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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

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Abstract

The rise and decline of many complex, pre-European maize-farming cultures in the American Southwest coincides with the warm, climatically quiescent Medieval Climate Anomaly (MCA, ca. 850–1350 CE) and transition to the cool, hydrologically variable Little Ice Age (LIA, ca. 1350–1850 CE). The effects of drought on early subsistence agriculture in the Southwest is well studied, but the impact of temperature stress and variability on the growth of maize crops and which areas were most resilient to such stress remain open questions. We statistically downscaled outputs from a paleo-climate model experiment (CESM1 LME) to map changes to cumulative growing degree days for maize (GDD, 30/10 °C) and precipitation over Utah between 850 and 1449 CE, and downscaled GDD changes to local Fremont Culture archaeological site occupations from radiocarbon-dated contexts mapped as spatially discrete kernel density estimates of summed probability distributions (SPDs). We then analyzed correspondences between Fremont SPDs and GDD/precipitation between 850 and 1449 CE. In general, we found (1) high Fremont occupation intensity coincident with GDD that is less volatile than the long term average, and low occupation intensity coincident with, or following, periods of volatile GDD; (2) intensified occupation of high-elevation sites during the MCA, followed by a retreat to lower elevation sites coincident with a sudden rise in annual temperature volatility and increasing drought conditions; and (3) these occupation changes occurred in spite of the greater temperatures and variability in GDD at low-elevation sites. We found evidence that increased inter-annual variability of growing seasons prior to the onset of the LIA, was likely a determinant of Fremont subsistence strategy decision making, and high-elevation site occupation. The most resilient Fremont occupations in the face of these challenges were sited where growing season lengths were least variable.

Significance

This study contributes to improving the general understanding of ancient Native Americans maize farmers' relationship with their environment during a period of significant, global scale climate change. Understanding the adaptive responses of ancient peoples to changes within their local environments improves our understanding of past societal responses more generally and informs our ability to anticipate and respond to environmental change at present and into the future. The methods used are scalable to other locations and time periods involving dryland, subsistence agriculture, making direct site-to-site comparisons possible

1. Introduction

The Fremont were a maize (*Zea mays*) farming culture who inhabited a region roughly centered on modern Utah (figure 1). This placed them at the northern periphery of the well-known Ancestral Puebloan (AP) cultural complex that flourished throughout much of the American Southwest between ca. 4th and 14th centuries CE [7]. The physical manifestations of the Fremont Culture thereafter vanished from archaeological view. Just what happened to the Fremont is an enduring question in pre-European American history, recorded in artifacts and shared cultural memory of some southern Puebloan descendants, and reconstructed from proxies of paleo-environmental change. Scholars have explained the dramatic contraction in AP range and socio-cultural complexity after the mid-12th century, coincident with the apparent decline of the Fremont Culture, as a consequence of drought (Douglass 1929) and ecological degradation (Diamond 1994, 2005), or the unbearable cost of maintaining their complex material and socio-economic cultures (Tainter 1988, 2006a), but generally warn against mechanistic environmental causation (Lekson and Cameron 1995, Coombes and Barber 2005, Butzer 2012). Local AP communities exhibited capacities for resilience and adaptation to large scale, regional environmental change at fine spatial scales (Blinman 2008). Crucially, features of environmental change that APs and the Fremont experienced, such as megadrought, warming, and variable precipitation regimes, are anticipated to arise in the region of the Southwest in the near future as a consequence of climate change (Loisel *et al* 2017), if they have not already (Williams *et al* 2020). It is natural, therefore, to reflect parallels to the likely impacts of climate change on smallholder farmers today (Swetnam *et al* 1999). Developing a predictive model for the integrated relationship between climate change, economies, local resilience and socio-ecological transformation has been a long term goal of research into the prehistoric Southwest experience (Dean *et al* 1998, Axtell *et al* 2002, Tainter 2006b, Spielmann *et al* 2016, Bocinsky and Kohler 2016). We believe there to be lessons for policy-makers and planners of future resilience and adaptation are embedded within the archaeological record of the Fremont response to climate change.

The period ca. 800–1150 CE, over which AP and Fremont populations grew to their largest, was roughly coeval with the Medieval Climate Anomaly (MCA, 850–1350 CE) (1998, Mann *et al* 2009, Moberg *et al* 2005, Christiansen and Ljungqvist 2012), a northern hemisphere climatic event characterized in the Southwest by more frequent and extreme droughts (Stine 1994, Macdonald 2007, Meko *et al* 2007, Woodhouse *et al* 2010, Asmerom *et al* 2013). For many Fremont, particularly on the northern Colorado Plateau, hydrologic changes in the early MCA may have induced intensification of maize farming as a subsistence strategy (Finley *et al* 2020). The end of the MCA is marked by a gradual transition to a cooler, more hydrologically variable mean climatic state, known as the 'Little Ice Age' (LIA, from ~ 1350 CE). This transition of mean climatic state, punctuated by droughts, is associated with the decline of maize-farming occupations in the archaeological record. Increasingly well constrained proxy reconstructions of the Southwest demonstrate that the peak of the Fremont and AP occupation is bracketed by 3 of the 5 most extreme 'megadroughts' in the last 1200 years (Coats *et al* 2016). Climatic variability strongly influenced crop yields in the ancient Southwest, just as it does throughout the world today (Ray *et al* 2015). Many of the longest lived AP sites on the southern Colorado Plateau showed the least hydrological variability (Bocinsky and Kohler 2014). Among the Fremont there was a preference to occupy sites with low maize yield variability, a direct consequence of hydrologic and temperature variability (Thomson *et al* 2018). Yet the MCA-LIA transition (ca. 12th–15th centuries CE) was marked by an increase in hydroclimatic variability over the Southwest (Loisel *et al* 2017), with more volatile stream discharges draining the northern Colorado Plateau (Meko *et al* 2007) and flooding (Ely 1997).

Modern daily average temperatures for the Great Basin range from about 35 °C in summer to −8 °C in winter, with respective day-night ranges of about 18.2 °C and 16 °C. On the Colorado Plateau, summer temperatures are some 15 °C cooler and 4 °C less variable (PRISM Climate Group 2018), sufficient for highland wetlands to persist, and even for multi-year snow to accumulate at certain high-elevation areas. While most of the annual precipitation depends on winter westerlies driving moisture in from the Pacific, a small but important source of summer precipitation is the North American Monsoon (NAM) (Adams and Comrie 1997, Higgins *et al* 1997, Jones *et al* 2015, Metcalfe *et al* 2015). The limit of the NAM is presently about 39°N latitude but the orography of the region continues to wring moisture from the atmosphere, adding a critical late-summer pulse to highland precipitation north of central Utah as well. Fremont sites often appear within canyon systems, where stream terraces are suitable for raising their maize; a short-season, drought resistant variety known as 'Fremont dent corn' (Cutler 2001). It is also likely that they took opportunistic advantage of temperature and moisture gradients, which both tend to decline with descent along canyon stream reaches, in addition to the

[7] Common Era (CE) measurement is numerically equivalent to Anno Domini (AD).

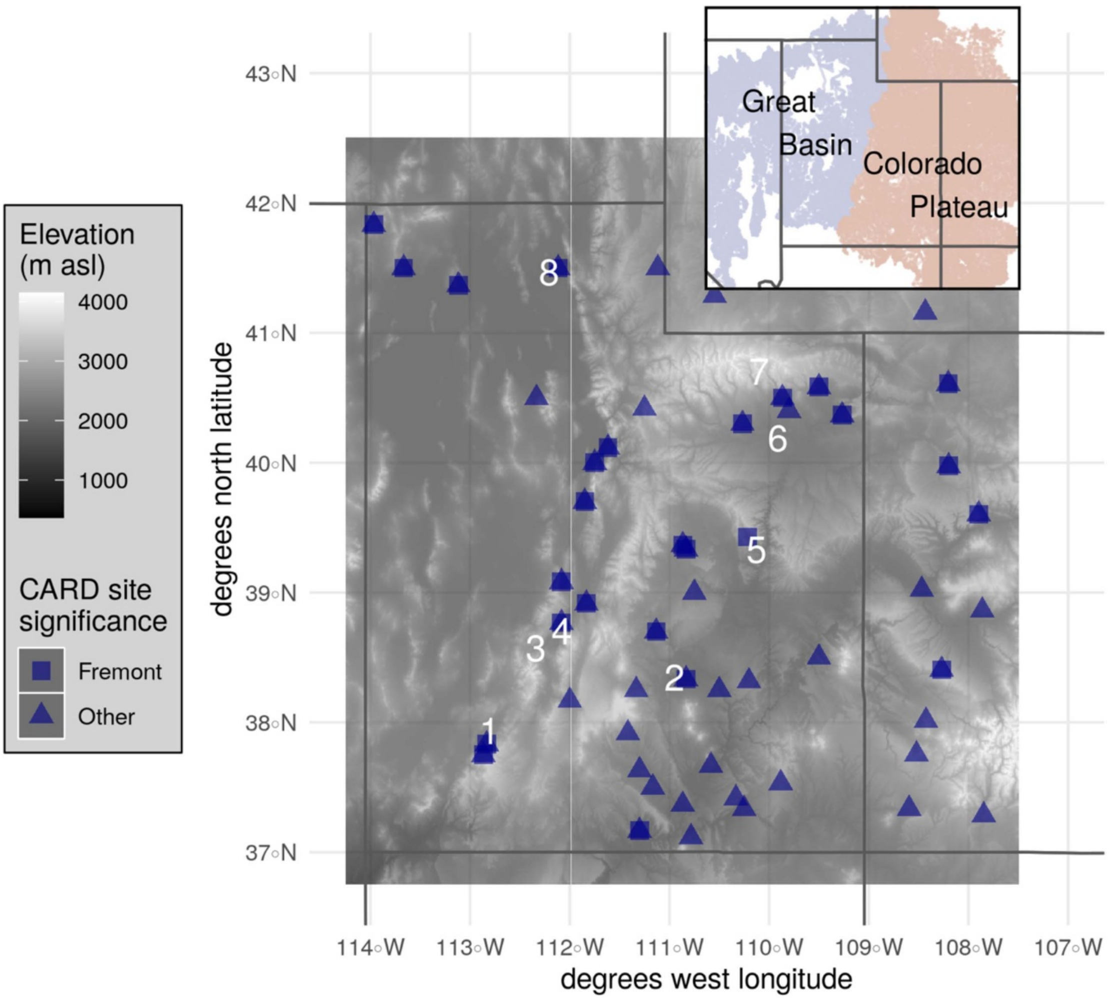

Figure 1. Topography of the Fremont region with a map of the relative positions of the Great Basin and Colorado Plateau watershed boundaries inset. Fremont and other Native American archaeological site locations from CARD are marked with squares and triangles, respectively. Modern state boundaries are included for orientation. Locations discussed in this paper include Parowan Valley (1), the Fremont River (2), Five Finger Ridge (3), Sevier Valley (4), Range Creek Canyon (5), the Uinta Basin (6), and the Uinta Mountains (7). Digital elevation model data from PRISM (PRISM Climate Group 2018); inset map watershed shapefiles from the USGS and Utah AGRC (Utah AGRC 2014). Archaeological site data from CARD (Martindale *et al* 2016).

variable soil and microclimatic conditions different canyon systems host over short geographic distances (Ronan *et al* 1998, Burnett *et al* 2008). While direct evidence for Fremont irrigation is sparse (Metcalfe and Larrabee 1985, Simms *et al* 2020), experimental archaeology at the Range Creek Fremont site has demonstrated that growing maize would have been challenging without somehow concentrating water (Boomgarden 2015, Boomgarden *et al* 2019). It seems probable that irrigation was part of the Fremont toolkit for crop management (Boomgarden *et al* 2019), but it was expensive, with a 4–6 year investment required to profit from construction and maintenance costs (Kuehn 2014), as well as especially vulnerable to damage from sudden flood events. This was exacerbated during droughts, when plant dieback limits the surface water absorption and enhances flood intensity.

Growing maize was itself among a suite of subsistence strategies practiced by the Fremont, as appropriate by time and location (Barlow 2002), including crop-storage in granaries, supplementing of diets with wild plants and game, as well as networks of trade (Marwitt 1973, Madsen and Simms 1998, Janetski 2002, Hockett and Morgenstein 2003, Simms 2016). Trade was valuable for APs as it built social capital and connected geographically distant, climatically disconnected places, promoting resilience in the face of local crop failures (Kohler and Van West 1996, Cordell *et al* 2007, Kohler *et al* 2012). Profound regional droughts in middle 12th and late 13th century almost certainly contributed to mass migrations and population reductions throughout the Southwest (Benson *et al* 2007a, 2007b, Kohler *et al* 2008, Benson and Berry 2009, Kohler and Reese 2014, Bocinsky *et al* 2016), but to an uncertain degree to less locally dense Fremont occupations on the northern Colorado Plateau. Fremont who inhabited the wetlands of the Great Salt Lake littoral gradually replaced maize in their diets with a complete reliance on wild foods

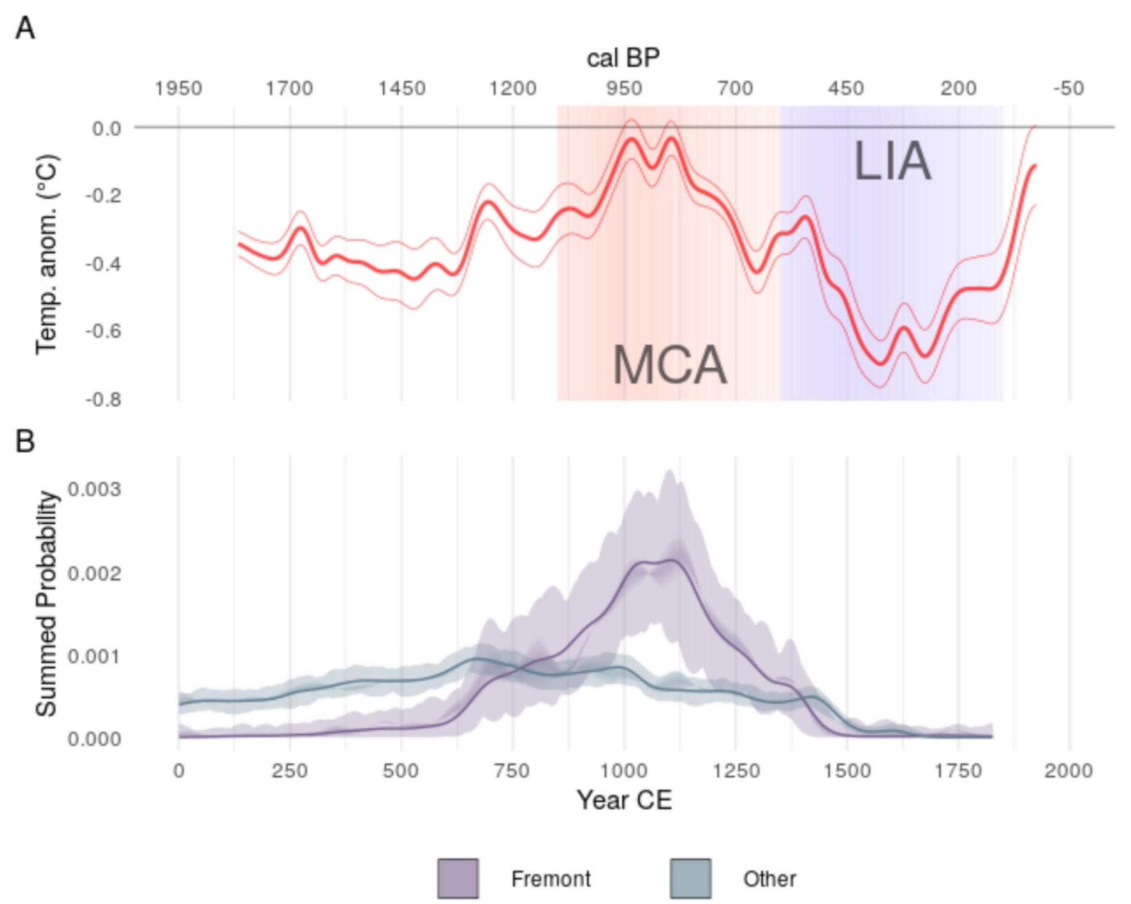

Figure 2. (A) Smoothed (low-frequency) Northern hemisphere temperature anomaly reconstruction (Moberg *et al* 2005); (B) shading gives composite kernel density estimates (CKDE) from the normalized SPDs of Fremont ($n = 154$) and nearby non-Fremont ($n = 821$) radiocarbon ages from the Canadian Archaeological Radiocarbon Database (Martindale *et al* 2016) and data from Range Creek published elsewhere (Boomgarden *et al* 2014); thick lines give mean values for each 1000 simulation ensemble. Red and purple bands represent the Medieval Climate Anomaly (MCA, 850–1350 CE) and Little Ice Age (LIA, 1350–1850 CE) periods described in the text.

by 1150 CE (Coltrain and Leavitt 2002). By 1300 CE, Fremont and more southerly AP occupations were in decline throughout the Southwest. There exist detailed reviews of pre-European Southwest maize agriculture in the context of environmental change (Benson 2011, Kohler *et al* 2012, Bocinsky and Kohler 2014), and a growing interdisciplinary literature mining lessons to inform the present from archaeologists' reconstructions (Jones *et al* 1999, Adger *et al* 2013, Chase and Scarborough 2014, Barton *et al* 2016, Bocinsky and Kohler 2016, Jackson *et al* 2018).

The climate of the MCA and MCA-LIA transition in the Southwest are increasingly well modeled at high spatial resolution, and its drivers are generally understood (Baek *et al* 2019, Steiger *et al* 2019). Long term changes in warming and aridity in the Southwest are influenced by sea surface temperature dynamics in the Pacific and Atlantic Oceans that are likely to become more frequent under global warming (Cayan *et al* 2017). Given the climatic sensitivity of the Southwest and its current importance for water resources and agriculture (Garfin *et al* 2014), the value in a comprehensive understanding, beyond archaeology (Ingram and Gilpin 2015), of the Fremont experience of the MCA and MCA-LIA transition is clear. Here we infer the potential sensitivity of Fremont agriculture to early climatic changes through the use of a database of radiocarbon dated archaeological sites and growing season length estimates derived from a statistically downscaled climate model to analyze temporally and spatially the correspondences between climatic changes likely to impact maize and Fremont occupation patterns between 850 and 1449 CE.

2. Data and methods

2.1. Fremont occupation time-series development

We used radiocarbon (^{14} C) dates from the Canadian Archaeological Radiocarbon Database (CARD, www.canadianarchaeology.ca/) supplemented with published data from Range Creek (Boomgarden *et al* 2014, Martindale *et al* 2016). See the supplementary information (SI) for details (available online at stacks.iop.org/ERL/15/105002/mmedia). We grouped these as Fremont ($n = 154$), based on CARD significance classifications, and non-Fremont/Other ($n = 821$) entries, based on proximity to Fremont-identified sites. Ages were calibrated for each individual element (Haslett and Parnell 2008,

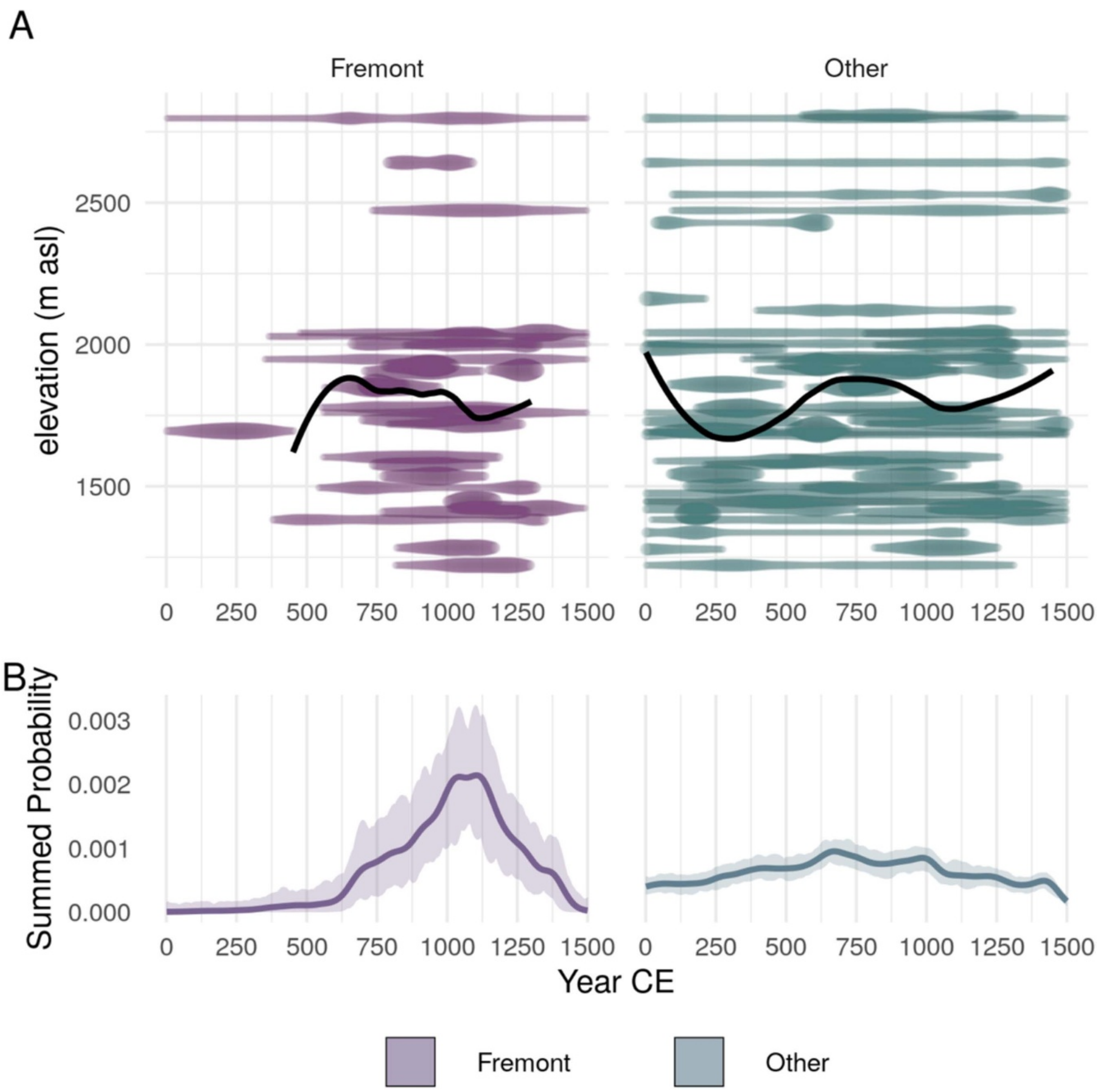

Figure 3. Contrasting site elevations of Fremont and non-Fremont SPDs in time-series. (A) Bands show the local elevations of subset components of the SPDs, with darker shading indicating greater summed probability. Heavy lines are locally weighted regression models to resolve the pattern of mean elevation preference over time until 1450 CE. (B) Shading gives composite kernel density estimates (CKDE) of the SPDs of Fremont ($n = 154$) and nearby non-Fremont ($n = 821$) radiocarbon ages from the Canadian Archaeological Radiocarbon Database Occupation intensity (by CKDE) for Fremont and non-Fremont sites Elevation data from the USGS (USGS 2017) via Mapzen (Mapzen 2017).

Reimer *et al* 2013) resulting in occupation intensities given by kernel density (CKDE) models of site-specific summed probability distributions (SPDs) (Bevan and Crema 2020). Summed probabilities given by these models may be read as site occupation likelihoods over the range of years for which they are declared. Site elevations were determined using the *elevatr* package for R (Hollister and Shah 2017) with DEM data from the USGS (USGS 2017) via Mapzen (https://registry.opendata.aws/terrain-tiles/).

2.2. Climate model downscaling and growing degree days

Using a bias-correction and spatial downscaling algorithm (Wood *et al* 2004) we statistically downscaled a climate model, CESM LME (Otto-Bliesner *et al* 2015), to produce daily temperature maxima and minima at high spatial resolution for the period 850–1449 CE, for model ensemble members em003, em004, and em005. (See SI for details.) The temperature maxima and minima were extracted as bilinearly interpolated pixel-values nearest each site co-ordinate for model-years 850–1449 CE from each downscaled ensemble member. Growing degree days (GDD) for year *i* were computed as the sum of degree days (DD_j) over the duration of the growing season *n*, computed for a growing season between May 1st, $j = 121$ non-leap year julian day equivalent, and October 31st, $n = 304$, of year *i*, i.e.

$$GDD_i = \sum_{j=121}^{n} DD_j$$

where

$$DD_j = \frac{T_{max} + T_{min}}{2} - T_{base}$$

under the conditions that

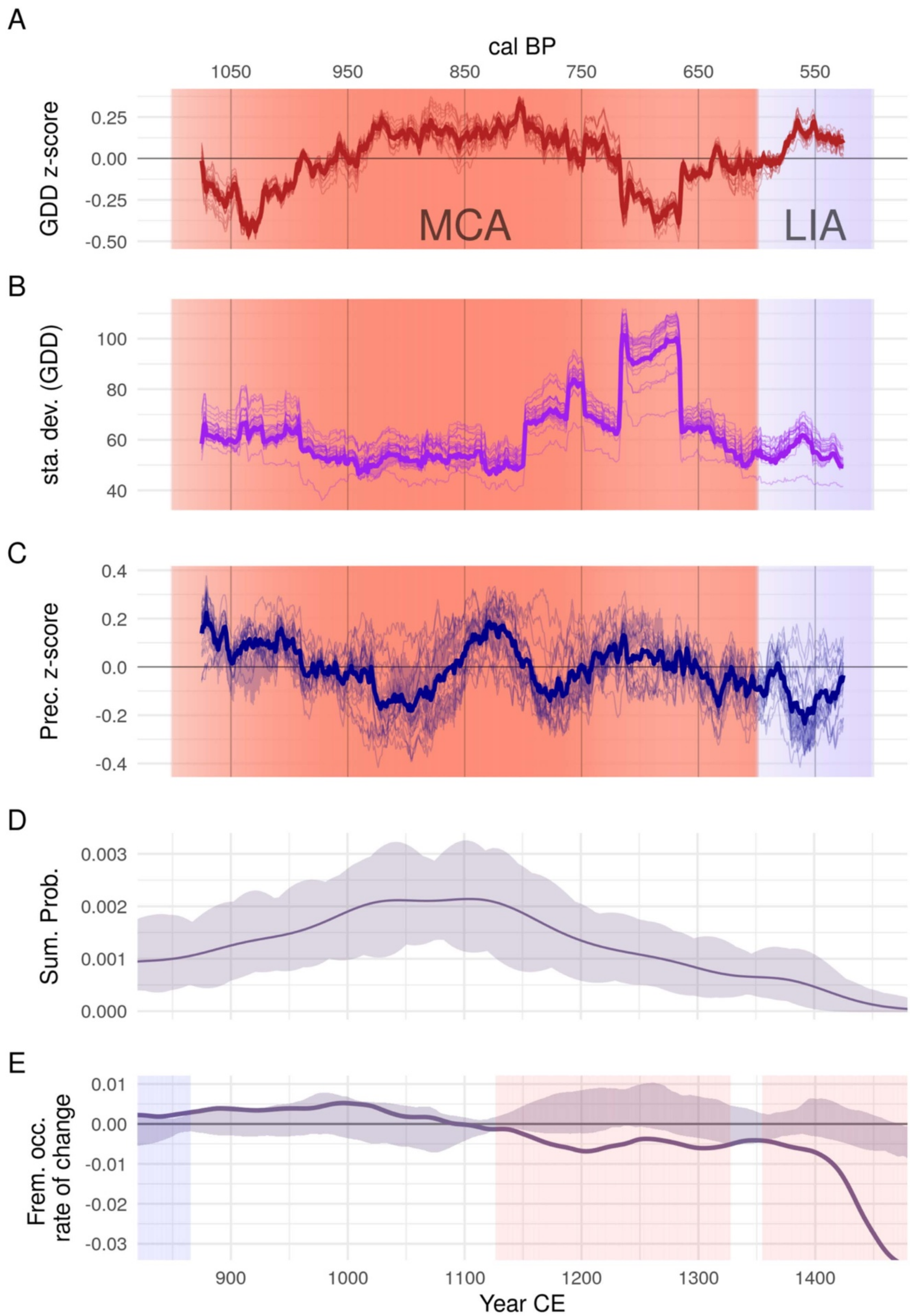

Figure 4. Stacked time-series of (A) downscaled growing degree day (GDD) z-scores (relative to 850–1449 CE mean), (B) and standard deviation of GDD, and (C) downscaled precipitation z-scores (relative to 850–1449 mean) for Fremont-identified sites in a 51-year moving window with averages shown by thick lines; and (D) CKDE of summed probabilities for Fremont sites (figure 2(b) 'Fremont' re-plotted along this axis). (E) Rates-of-change of the SPD (solid line) compared to Monte Carlo simulations over the same time series (envelope of 100 simulation results). The blue shading indicates statistically significant positive SPD growth (ca. 607–865 CE, $p < 0.01$), and the red shading indicates SPD decline (ca. 1127–1327 CE and ca. 1355–1582 CE, $p < 0.01$). The MCA and LIA are indicated with shading in (A) –(C). Data used to generate (A) –(C) is based on downscaled CESM (Otto-Bliesner *et al* 2015).

Figure 5. Growing season variability for Fremont ($n = 23$) and non-Fremont ('Other') sites ($n = 22$) occupied anytime during the period 850–1449 CE, evaluated only over those years occupied. The standard deviation of modeled GDD is significantly correlated for Fremont sites ($r = -0.41$, $p < 0.05$). Solid lines show linear models and with standard errors shaded. (See SI for an expanded suite of climatic variables).

$T_{max} \equiv 30°C$ if $T_{max} > 30°C$, $DD_j \equiv 0°C$ if $\frac{T_{max}+T_{min}}{2} < T_{base}$, and $T_{base} \equiv 10$ °C for *Zea mays*.

Precipitation from CESM LME (i.e. convective and frontal precipitation simulations of the same ensemble members) was similarly downscaled, and analyzed in terms of the ensemble mean of total precipitation for each site, summed over the 183-d growing season between May 1st and October 31st. (We also calculated total precipitation using 365-d years to test the robusticity of the analysis shown in figure 5 and found no significant difference.) For a more detailed description of the calibration and downscaling procedures, please see SI.

3. Results

The shape of the SPD (figure 2(b)) appears to correspond to that of temperature anomalies (figure 2(a)) for the Northern Hemisphere (Moberg *et al* 2005). The Moberg *et al* low-frequency anomalies and the aggregated Fremont SPD are not independent, by Pearson's chi-square test ($p < 0.002$), but this may be influenced by the radiocarbon calibration curve applied to both series. When tested against Monte Carlo (MC) simulations to estimate the influence of the calibration curve, the SPD shows significant ($p < 0.01$) positive deviations above the MC envelope between ca. 735 and 1247 CE (see SI). A Kolmogrov–Smirnov goodness-of-fit test on normalized cumulative distributions, within the 735–1247 CE range, of the low-frequency Moberg *et al* anomalies and the cumulative kernel density estimation (CKDE) of the Fremont SPD shows dependence ($p < 0.001$); however, chi-square tests do not.

Next, we compared kernel density estimates for Fremont and non-Fremont identified sites (figure 3(b)), and then disaggregated these by elevation (figure 3(a)). The bands in figure 3(a) show occupation likelihoods for sites throughout the region clustered by elevation, with over-plotted lines highlighting site elevation means with locally weighted smoothing (LOWESS) models. The Fremont occupation represents a general relocation to higher elevation for all sites in the region over the period, particularly between ca. 950 and 1150 CE. This also appears to have coincided with the warmest mean annual temperatures for the period (cf figure 2, figure 4(a)).

Downscaled temperature dailies from CESM LME were used to compute GDD for maize, with 10 °C base and 30 °C maximum temperature growth limits, between 850 and 1449 CE. Figure 4(A) shows GDD (30/10 °C) z-scores (deviations from the long-term average divided by standard deviation in a 51-year moving window) computed for all Fremont-identified sites. Variability in these GDD values is explicitly shown in figure 4(b) by the 51-year moving window standard deviation for each GDD by site. In both cases, ensemble member values are first averaged and then over-plotted for all sites to indicate a measure of uncertainty, and heavy lines added to represent aggregated averages for all sites. In figure 4(c), ensemble means of downscaled precipitation for each site, summed over the GDD growing season (May 1st to October 31st) for each model-year, were used to compute z-scores in a 51-year moving window, with a thick line over-plotting the aggregated average of all sites. These climatic signals are contrasted with cumulative SPD kernel density estimates for Fremont-only occupations (figure 4(d), also shown for the extended time-series in figure 3(b) above) and the time rate of change (figure 4(e)), which shows that the Fremont occupation was in decline by 1127 CE.

The climate model indicates that during the early MCA, between ca. 850 and 1000 CE, growing seasons were getting longer while experiencing moderate to low-volatility. Conditions also grew drier relative to previous years; however, compared to the long-term average, conditions were relatively mesic. Occupations remained elevated for about a century, while growing seasons were long and consistent, and though precipitation grew scarcer in aggregate, changes varied widely across occupations. For model-years 1100–1150 CE, both GDD and precipitation conditions were favorable, with the latter becoming less variable across occupations and pluvial in aggregate. By ca. 1127, the Fremont occupation was in decline. While mean annual temperature and precipitation were above average during this period according to the climate model, it was also a period of rising interannual temperature variability; and after 1150 CE, temperature volatility suddenly increased by nearly half and precipitation declined. Precipitation remained quite variable throughout the 13th century CE, but the dominant climatic features were mid-century cooling and high growing season length volatility. The temperature and precipitation conditions that coincided with the period of intensifying Fremont occupation, during the early and middle MCA, did not return.

To quantify and compare site resiliency of occupation, we used as an index the sum of occupied years between 850 and 1449 CE, which we term 'longevity'. This required cutting occupations older than 850 CE, the earliest modeled climate data; so we analyze fewer Fremont ($n = 23$) and non-Fremont ($n = 22$) sites here. Earlier, we noted the association between SPD decline and increasing GDD variability in time-series. Correspondingly, we expected to find that longer occupations would experience relatively lower GDD variability. This was supported by the data in figure 5, which shows that high longevity correlated with low-variability growing seasons, although this was true for Fremont sites only.

4. Discussion and conclusions

Annual proxy-based temperature anomalies for the northern hemisphere correlate with the shape of cumulative kernel density estimates of Fremont radiocarbon ages during the MCA and early LIA. Our evidence suggests a dependency between temperature, and/or temperature-associated environmental changes such as drought, and Fremont occupation, including population growth and decline, in the region of modern Utah state, in the US Southwest. To investigate the effect of high-resolution climatic changes on maize productivity, a staple crop for the Fremont, we downscaled a climate model and computed GDD for maize and mean annual precipitation for Fremont and nearby non-Fremont archaeological sites between 850 and 1449 CE, from the earliest available model-year to a point after which the Fremont were no longer a cohesive cultural complex in the region.

Using kernel density estimates of radiocarbon-derived SPDs as a proxy for population size, we found that over the period of roughly 850–1000 CE, the total Fremont population increased. According to the climate model, spatially downscaled and evaluated at the site locations, growing seasons for the Fremont were longer and less volatile, while precipitation generally declined. Paleo-hydrologic proxies agree that this period was dry with drought in the Uinta Basin (Knight *et al* 2010) and upper Colorado River watershed (Meko *et al* 2007). The balance of this population growth occurred at higher elevations, although we cannot say whether this was due to intrinsic growth or migration. The Fremont may have been drawn by local warming to migrate up the natural moisture gradient to more mesic, cooler but less temperature-variable highland sites, or perhaps they were pushed by increasingly frequent droughts. Others have suggested that periodic drought, and reduced hydroclimatic variability on the northern Colorado Plateau may have induced Fremont forager-farmers to increase their maize dependence, and consequently their overall population size (Finley *et al* 2020). Fremont upland migrations may have been exploratory, perhaps in conjunction with intrinsic population growth as a means of broadening the community resource base (Morgan *et al* 2012). Neither the Fremont nor their neighbors abandoned lower elevation sites in this period, at least where surface water remained available. The Fremont population likely peaked during the next century, ca. 1000–1100 CE. While growing seasons were conducive to maize agriculture, the hydrologic regime was especially dry and variable during this period. Although the aggregate population appears to have been at its largest, occupation intensities declined at higher elevation Fremont and nearby non-Fremont sites alike. The timing of this change in elevation is consistent with out-migration due to drought stress, as others have argued (Benson *et al* 2007b). Then sometime over the next half-century, ca. 1100–1150 CE, summed probability growth turned negative and never recovered. This suggests either depopulation of Fremont sites, or alternatively, material cultural transition to less archaeologically visible modes of subsistence. According to the climate model, this reversal coincided with the peak of a pluvial, and site occupation declined as conditions grew drier. The hydrologic regime was dry and becoming more so, growing seasons were warm and trending towards cooler conditions over time, when by 1150, interannual variability jumped by nearly 40%. These sequential changes in the prevailing climate regime, from warm to cool drought, and increased hydrologic erraticism, may have overwhelmed the capacities of the Fremont to adapt. By the middle 13th century CE, GDD declined for about a century to the greatest excursion below its mean-state of the modelled time-series, and there began a long-term trend to drought conditions and increasing hydroclimatic variability. Over the following century, temperatures warmed and stabilized, but previously occupied Fremont sites do not appear to re-colonize. Increasing precipitation erraticism in the early LIA may have been a factor.

The most resilient occupations (in the range 850–1449 CE), which were either continuously inhabited or potentially re-occupied, were sites where inter-annual growing season variability was low. Dryland maize farming in this region was never easy, and was likely not possible in all years without means to concentrate surface water runoff. On the other hand, variable precipitation can raise the risk of crop loss in the arid Southwest, particularly on stream terraces vulnerable to changes in the prevailing hydrologic regime, with high interannual variability associated with channel downcutting. Transitions from periods of terrace aggradation to downcutting are associated with abandonments of AP sites (Bryan 1941, Hall 1977). Networks of trade can increase societal resilience, at least when droughts are localized, because they distribute risk and generate opportunities for 'banking' social capital. Our study treats all sites as potentially agricultural, but this need not have been the case. In addition, there appears to have been a general uptick in warfare throughout the Southwest ca. 1000 CE, potentially due to population and resource pressure (Novak and Kollmann 2000, Lambert 2002). Fossil faunal assemblages from Fremont sites show that the most desirable game declined over time, likely as a result of population growth and hunting pressure (Janetski 1997, Badenhorst and Driver 2009). This may be reflected in defensive architecture, rock falls, and storage of surplus maize in hidden caches, or 'granaries', that appears in the late-stage occupation of Range Creek (Kloor 2007) and throughout the Fremont range. Our analysis does not preclude other factors noted from ethnographic studies of subsistence farmers and migrants; on the contrary, we expect that these mobilizations were happening in the context of evolving social relations within the Fremont occupations themselves, and among the broader AP community.

The Fremont emerged within the first few centuries of the Common Era, and were well established throughout the region by 850 CE, the earliest year simulated by the climate model. Their formative period is therefore invisible to this analysis. The middle range of our downscaled GDD values appear to be over-estimated, and the low and high ranges underestimated, as compared with modern values computed for the same locations (see SI). Likewise, we may have under-estimated mean annual precipitation for the most mesic sites. Inter-comparison with other modeled and proxy-derived spatially explicit data, when these become available, would add value and improve confidence in these findings. Furthermore, others have found positive relationships between resilience and spatial clustering of AP sites (Reese *et al* 2019), which are not readily replicated here given the relative dearth of published, well-dated Fremont sites in our data set. Finally, radiocarbon ages are affected by the so-called 'old wood problem', post-depositional diagenetic changes, and differences between lab controls and equipment over the decades during which the dates were measured. These are expected to cause lags of varying duration in the SPD time-series. The agreement we found between the shapes of the curves in figure 2 suggests that these lags were either small or systematically similar.

In summary, our results indicate that increasingly shorter and more variable growing seasons, combined with disruptions to the prevailing hydrologic regime, such as rising variability in precipitation, were coincident with the decline of Fremont populations at sites distributed over a large geographic area roughly equivalent to modern Utah. The Fremont encountered a sequence of environmental challenges as they entered the 12th century CE that were individually not without precedent, but they were novel in concert. These challenges narrowed the range of available options to the Fremont, raising the risk of local migration along the moisture gradient, on which they had relied previously. To plan for likely impacts of present and future climate change on smallholder, subsistence farmers, we require predictive models that account for complex human adaptive responses (Morton 2007, Barton *et al* 2012); and the experience of pre-European agriculture in the Southwest offers a completed experiment in similarly resourced agriculturalists' responses to climate change (Peeples *et al* 2006). However, conditions that prevailed in the Southwest during the MCA are just one possible scenario for those expected under anthropogenic global warming. There is evidence, for instance, that 21st century climate in the region may combine the heat and aridity of the MCA with the hydrological variability of the LIA (Loisel *et al* 2017). Based on the Fremont experience, this might well be the most challenging circumstance for smallholder dryland farmers. While it is important to take stock of the experiences of the past, planners should be cautious about drawing too many parallels to those of smallholder dryland farmers today. We should also not lose sight of the descendants of pre-European agriculturalists, the Zuni and Hopi among others in the Southwest, whose persistence on the very same landscape is a similarly instructive lesson for the future in the societal capacity for resilience, and potentially even transformational change.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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