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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, because 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.

Resumen

Los Fremont constituyen un importante caso de estudio para examinar la resiliencia de las comunidades agrícolas del pasado frente a las crisis climáticas, ya que habitaron en el límite septentrional de la agricultura intensiva de maíz en el Oeste Americano, donde las limitaciones a la producción de maíz se hacen evidentes. A partir de la reconstrucción, basada en anillos de árboles y simulaciones, de la precipitación media anual y la suma térmica del maíz, junto con el coste-distancia a arroyos perennes, modelamos la variabilidad espacial en la densidad de yacimientos Fremont en el este de la Gran Cuenca. Los resultados de nuestros análisis tienen implicaciones para la definición del rango ecológico en el que el cultivo es una estrategia viable en esta región árida, y pueden ser utilizados para predecir dónde y por qué las estrategias de cultivo de maíz podrían evolucionar y eventualmente colapsar a medida que el clima cambia con el tiempo.

Keywords: ideal free distribution; Great Basin; paleoclimate reconstruction

Palabras clave: distribución libre ideal; Gran Cuenca; reconstrucción paleoclimática

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, such as irrigation methods, trade, and seasonal high-elevation hunting (e.g., Barlow et al. 2008; Boomgarden et al. 2019; Hart

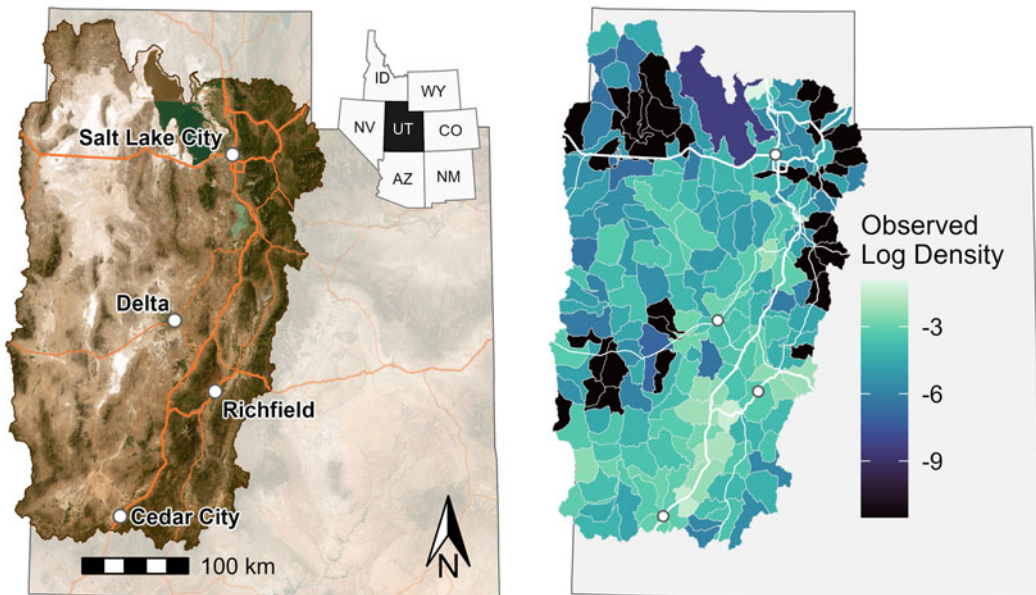


Figure 1. On the left is an overview map showing the project area with modern satellite imagery. The green areas indicate plant growth and the beige areas indicate empty desert. The green areas are also the mountainous areas. Thick orange lines are interstate highways. Thin orange lines are major state 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. (Color online)

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 to which the western Fremont adapted provide a useful backdrop for exploring Fremont settlement, because variation in that environment exhibits abrupt and quite dramatic changes over short distances of space and time, thereby heightening the differences between areas the western Fremont did and did not occupy. We explore those differences from a socioecological 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 (IFD) model from behavioral ecology, given that 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 (Coddington and Bird 2015; Fretwell and Lucas 1969; Winterhalder et al. 2010).

The fundamental assumption underlying the IFD is that individuals will behave optimally. They will choose to settle the habitat with the highest suitability first—that is, 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 and that they will always do exactly

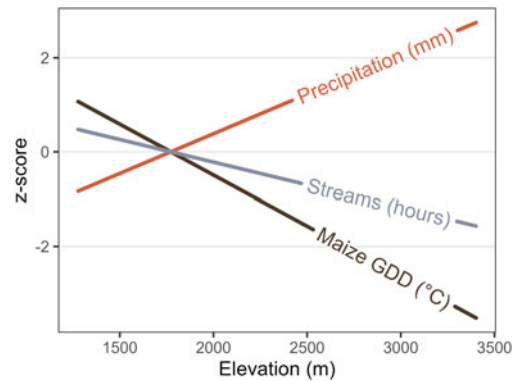


Figure 2. Linear responses of the centered and scaled average water-year precipitation (mm), average growing-season maize growing degree days ($^{\circ}\text{C}$ days), and cost-distance to streams (hours) to changes in elevation (m). See methods for how these values were calculated and results for more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

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 and Leathwick 2009; Elith et al. 2006) 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, one will sometimes hear this approach referred to as “ecological niche modeling” (e.g., Feng et al. 2019; Sillero and Barbosa 2021; Sillero et al. 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 are 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.

Background

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 for 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.

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 (Grayson 2011). As shown in Figure 2, net water-year precipitation in the eastern Great Basin tends to increase with elevation, whereas maize growing degree days (GDD)

over the growing season tends to decrease. An important trade-off therefore 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, although 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 semisedentary agricultural practices from the Southwest in a piecemeal fashion over several hundred years (Jennings 1978; Winter and Wylie 1974). Although archaeologists have marshaled an impressive array of arguments and counterarguments 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 produced the archaeological 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 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, 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 1994; 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 2002; Leavitt 1994; Salzer et al. 2014; Stine 1990), although 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—that includes lots of up-front 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). Consequently, demographic pressure reduced the efficiency of foraging strategies, 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, the Fremont 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, such as 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).

Materials and Methods

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, and at its southern boundary are the Bull and Pine Valley Mountains, which separate the Great Basin from the Virgin River watershed just north of St. George, Utah. This is a region approximately 107,000 km² 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).

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 (USGS) and the Natural Resources Conservation Service (NRCS) 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, because watersheds determine how much water might accumulate at a location and what its potential for irrigation is.

Although 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, given that 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 (such as the ones outlined above), they can be relied on 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 given that 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.

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 Coddington et al. 2022, 2024; Contreras and Coddington 2023). Unfortunately, our dataset does not represent all recorded Fremont sites in the study area, because 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, whereas villages should follow 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 we 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 pit structures, pueblos, roomblocks, or wickiups were included. 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. Consequently, 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 room block with seven rooms counts as seven sites. This brings the total weighted site count to 2,447, with minimum and maximum values of zero and 119, respectively.

Figure 1 shows the log density of Fremont sites across watersheds. The log is used mainly for visualization purposes given that 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 use $\log(1e-5)$ because $\log(0)$ is undefined. It should be emphasized that we do not have an independent estimate of the absolute number of Fremont sites in the area. Because we only have an estimate based on a thinned sample, the map is more appropriately interpreted as showing relative differences in the density of recorded sites across watersheds.

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 (US Geological Survey [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) from October to September and maize growing degree days (GDD, in Celsius [C]) over the growing season from May to September because these have a large effect on maize productivity, thereby 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, it 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 (AD 400 to 1400) 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 (for further details, see Bocinsky and Kohler 2014; Bocinsky et al. 2016). In this case, we use interpolated precipitation and temperature estimates from the approximately 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 Data Bank 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 (i.e., the effects of mountains and elevation) are rampant in these data, so it is reasonable to expect that the covariates will exhibit some multicollinearity. Consequently, as part of the exploratory phase of this analysis, we perform a series of pairwise 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 is 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 twofold. 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, 1,200 m asl. They choose that location *because* it has the right combination of water availability and temperature—in other words, 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.

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:

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

with r being a dispersion parameter, and λ_i the expected number of sites per watershed: $E(N_i) = \lambda_i$. 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 nonlinear responses to the covariates. In our model, ϵ_i incorporates an exponential

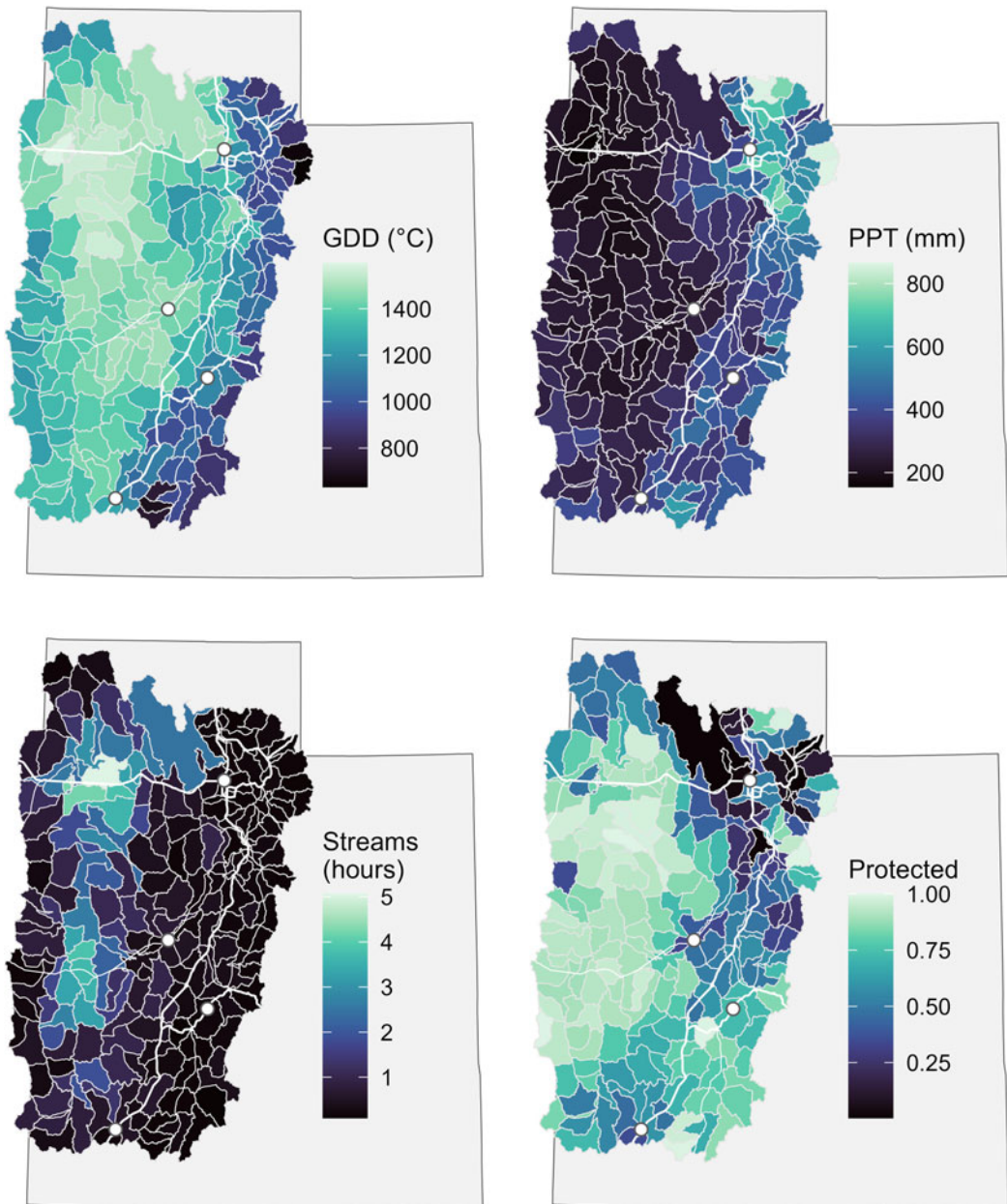


Figure 3. Distribution of covariates across watersheds. These include maize growing degree days (GDD), annual precipitation (PPT), and cost-distance to streams (Streams). Lighter colors represent larger values; darker colors represent smaller values. (Color online)

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. Although 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 because 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 $\sum_{k=1}^K s(x_{ik}) = 0$. 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. For these data, it is notable that those impacts 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, and the more sites we should observe.

Model evaluation includes checks for concavity or nonlinear correlation in the smooth terms of the GAMM, as well as a variance inflation factor (VIF) 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 nonlinear response in the data. We, therefore, remove the smooth terms for those covariates in the final model, leaving only precipitation with a potential nonlinear effect.

All analyses are conducted in the R programming language and environment (R Core Team 2022). For details of this analysis, please see Supplemental Text 1.

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, although 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, which confirms our expectation that more sites occur in watersheds with a larger proportion of federal land. Site counts increase in watersheds with larger GDD values, although the effect is small ($\exp \beta = 1.00$, $p < 0.001$), and site counts decrease with distance from perennial streams—although, 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 ($\text{edf} = 3.25$, $p < 0.001$). The effective degrees of freedom (EDF) for precipitation suggests a strong nonlinear effect of that covariate on site counts, which increases up to about 450 mm and decreases thereafter.

A concavity test on the final model was not conducted because 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 ($I = 0.233$, $\text{rank} = 381$, $p = 0.476$).

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

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

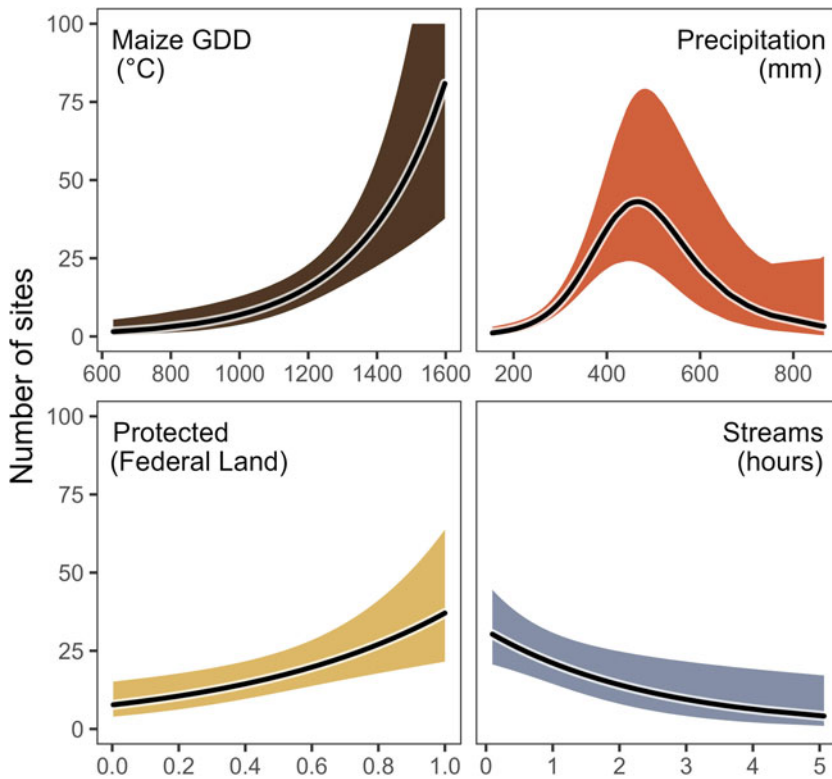


Figure 4. Partial dependence plots. Each plot shows the response of site counts to changes in a target covariate while holding all other variables at their mean.

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](#).

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: 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 (1) total site counts in each watershed, not the contemporaneous site counts, and (2) the median values of the climate variables over the entire Fremont sequence rather than over the years that individual Fremont sites were occupied. Although 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 2,000 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. Consequently, 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.

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, given that those inferences would conflate settlement patterns due to constraints on foraging and settlement patterns due 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 this whole article, 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%–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 (AD 850), and they do not show signs of full reliance on foraging until nearly 800 years BP (AD 1150). 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 be partially 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.

Trade-Off between Precipitation and Temperature

Although 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. In addition, 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), although 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 overinterpret this metaphor, because 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

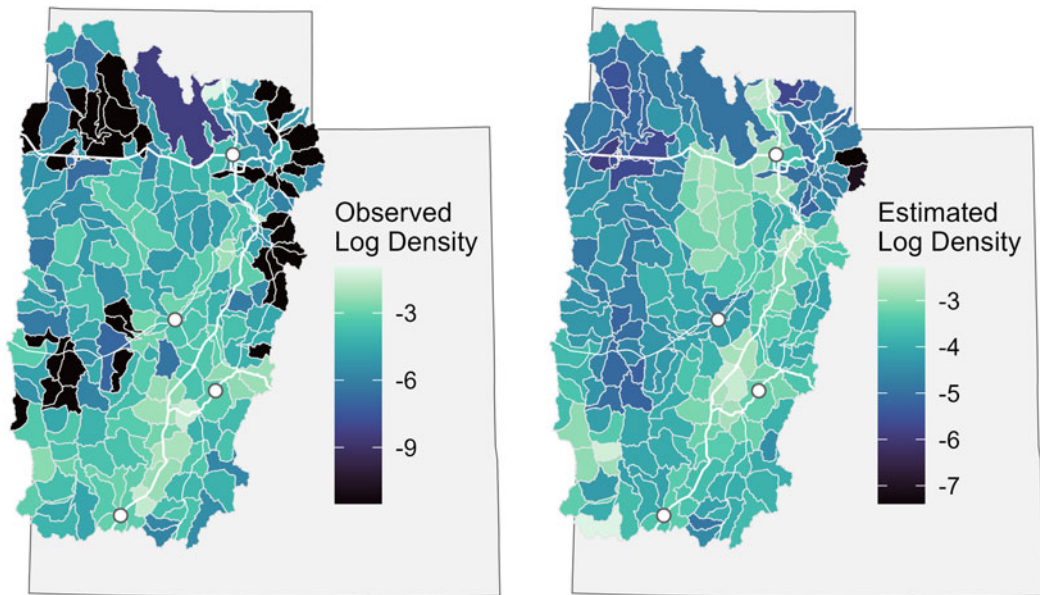


Figure 5. Geographic distribution of Fremont sites across watersheds. The left panel shows the relative density derived from observed site counts, and the right panel shows the relative density from the estimated site counts. (Color online)

model. The unaccounted-for variation could also be due to the fact that what matters most for maize agriculture is not necessarily where precipitation falls, but where it accumulates once it enters the streamflow 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, although 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 streamflow 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).

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 1,000°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 6 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 (≥ 500 years, in this case).

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 nonnegligible 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

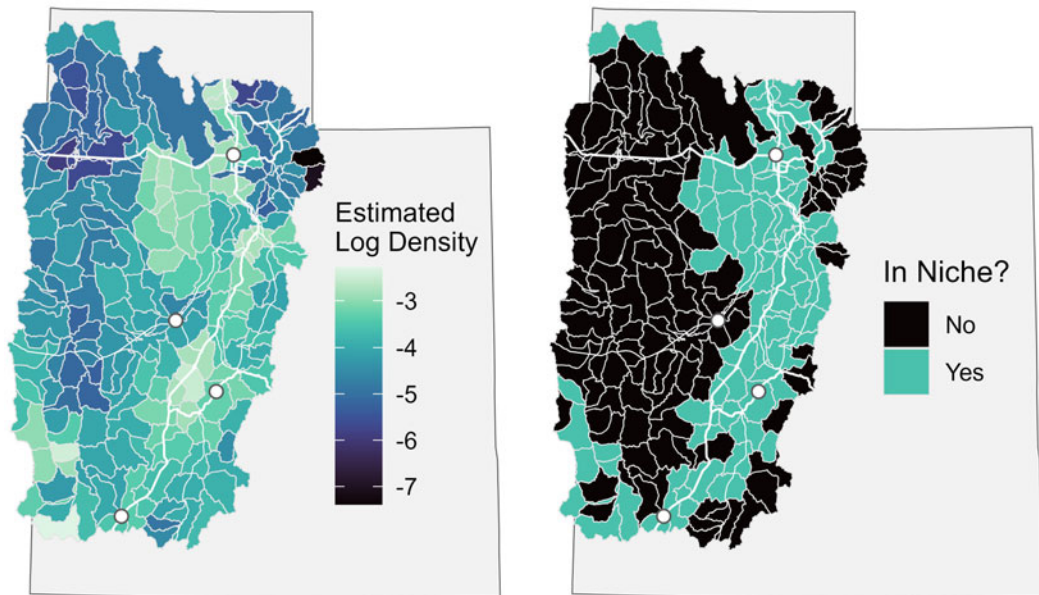


Figure 6. The map on the left shows the log density of feature-weighted site counts as estimated by the model, with lighter colors representing larger relative densities, and darker colors representing smaller relative densities. The map on the right shows which watersheds are in the rain-fed maize-farming niche for at least half of the Fremont sequence. The light green color indicates those that are in the niche. (Color online)

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, given that 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, therefore 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 $1,000^{\circ}\text{C}$, 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, because 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 would have been 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.

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 therefore 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 and colleagues (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. Whereas 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 increased, the benefits of increased sedentism and cultigen adoption would have slowly begun 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.

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 and MacDonald 2020; Thomson et al. 2019). We follow Lindsay (1986) in thinking this was likely due 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, because it involved higher temperatures and more growing-season precipitation due to the northward intrusion of summer monsoons. This period lasted from roughly 1000 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 (Coddington 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 increased population packing across all habitats during this time, thereby 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. Consequently, just as temperatures were beginning to cool, precipitation levels collapsed. By extension, this would have decreased overall water availability and, therefore, the potential for irrigation. Opportunities for the Fremont to recover from such a drought would also have been limited, given that 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.

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Supplemental Text 1. Fremont Models.

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