriculture in the great salt lake basin [Edition: 2017/01/20 Publisher: Cambridge University Press]. *American Antiquity*, *67*(3), 453–485. https://doi.org/10.2307/1593822

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. W. (2004). Long-term aridity changes in the western united states. *Science*, *306*, 1015–1018.

Cordell, L. S., & McBrinn, M. (2012). *Archaeology of the southwest* (3rd). Routledge.

Dean, P. A. (1992). *Prehistoric pottery in the northeastern great basin: Problems in the classification and archaeological interpretation of undecorated fremont and shoshoni wares* [Doctoral dissertation] [Citation Key: dean1992prehistoric].

Dennett, D. (1995). *Darwin's dangerous idea*. Simon & Schuster.

Dodd, W. A. J. (1982). *Final year excavations at the evans mound site* (tech. rep.). Salt Lake City, Utah.

Elith, J., & Leathwick, J. R. (2009). Species distribution models: Ecological explanation and prediction across space and time [_eprint: https://doi.org/10.1146/annurev.ecolsys.110308.120159]. *Annual Review of Ecology, Evolution, and Systematics*, *40*(1), 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Finley, J. B., Robinson, E., DeRose, R. J., & Hora, E. (2020). Multidecadal climate variability and the florescence of fremont societies in eastern utah [Edition: 2019/10/07 Publisher: Cambridge University Press]. *American Antiquity*, *85*(1), 93–112. https://doi.org/10.1017/aaq.2019.79

Fretwell, S. D., & Lucas, H. L. (1969). On territorial behavior and other factors influencing habitat distribution in birds i. theoretical development. *Acta Biotheoretica*, *19*, 16–36.

Graumlich, L. J. (1993). A 1000-year record of temperature and precipitation in the sierra nevada. *Quaternary Research*, *39*(2), 249–255. https://doi.org/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, D. K. (2011). *The great basin: A natural prehistory*. University of California Press.

Grayson, D. K. (2006). Holocene bison in the great basin, western usa [Publisher: Sage Publications Sage CA: Thousand Oaks, CA]. *The Holocene*, *16*(6), 913–925.

Greene, C., & Stamps, J. (2001). Habitat selection at low population densities. *Ecology*, *82*, 2091–2100.

Hakiel, B., Hakiel, N., Mackey, J. C., Reust, T., & Laurent, R. (1987). The archery site (48sw5222): A uinta fremont campsite in southwestern wyoming [Citation Key: hakiel1987archery]. *Southwestern Lore*, *53*(2), 1–22.

Hart, I. A., Brenner-Coltrain, J., Boomgarden, S., Brunelle, A., Coats, L., Metcalfe, D., & Lewis, M. (2021). Evidence for a winter-snowpack derived water source for the fremont maize farmers of range creek canyon, utah, usa [Publisher: SAGE Publications Ltd]. *The Holocene*, *31*(3), 446–456. https://doi.org/10.1177/0959683620972767

Hemphill, M., & Wigand, P. E. (1995). *A detailed 2,000-year late holocene pollen record from lower pahranagat lake, southern nevada, usa* (tech. rep.).

Hockett, B. S. (1998). Sociopolitical meaning of faunal remains from baker village [Edition: 2017/01/20 Publisher: Cambridge University Press]. *American Antiquity*, *63*(2), 289–302. https://doi.org/10.2307/2694699

Janetski, J. C. (1997). Fremont hunting and resource intensification in the eastern great basin. *Journal of Archaeological Science*, *24*(12), 1075–1088. https://doi.org/10.1006/jasc.1996.0187

Janetski, J. C. (1998). *Archaeology of clear creek canyon* (tech. rep.). Provo, UT.

Janetski, J. C. (2002). Trade in fremont society: Contexts and contrasts. *Journal of Anthropological Archaeology*, *21*(3), 344–370. https://doi.org/10.1016/S0278-4165(02)00003-X

Janetski, J. C., Jardine, C. B., & Watkins, C. N. (2011). Interaction and exchange in fremont society. *Perspectives on Prehistoric Trade and Exchange in California and the Great Basin*, 22–54.

Janetski, J. C., & Talbot, R. K. (2000). Fremont social and community organization. *Clear Creek Canyon Archaeological Project: Results and Synthesis*, 247–262.

Jennings, J. (1978). *Prehistory of utah and the eastern great basin* (tech. rep.). Salt Lake City, UT.

Jochim, M. A. (2022). Dots on the map: Issues in the archaeological analysis of site locations. *Journal of Archaeological Method and Theory*. https://doi.org/10.1007/s10816-022-09580-8

Kennett, D. J., Anderson, A. J., & Winterhalder, B. (2006). The ideal free distribution, food production, and the colonization of oceania. In D. J. Kennett & B. Winterhalder (Eds.). University of California Press.

Kennett, D. J., & Winterhalder, B. (Eds.). (2006). *Behavioral Ecology and the Transition to Agriculture*. University of California Press.

Kidder, A. V. (1924). *An introduction to the study of southwestern archaeology with a preliminary account of the excavations at pecos.* Yale University Press.

Leavitt, S. W. (1994). Major wet interval in white mountains medieval warm period evidenced in 13c of bristlecone pine tree rings [DOI: 10.1007/978-94-011-1186-7_11]. In M. K. Hughes & H. F. Diaz (Eds.). Springer Netherlands. https://doi.org/10.1007/978-94-011-1186-7_11

Lindsay, L. W. (1986). Fremont fragmentation. In C. J. Condie & D. D. Fowler (Eds.), *Anthropology of the desert west: Essays in honor of jesse d. jennings* (pp. 229–251).

Madsen, D. B. (1989). *Exploring the fremont*. University of Utah Press.

Madsen, D. B., & Berry, M. S. (1975). A reassessment of northeastern great basin prehistory [Edition: 2017/01/20 Publisher: Cambridge University Press]. *American Antiquity*, *40*(4), 391–405. https://doi.org/10.2307/279326

Madsen, D. B., & Simms, S. R. (1998). The fremont complex: A behavioral perspective. *Journal of World Prehistory*, *12*(3), 255–336. https://doi.org/10.1023/A:1022322619699

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., & Ni, F. (2009). Global signatures and dynamical origins of the little ice age and medieval climate anomaly [_eprint: http://www.sciencemag.org/content/326/5957/1256.full.pdf]. *Science*, *326*(5957), 1256–1260. https://doi.org/10.1126/science.1177303

Marwitt, J. P. (1968). *Pharo village* (tech. rep.). Salt Lake City, Utah.

Marwitt, J. P. (1970). *Median village and fremont culture regional variation* (tech. rep.). Salt Lake City, Utah.

Matson, R., Lipe, W. D., & Haase, W. R. I. (1990). *Human adaptations on Cedar Mesa, Southeastern Utah*. https://dx.doi.org/10.14288/1.0058473

Matson, R. G., Lipe, W. D., & Haase, W. R. (1988). Adaptational continuities and occupational discontinuities: The cedar mesa anasazi [Publisher: Taylor & Francis]. *Journal of Field Archaeology*, *15*(3), 245–263.

Metcalfe, D., & Larrabee, L. V. (1985). Fremont irrigation: Evidence from gooseberry valley, central utah [Publisher: Malki Museum, Inc.]. *Journal of California and Great Basin Anthropology*, *7*(2), 244–254. http://www.jstor.org/stable/27825240

Morgan, C., Fisher, J. L., & Pomerleau, M. (2012). High-altitude intensification and settlement in utah's pahvant range [Publisher: Malki Museum, Inc.]. *Journal of California and Great Basin Anthropology*, *32*(1), 27–45. http://www.jstor.org/stable/24644287

Parker, G. A. (1978). Searching for mates. In J. R. Krebs & N. B. Davies (Eds.). Oxford, UK: Blackwell Scientific.

Patterson, J. (2015). Maize growing, processing, and storage: Evidence from nine mile canyon. *Arizona. Archaeol. Southwest Mag*, *29*.

Patterson, J., & Flanigan, T. (2010). Utah. paper presented at the 32nd great basin anthropological conference. layton, utah, usa.

PRISM Climate Group, O. S. U. (2014). https://prism.oregonstate.edu

Ramankutty, N., Foley, J. A., Norman, J., & McSweeney, K. (2002). The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography*, *11*(5), 377–392.

Rhode, D., & Madsen, D. B. (2000). *Late quaternary paleoecology in the great basin* (null, Ed.; Vol. 130).

Salzer, M. W., Bunn, A. G., Graham, N. E., & Hughes, M. K. (2014). Five millennia of paleotemperature from tree-rings in the great basin, usa. *Climate Dynamics*, *42*(5), 1517–1526. https://doi.org/10.1007/s00382-013-1911-9

Sharrock, F. W., & Marwitt, J. P. (1967). *Excavations at nephi, utah 1965-1966* (tech. rep.). Salt Lake City, Utah.

Simms, S. R. (1986). New evidence for fremont adaptive diversity [Publisher: Malki Museum, Inc.]. *Journal of California and Great Basin Anthropology*, *8*(2), 204–216. http://www.jstor.org/stable/27825272

Simms, S. R. (2008). *Ancient peoples of the great basin and the colorado plateau*. Left Coast Press.

Smith, C. S. (1992). The fremont: A view from southwest wyoming [Citation Key: smith1992fremont]. *Utah Archaeology*, *5*(1), 55–75.

Spangler, J. D. (1993). Site distribution and settlement patterns in lower nine mile canyon: The brigham young university surveys of 1989-91 [Publisher: Brigham Young University, Department of Anthropology].

Spangler, J. D. (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.

Spangler, J. D. (2013). *Nine mile canyon: The archaeological history of an american*. University of Utah Press.

Spangler, J. D., Yaworsky, P. M., Vernon, K. B., & Codding, B. F. (2019). *Hisatsinom of the high plateaus: A class i overview of prehistoric cultural resources in grand staircase-escalante national monument* (tech. rep.). Salt Lake City, UT.

Spangler, J. D., Yentsch, A. T., & Green, R. (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 [Publisher: [Salt Lake City]: Antiquities Section, Division of State History].

Stine, S. (1990). Late holocene fluctuations of mono lake, eastern california. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *78*(3), 333–381. https://doi.org/10.1016/0031-0182(90)90221-R

Team, R. C. (2022). *R: A language and environment for statistical computing* (tech. rep.) (tex.organization: R Foundation for Statistical Computing). Vienna, Austria. https://www.R-project.org/

Thomson, M. J., Balkovič, J., Krisztin, T., & MacDonald, G. M. (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. https://doi.org/10.1016/j.quaint.2018.09.031

Thomson, M. J., & MacDonald, G. M. (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 [Publisher: IOP Publishing]. *Environmental Research Letters*, *15*(10), 105002. https://doi.org/10.1088/1748-9326/aba57e

USGS. (2022a). 3d elevation program 1/3 arc-second resolution digital elevation model [Type: dataset]. https://www.usgs.gov/the-national-map-data-delivery

USGS. (2022b). National hydrography dataset [Type: dataset Version: USGS National Hydrography Dataset Best Resolution (NHD) for Hydrologic Unit (HU) 4 - 2001 (published 20191002)]. https://www.usgs.gov/national-hydrography/access-national-hydrography-products

USGS & NRCS, U. (2013). *Federal standards and procedures for the national watershed boundary dataset (wbd) (4 ed.): Techniques and methods* (tech. rep.). https://pubs.usgs.gov/tm/11/a3/

Varien, M. (1999). *Sedentism and mobility in a social landscape: Mesa verde & beyond*. University of Arizona Press.

Vernon, K. B., Yaworsky, P. M., Spangler, J. D., Brewer, S., & Codding, B. F. (2021). Decomposing habitat suitability across the forager to farmer transition. *Environmental Archaeology*. https://doi.org/10.1080/14614103.2020.1746880

Vernon, K. B. (2021). *Hiker: Model hiking paths over costly terrains* (tech. rep.) (R package version 0.1.0). https://github.com/kbvernon/hiker

Winter, J. C., & Wylie, H. G. (1974). Paleoecology and diet at clydes cavern [Edition: 2017/01/20 Publisher: Cambridge University Press]. *American Antiquity*, *39*(2Part1), 303–315. https://doi.org/10.2307/279590

Winterhalder, B., Kennett, D. J., Grote, M. N., & Bartruff, J. (2010). Ideal free settlement of california's northern channel islands. *Journal of Anthropological Archaeology*, *29*, 469–490.

Wood, S. N. (2004). Stable and efficient multiple smoothing parameter estimation for generalized additive models [Publisher: Taylor & Francis]. *Journal of the American Statistical Association*, *99*(467), 673–686. https://doi.org/10.1198/016214504000000980

Yaworsky, P. M., Vernon, K. B., Spangler, J. D., Brewer, S. C., & Codding, B. F. (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. https://doi.org/10.1371/journal.pone.0239424

Yaworsky, P. M. (2021). *Prehistoric land use in the grand staircase-escalante national monument and west tavaputs plateau, utah* [Doctoral dissertation].