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Simulated impact of paleoclimate change on Fremont Native American maize farming in Utah, 850–1449 CE, using crop and climate models

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ABSTRACT

The Fremont were members of an expansive maize-based Ancestral Puebloan (AP) cultural complex who disappeared from Utah between the 12th and 13th centuries CE. This period brackets that of a climatic transition in the Southwest from the warm, dry Medieval Climate Anomaly (MCA, ca. 850–1350 CE) to the cool, hydro-climatically variable Little Ice Age (LIA, ca. 1350–1850 CE). We simulated maize (*Zea mays*) crop productivity for Fremont AP archaeological sites in Utah between 850 and 1449 CE using a process-based crop model driven by climatologies from a statistically downscaled a climate model. We compared the model-simulated crop yields to time-series of archaeological site occupations given by spatially discrete, chronologically summed probability distributions (SPDs) of radiocarbon-dated Fremont artifacts. We found that the anomalous abandonment of different sites throughout Utah may be explained by site-specific combinations of reduced mean yield due to volatile year-to-year yields caused by increasing temperature variability, increasing hydro-climatic variability, and loss of soil quality, which depended on crop management strategy. In other words, we model the elimination of the Fremont AP ecological niche by exogenous influences of temperature and precipitation variability at the MCA-LIA transition and endogenous degradation of soil from organic carbon and nitrogen loss. Our method has broad applicability to contexts of low-technology, dryland farming human-environmental interactions.

1. Introduction

Ancestral Puebloans (APs) were members of an expansive cultural complex of Native American maize-farmers who once occupied large swaths of the southwestern United States (hereafter, the Southwest), as well as northern Mexico. APs built some of the largest and most architecturally complex structures north of Mexico, leaving behind ruins which have inspired theories of "civilizational collapse" for nearly a century. Ever since Douglass (Douglass, 1929, 1935) explained their disappearance in terms of a "great drouth" [sic.] found in patterns of ancient tree rings dated 1276–1299 CE (674-651 cal BP), the question of the AP "collapse" has been hotly debated (Diamond, 2005; McAnany and Yoffee, 2010; J. Tainter, 1988; J. A. Tainter, 2006). Changes in AP populations and occupation sites scattered throughout the Southwest resist simple, mechanistic explanations (Allison, 1996). Yet the period ~1150–1350 CE (800-600 cal BP) coincided with reduced mean annual temperatures throughout the northern hemisphere (Cook et al., 2004; Mann et al., 1998; Woodhouse et al., 2010a,b) as well as the onset of significant changes in hydro-geographic conditions, such as greater interannual variability of precipitation (Loisel et al., 2017). Coeval paleoenvironmental changes occurred throughout the Southwest, although at anomalously different rates at sites with apparently similar environmental characteristics. Changes to prevailing paleoenvironmental conditions bear on rational economic choices that emerge from the coupled influence of social, environmental, and climatic stressors (Benson and Berry, 2009; Bocinsky et al., 2016; Kohler et al., 2000). Because of the importance of maize (*Zea mays*) to AP culture and diet, researchers have sought to estimate maize productivity using proxies of paleoenvironmental change (Burns, 1983; Kohler et al., 2012; Van West, 1994). One challenging aspect of developing models of productivity in the places that AP growers lived is to generate paleoclimatology fields over the range of spatiotemporal geographies they occupied (Bocinsky and

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Kohler, 2014); another is understanding how AP maize landraces grew (Bocinsky and Varien, 2017). We contribute to this line of research by directly evaluating the impacts of ancient climate change in Utah on AP maize yield using a process-based crop model driven by climatology field dailies from a statistically downscaled climate model.

Native Americans known as the Fremont were APs who inhabited roughly within the bounds of modern Utah, between ∼400 and 1350 CE. The Fremont were so named after an archaeological survey along the Fremont River catchment in southern Utah found sites that were initially believed to a distinct culture on the AP periphery (Morss, 1931). The Fremont practiced a variety of subsistence strategies in the canyons and valleys at of the high Colorado Plateau and the alluvial flats of the Great Basin. However, their diets were more or less based upon a suite of staple crops including legumes (*Phaseolus* spp.), gourds (*Cucurbita* spp.), and maize, the production and consumption of which is a defining feature of their material culture (Ford, 1981; Jennings, 1978). They likely raised a variety of maize landraces, including one called "Fremont dent [corn]" known only in Utah (Cutler, 2001). They relied on maize for a majority of their caloric needs (Coltrain, 1993; Coltrain et al., 2007; Coltrain and Leavitt, 2002; Ugan and Coltrain, 2012). Yet the Fremont also adapted their diets to suit their immediate circumstances, foraging for wild foods such as the seeds of two-leaf (*Pinus edulis*) and single-leaf piñons (*P. monophylla*), the rhizomes of bulrush (*Typha* spp.), fishing and hunting of deer, rodents, and fowl (Madsen and Simms, 1998; Marwitt, 1973; Simms, 1986), They likely did not expect to produce maize crops every year, relying instead on storage of foodstuffs in granaries, mobility, and possibly networks of trade (Hockett and Morgenstein, 2003; Janetski, 2002), strategies which promote resilience in the face of local crop failures (Hegmon et al., 2008; Kohler et al., 2012; Kohler and Van West, 1996).

The Fremont occupied canyon and wash tributaries of major rivers of the Colorado Plateau (CP), and valleys of the eastern Great Basin (GB) piedmont, which runs along a roughly southwest to northeast diagonal across Utah (see Fig. 1). Highland Fremont sites are clustered by elevation between 1700 and 1850 m, approximately within the modern band of mixed piñon-juniper forest that characterizes Utah's montane (Kelly, 1997). Lindsay (1986) noted this correspondence with pine distribution and proposed that AP occupants struck a balance between frost-free days and aridity, as the landscape becomes increasingly warm and xeric with descent to lower elevations. Anecdotal evidence of widespread destruction of archaeological sites by 19th century pioneer settlers (Wheeler et al., 1875), whose descendants now occupy the prime agricultural land, suggests that large quantities (perhaps the majority) of archaeological data have been destroyed, or remain publicly unknown on private land. Range Creek, which has been called the most pristine large archaeological site in the United States, reveals a story of Fremont occupation which fits the most widespread narrative of AP decline on the Colorado Plateau: the Range Creek Fremont cropped alluvial terraces along the upper reach of the canyon, ∼950–1150 CE; into the 1100s, they began occupying defensible positions on high rock outcrops, and building maize-cob storage granaries camouflaged and set almost inaccessibly into the faces of the canyon walls.

Proxy-based reconstructions and downscaling techniques of climate are valuable tools for scholars of ancient agro-ecological systems (Contreras et al., 2018). Many others have linked AP occupation patterns elsewhere in the Southwest to reconstructed drought (West and Dean, 2000), hydroclimatic variability (Bocinsky and Kohler, 2014), and environmental changes imposing constraints on socioeconomic organization (Axtell et al., 2002; Kohler et al., 2012, 2000; Kohler and Van West, 1996). Fremont occupation changes may, of course, have been partly due to other factors not captured in our simulations, such as technology transfer, innovation, and trade. The long history of Ancestral Puebloans in Southwest is complex and intersectional; but the synchronous transition to different modes of subsistence of all or most

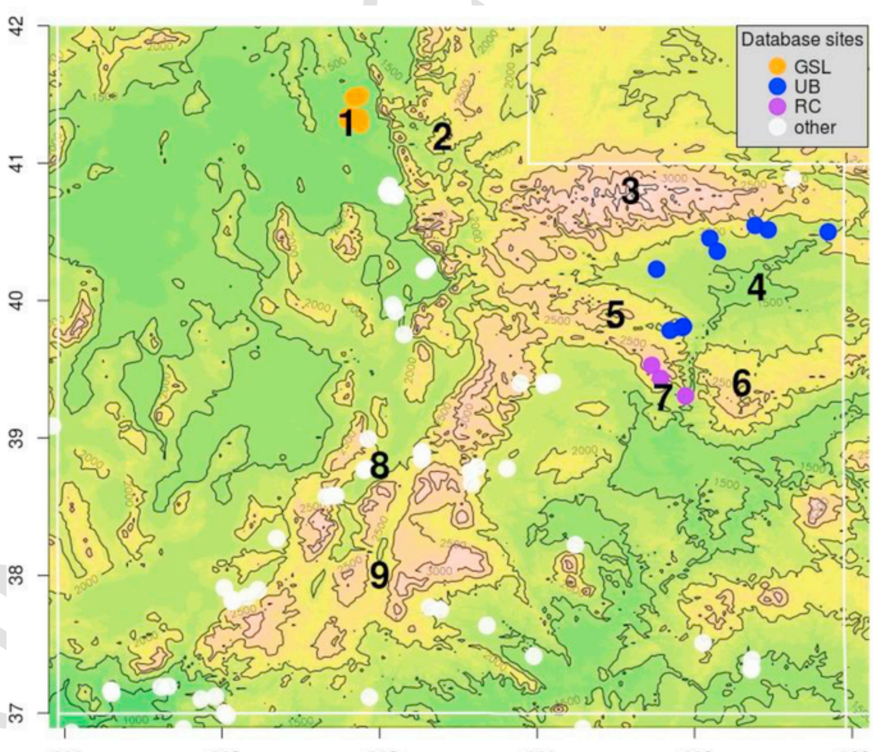

Fig. 1. Study area with shaded topography. The locations of Fremont sites in our database are marked. Notable features discussed in this paper include: (1) the Great Salt Lake (GSL) subregion; (2) the Wasatch Range; (3) the Uinta Mountains; (4) the Uinta Basin (UB) subregion; the (5) western and (6) eastern segments of the Tavaputs Plateau; (7) the Range Creek (RC) subregion; (8) the Sevier River Valley; and (9) the Markagunt Plateau. Modern state political boundaries are shown in white. Elevation contours show 500 meter intervals asl. Data: PRISM Climate Group (2004).

APs over the entire region between ~1150 and 1350 CE, the MCA-LIA transition, implies a regional change from previous environmental conditions through which APs thrived. For this study, we used a statistically downscaled climate model to drive a model for maize crop productivity between 850 and 1449 CE, and compared maize yield and yield variability to archaeological site occupation intensities given by radiocarbon data.

We argue that the abandonment of Fremont occupation of sites in Utah resulted from a combination of (1) changes in the prevailing temperature and precipitation annual mean and variability from ~1150 CE through the MCA-LIA transition, and (2) anthropogenic soil nutrient degradation. The importance of either of the combined factors differed between sites, with the climatic component particularly strong for Colorado Plateau sites. This is because longer growing seasons during the early MCA opened higher elevation sites to exploitation for subsistence foraging and the farming of maize. A significant excursion to cooler mean annual temperatures shortened growing seasons, in particular on the Colorado Plateau (see Fig. 2), coincident with profound drought (Benson and Berry, 2009; Woodhouse et al., 2010a,b), compelled the change.

Maize is difficult to grow in Utah in the absence of extensive irrigation infrastructure, even for farmers during the historical period who had access to draft animals and ploughs. In 2017 with the benefits of dynamically controlled irrigation, pesticides, fertilizer, highly specialized hybrid maize varieties, and weather monitoring, the average Utah farmer produced some 9 tonnes of maize for feed and grain per hectare. In 1940, with mechanization and some water control, farmers produced fewer than 2 tonnes/ha; but in the 19th century, less than 1 tonne/ha was produced (see table and figure in SI). Except for abnormally wet years, Utah was considered marginal for maize cropping (Harris et al., 1920; Walker, 1883; Wenda and Hanks, 1981). Moreover, Fremont irrigation was rudimentary, likely not more than rough channels and weirs to redirect low-energy water flows (Boomgarden, 2015; Metcalfe and Larrabee, 1985; Simms, 2016). Benson (2011) gives a detailed review of the physical and chemical barriers to maize production in the Southwest, as well as Puebloan Native American maize farming practices which likely follow, at least in part, from their AP forebears.

The period of most intense Fremont occupation (ca. 1000–1100 CE) occurred when the Northern Hemisphere was warmer than the millennial average by about 0.5 °C (Christiansen and Ljungqvist, 2012; Mann et al., 1998, 2009; Moberg et al., 2005). Because changes in the Medieval-era climate of the Southwest are understood more by hydrographic drought than by temperature, the term Medieval Climate Anomaly (MCA, ~850–1350 CE) is used here to describe this period after Stine (1994), who noted its coincidence with extraordinary drought events. Perhaps the long-term focus on the role of the warm MCA and drought is why relatively few scholars have noted the correspondence between denudation of the AP occupation and the onset of the cooler and wetter, and more hydroclimatologically more variable, "Little Ice Age" (LIA; ~1350–1850 CE). A drop in mean annual temperature at the MCA-LIA transition was more keenly felt on the highland, northern Colorado Plateau, where many Fremont lived, than in the warm, dry Great Basin (Salzer et al., 2014; Salzer and Kipfmueller, 2005).

Over the past ~2000 years, drought conditions have been an episodically marked feature of the Southwest (Asmerom et al., 2013; MacDonald, 2010; Stine, 1994; Woodhouse et al., 2010a,b). The most severe droughts on record are linked to years in which low winter precipitation was followed by a weak North American Monsoon system, NAMS (Griffin et al., 2013). The MCA coincided with a period of exceptionally quiescent volcanism and a natural uptick in solar irradiance (Bradley et al., 2016), and cooling in the eastern Pacific Ocean

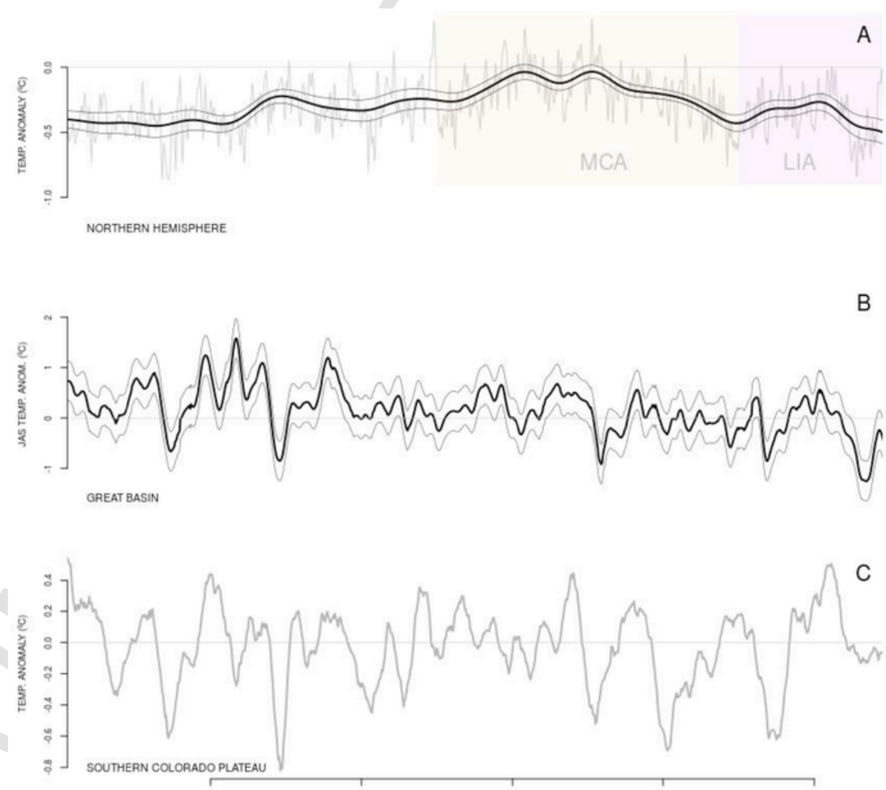

Fig. 2. Tree-ring-based paleotemperature reconstructions for: (A) the Northern Hemisphere from Moberg et al. (2005), with MCA (850–1350) and LIA (1350–1850) emphasized; (B) the Great Basin from Salzer et al. (2014); and (C) Navajo Mountain and Canyon de Chelly on the southern Colorado Plateau in northern Arizona from Salzer and Kipfmueller (2005). Broad lines in (A) are low-frequency trends from Moberg et al. (2005), and in (B) are 21-year rolling means. Narrow lines in (A) and (B) are 2-sigma confidence intervals.

(MacDonald Glen et al., 2008), forcing mechanisms which likely contributed to its relatively high drought frequency (Ault et al., 2017; S. E. Metcalfe et al., 2015). The Sierra Nevada on the western edge of the Great Basin, was warm during the MCA, with a thermal maximum 1150–1169 CE (Graumlich, 1993). The Great Basin temperatures were consistently equal to or warmer than the millennial average over the MCA (Reinemann et al., 2014; Salzer et al., 2014). Temperatures over the Colorado Plateau (Fig. 2) were likewise greater during the MCA but relatively more volatile (Salzer and Kipfmueller, 2005).

2. Regional setting

The geographic variations in climate in Utah has much to do with its complex topography. Utah is diagonally bisected by the union of the Great Basin and the Colorado Plateau, whose edge is a spectacular edifice of montane plateaus, riven with canyons and divided by valleys that access the high interior of the American continent. In the desert Great Basin, summer (or "hot season") temperature highs routinely above 35 °C and lows below −8 °C, with respective diurnal ranges of about 18.2 °C and 16 °C (PRISM Climate Group, 2004). Elevation has a moderating effect on hot season temperatures, which tend to be about 15 °C cooler and 4 °C less variable than in the desert below, where diurnal fluctuations are large. Winters (cold seasons) can be bitterly frigid even in the basins, with significant snow accumulation at high elevation. Cold-season precipitation is the major contributor to average precipitation of about 50 mm or more above 2100 m in elevation (PRISM Climate Group, 2004). Highland forests of the northern Colorado Plateau depend on winter westerlies driving moisture in from the Pacific, most of which overshoots the Great Basin and rains out over the Wasatch and Uinta Mountains. The accumulation of winter snowpack over the Colorado Plateau for is critical for Utah's perennial streams, as these transport water into its Great Basin population centers around the Great Salt and Utah Lakes, and the stream valleys on the western side of the Wasatch Range. A small but important source of hot-season precipitation over southern Utah is due to the NAMS, an exclusively late-summer phenomenon arising from the south (Adams and Comrie, 1997; Higgins et al., 1997; Jones et al., 2015; Metcalfe et al., 2015). The Colorado Plateau is interlaced with canyon systems, most of which drain into the Colorado River and its tributaries. With descent to lower elevations canyon temperatures generally increase, but display highly variable soil and microclimatic differences over short geographic distances (Burnett Benjamin et al., 2008; Ronan et al., 1998). Whereas the intermountain plateaus are sufficiently mesic for mixed pine-fir forests, wetland meadows, ponds and small lakes above 1700 m asl, the vegetation of canyon systems varies from desert-type shrub and herb dominated vegetation to sages to cottonwoods in mesic refugia with perennial streams or ephemeral surface water. The limit of the NAMS is presently about 39°N latitude; however, the topography of the Colorado Plateau and its orientation continue to wring moisture from the atmosphere at high elevation, adding a critical summer pulse to annual precipitation north of central Utah. Entering the MCA-LIA transition, the geographic scale and strength of the NAMS may have been enhanced (Miller et al., 2010), raising the risk of flash floods in low-lying or constrained canyon environments. In addition, winter precipitation over the intermountain Southwest can contribute to a negative feedback, reducing the strength of the NAMS during the following season (Griffin et al., 2013; Lo and Clark, 2002).

3. Materials and methods

3.1. Production of occupation time-series

Fremont occupations were represented by summed probability distributions (SPD) Fremont-associated radiocarbon dated artifacts collected from 107 distinct locations, directly or by context with maize farming (see SI for dataset). Raw radiocarbon ages and uncertainties were batch-calibrated (1-sigma) using the *Bchron* package for R (Parnell, 2018) according to the *Intcal13* calibration curve for Northern Hemisphere terrestrial radiocarbon ages (Reimer et al., 2013). This resulted in a series of density weightings for the range of each calibrated radiocarbon date; that is, the probability density distribution (PD) for each location is normalized such that for each individual calibrated date, the PD sums to unity. PDs for all calibrated dates were superposed and summed for all years within the range.

For each individual artifact at a location x_i there is an associated probability distribution summation normalized to unity, viz.

$$\sum_{t=0}^{\tau} P(x_i, t) = 1,$$

The value $P(x_i, t)$, hereafter labelled as P_t^i for brevity, is the probability that the artifact's real age is t. Ideally, each site occupation x_i will be evidenced by the presence of multiple artifacts. Holding t constant, we sum the values of P_t^i for all artifacts at the same site to produce a summed probability, SP_t^i, which we take as some function of the relative likelihood of occupation of location x_i at time t, viz.

$$SP_t^i = \sum_{i=1}^{N} P_t^i,$$

for N sites at the same location. The summed probability distribution for each site, SPD_i, is given by the sum of the summed probability over time,

$$SPD_t^i = \sum_{i=1}^{\tau} SP_t^i,$$

which is normalized to unity.

If SPDs are to be reasonable proxies for occupation intensity, a threshold for occupation settlement and abandonment must be determined, as SPD functions themselves may be non-zero for the entire period of our analysis. We estimated the fraction of each site's occupation time-series over which the SPD is significant; in other words, the time-series which are subtended by 95% (2-σ; or 68.4%, 1-σ) of the total integral of each site's SPD. Our algorithm finds the maximum value of each site's SPD and its associated year, and performs a Riemann sum of subsequent SPD maxima, keeping track of their associated years, until the desired proportion of the total integral of each site's SPD is reached. We indicate data treated thus as $SPD_{2\sigma}$ and $SPD_{1\sigma}$ for 95% and 68.4% confidence interval estimates, respectively.

Finally, we were missing several pieces of information from the Range Creek sites. As a result, we treated the data differently and did not include it in the aggregated analyses shown previously. We did not have non-calibrated ("raw") radiocarbon ages for the 21 direct maize dates from Range Creek; so we estimated SPDs for each as normally distributed probability distribution functions whose means and standard deviations were given by the calibrated ages.

3.2. Statistical downscaling and maize crop simulations

The Community Earth System Model (CESM) is a fully coupled land-sea-atmosphere general circulation model (GCM) with hind-casted climatologies for the pre-Industrial (850–1849 CE) and Industrial (1850–2005 CE) periods for the Last Millennium Ensemble experiment (Otto-Bliesner et al., 2015). We followed a two-stage procedure to statistically downscale, bias correction and spatial disaggregation (Wood et al., 2004). Bias-correction (BC) of CESM dailies of total precipitation and reference height temperature was performed by quantile mapping with the gridded precipitation and temperature fields from the NCEP-

DOE Reanalysis 2 dataset (Kanamitsu et al., 2002). Spot-checking found bias-corrected precipitation and temperature dailies to be in good agreement with station-based observations over the modern instrumental record. For the spatial disaggregation (SD) of the GCM temperature field, we interpolated the bias-corrected reference-height (2 m) surface temperature maximum (TREFHTMAX) and minimum (TREFHTMIN) fields and summed these with the residuals (see SI) of daily climatologies from the Parameter elevation Regression on Independent Slopes (PRISM) model, a semi-empirical gridded interpolation of station-based climate data (PRISM Climate Group, 2004). For precipitation, we aggregated PRISM precipitation dailies to CESM-spatial scale and associated the patterns between BC CESM and aggregated PRISM dailies by Pearson correlation. If the correlation test failed, which occurs on very low precipitation days, root mean-squared error (RMSE) was used. Aggregated PRISM dailies are ranked and the highest ranked PRISM daily (i.e., that which most closely resembles the distribution of precipitation from CESM) is substituted for its aggregate. This method downscales the frequency and spatial distribution of precipitation predicted by CESM, but it does not rescale the magnitude.

For maize yield estimates, we used the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989). EPIC is a biophysical crop growth model that we adapted with Southwest Native American maize farming parameters and environment files driven by downscaled daily temperature maxima and minima, total precipitation and shortwave radiation from CESM, and with annual atmospheric CO_2 concentration from the Law Dome Greenland ice core record (MacFarling Meure et al., 2006). Because of the uncertainty in growth characteristics of AP maize, and planting practices of Fremont horticulturalists (Benson, 2011), we ran seven different crop management strategies (see Supplementary Table S1), under 16 different planting and soil nitrogen enrichment condition-sets (see Supplementary Table S2), each for the first and second highest productivity soils near each site. The management strategies (i.e., 4 intercropping strategies with maize and beans, 2 mono-cropping strategies with maize only, and a maize-and-fallowing cycle to approximate the Mesoamerican milpa system) were selected to represent a wide range of potential Fremont rotation methods. Yield estimates corresponded to a recovery of 25% of the simulated aboveground biomass grown per season. Yields for all sites, strategies, and conditional-cases were repeated for ten iterations, with the sequence order permuted by one simulation-year each time, and the results averaged. (See SI for link to EPIC simulation data; and although we also produced bean yields, we do not report them here.) EPIC uses precipitation dailies, and then computes runoff and daily infiltration, runoff and subsurface flows to quantify water available to biomass growth. Since real watering intensity and schedule was unknown, we set the model up to compute a range between “dry” rain-fed (RFD) and “wet” irrigated (IRR) cases. In the “dry” case, once EPIC uses up the root-zone available water, it ceases to grow any more that day regardless of temperature or light conditions. In the “wet” case, EPIC adds water to the simulation once available water is used up, until the annual water budget is spent. In other words, the “wet” simulations allowed us to imitate small reservoir of cold-season water (partially accounting for runoff due to snowmelt), canyon soil-moisture storage, or anthropogenic crop watering. Thus, they are likely a better representation of growing conditions overall than the “dry” simulations.

Further, EPIC soil characteristics are based on a gridded soil map based on the Harmonized World Soil Database (Nachtergaele et al., 2008) with up to 20 soil types, given by percentage per 30 arc seconds of spatial coverage in the study area. We did not have data on precisely which soils the Fremont were tilling. We proceeded on the assumption that the Fremont favored the most productive soils, but since we could not locate these precisely to confirm that they could be practicably farmed for maize, the simulation results were computed for all soil types for each location, we simulated yields for all soil types and derived our results as a weighted mean of these. Start-years for EPIC runs were determined algorithmically, as the lowest calendar year value of the $SPD_{2\sigma}$ or, 850 CE if the calendar year value was less than the earliest CESM calendar year (i.e., 850 CE). Our setup of iteration sequences for occupation start-years of 850 CE actually started some simulations prior to 850 CE. For these cases, a further 3650 days (i.e., 840–849 CE) were added to the start of the climatology sequence by resampling same-day temperature and precipitation from the 850–949 CE reconstruction (see Fig. 3).

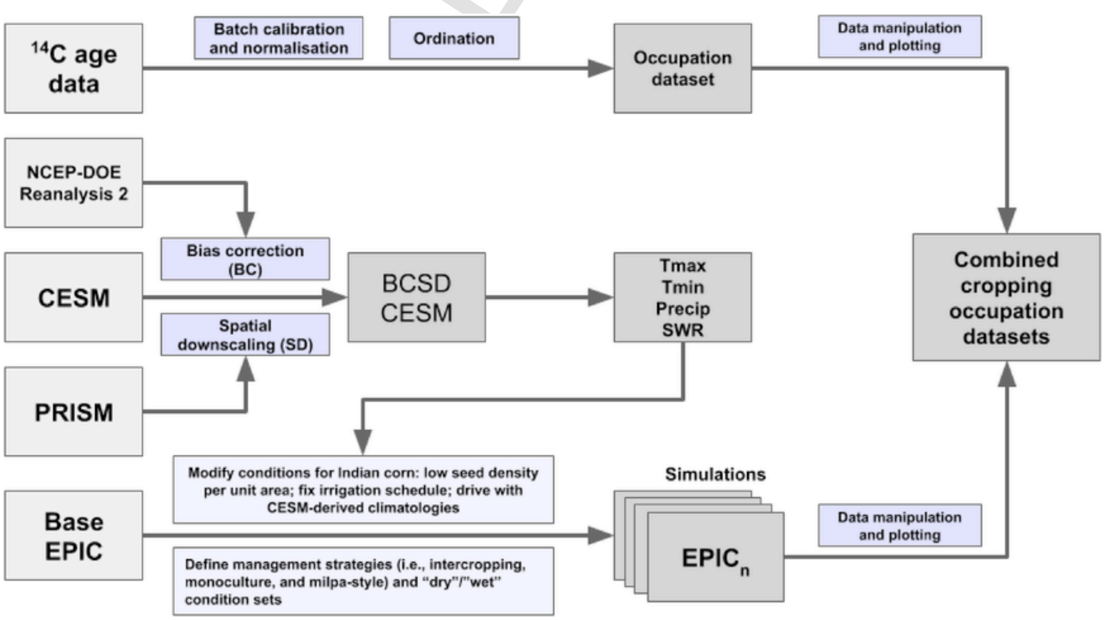

Fig. 3. Workflow schematic showing the relationships between datasets (left hand side, light grey background) and the products we generated (dark grey background). EPIC simulations subscripted by *n* indicate runs for which conditions were modified, such as by different crop rotation strategies. Intermediate text boxes (violet background) indicate scripting steps in R and, for EPIC, Microsoft Access. (For growing season lengths, see SI.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Yield curves and correspondence testing with SPDs

Our procedure generated combined cropping-occupation datasets (see SI for examples); i.e., crop yield curves and summed probability distributions (SPDs) for each Fremont site (excluding Range Creek, for reasons stated above). We noticed common (but not universal) features among our simulation results: most of the simulated yields declined over time; and many of the SPDs had topologies that coincided with features seen in the crop yield, and particularly yield variability, curves. We carried out several tests to quantify yield changes and yield-SPD correspondence, two of which appear in section 4.0 (see SI for additional tests).

First, we compared the cumulative maize yield over the first century (years 1–100) of occupation to that over the second century (years 101–200), and computed the percent difference. We computed cumulative maize yields as the sum of the ensemble mean maize yield for each management strategy, beginning with the $SPD_{2\sigma}$ start-time (or 850 CE, if the occupation onset predated the simulation start-time). These data show the potential change in crop productivity for the various management strategies over a 200-year occupation period.

Next, we determined Spearman's rank correlation coefficient (ρ) within a 75-year rolling subset of the time series shared by a site's yield curve and SPD. The test indicated whether 75-year subsets of both series were moving concordantly or divergently. The purpose of this test was to determine at what point in the time series they grew more or less coupled. We hypothesized that, if food stress caused population pressure, the coupling between the yield and SPD curves would be strongest during the latter part of the occupation; that is, if population size was inhibited by lack of available maize, ρ would increase in time. Through ad hoc testing of the stability of ρ for different window sizes and time series (i.e., "ρ-series"), we determined to use hard cut-off dates for each subregion based on the number of SPDs available, as we found that these led to spurious results based on too few SPDs. We generated fourteen ρ-series for each site (i.e., one for each of seven management strategies for both "dry" and "wet" conditions) within each subregion. We treated the dozens of ρ-series as ensembles for each subregion and used an ensemble mean for each management strategy to produce linear trend lines. These data suggest the relative importance of mean yield or yield volatility to SPD, and indicate points of departure (i.e., "coupling" and "uncoupling") in the time-series.

4. Results

We found that, in general, maize yields (maxima $\lesssim$1 tonne/ha for GSL and the best RC sites; $\lesssim$0.3 t/ha for the UB sites) were modest by modern standards, but in good agreement with the earliest recorded yields for Utah (~1–2 t/ha; see SI) and that measured in experimental field trials of Native American maize (Bocinsky and Varien, 2017). Relatively low yields followed from a variety of conditions in the simulations, such as aridity, poor soil nutrient profile, and occasionally low temperatures. Areas that were sufficiently warm for maize growth tended to be too dry for good crops; and sufficiently mesic areas tended to suffer short growing seasons. Initial maize yields were suppressed by competition with beans when intercropping in the same year, but planting beans in alternate years slowed the rate of interannual yield decline as a result of root-zone nitrogen fixation. Yields declined most rapidly for maize-only regimes in well-watered areas due to a combination of high initial yields stripping nitrogen and phosphorus from soils, and the leaching nutrients from the root-zone without replenishment. Burning of unharvested biomass was a poor strategy in our simulation, as it increased the rate of interannual yield decline. Low SPD values corresponded to periods of high yield variability, suggesting that Fremont occupations were sensitive to variable climatic conditions. We report detailed results by subregions that represent different environments across the northern Fremont range. Except for Fig. 8 for Range Creek, all plots in this section were generated from "wet" simulation data. See SI for the corresponding "dry" simulation plots.

4.1. Subregions

4.1.1. Great Salt Lake (GSL)

In the Great Salt Lake (GSL) littoral, there is little topographic relief on the floodplain, but, unlike many of the canyon sites, there is year-round stream water access; and temperatures tend to be mild, with ample time during the growing season to produce Fremont maize. Fig. 4 shows the mean yield, in tonnes per hectare, for GSL Fremont sites. Mean productivity strongly depends on management strategy; the cumulative choices of crop spacing; seed-planting depth; nitrogen fertilization; and the schedule of seeding and letting plots fallow (see SI for management strategy details). For the GSL Fremont, the IC2, IC4, MC1, and MC2 cropping strategies produce ~1 t/ha of maize over the first few seasons; but IC2 and MC4 rapidly decline (among the most rapidly of any we simulated in Utah). The volatility of the yield was represented by 21-year rolling standard deviation of the ensemble mean yield. We found a remarkable correspondence between the yield volatility and the shape of SPDs at many sites throughout Utah, as can be seen for the GSL sites in the bottom panels of Fig. 4; and we therefore analyzed the geometric correspondence of the yield, yield volatility, and SPD curves (see Figs. 10 and 11, and also Figs. S8 and S9 in SI).

The cumulative costs of interannual declines in maize productivity are illustrated in Fig. 5, which overlays histograms of cumulative yield (tonnes of maize harvested from one hectare on average over a century) for the first century of maize agriculture by that of the subsequent century of maize agriculture over all GSL sites, and gives the associated percent change in cumulative yield. Here the relative superiority of the IC2 and MC2 strategies, which produce relatively high, sustainable cumulate yields over time, are clear.

4.1.2. Uinta Basin (UB)

The UB Fremont were among the first to abandon the region (or the subsistence practices that previously defined them). As a result, the SPDs for UB Fremont sites peak and begin to decline prior to 850 CE, the start-year for our simulations. They were also among those whose local environments were most susceptible to change during the MCA and transition to LIA conditions. Rain fed ("dry") simulation yields were very poor in general (see SI). But the MCA brought, on average, longer growing seasons to highland Utah. This is clear from the jump in maize productivity ~990–1000 CE in Fig. 6: we simulated modest "wet" mean yields of up to 0.34 ± 0.06 t/ha, averaged over the years 1001–1100 CE, up from 0.27 ± 0.06 t/ha averaged over 901–1000 CE. However, it is also clear from Fig. 6 that in spite of higher simulated yield for all management strategies (see Fig. 7), the SPD declines. Recall that general occupation decline in the UB was underway by this time, and lower overall occupation densities were sustained even during the period of bumper crops. Interestingly, longer mean annual growing season also coincided with greater interannual volatility; and that volatility increased by ~20% over the first several decades of the simulation, preceding the first drop in SPD as well as the sustained subsequent low SPD. In addition, among subregions we analyzed, the UB Fremont sites began as highly coupled to yield (Fig. 10) and yield volatility (Fig. 11) .

4.1.3. Range Creek (RC)

As with other sites situated within canyons on the Colorado Plateau, higher elevation correlates strongly with increasingly mesic conditions. We did not have precise provenience information for dated

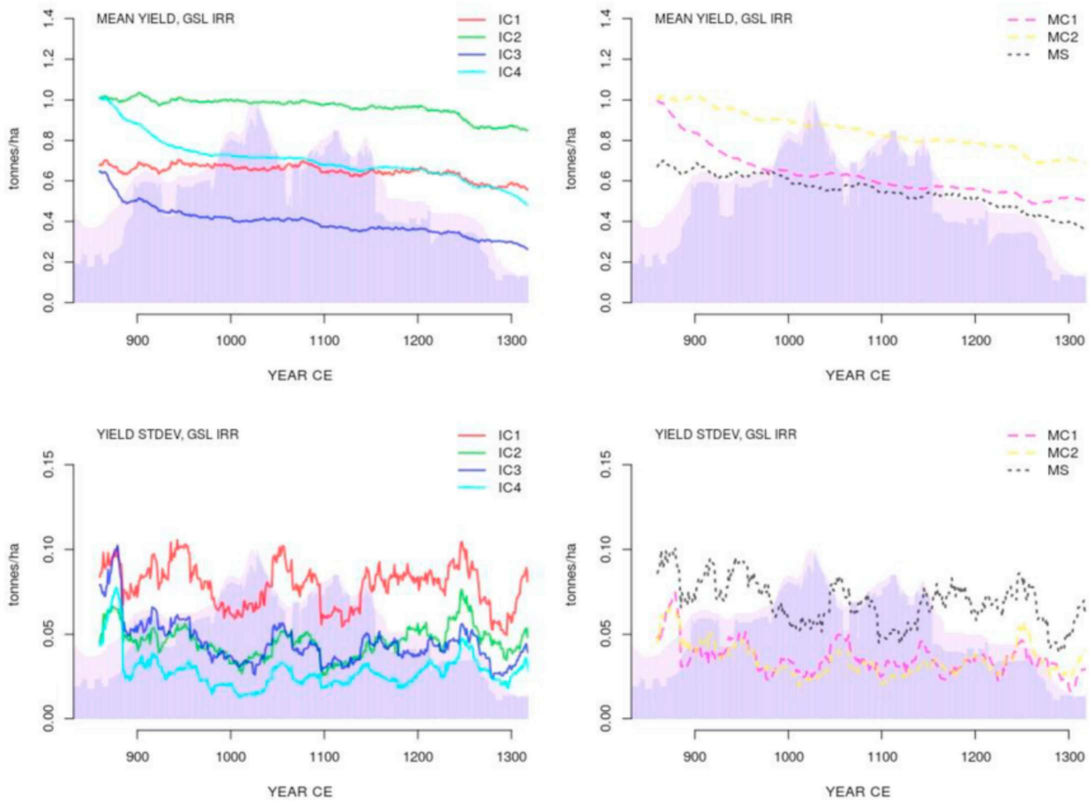

Fig. 4. Combined cropping-occupation plot for GSL Fremont. Mean yield and 21-yr rolling standard deviation ("volatility") of yield from all "wet" simulations in the ensemble for seven management strategies, averaged over all GSL sites. Yield curves overly cumulative $SPD_{1\sigma}$ and $SPD_{2\sigma}$ for all GSL sites, which are arbitrarily rescaled for the purposes of comparison.

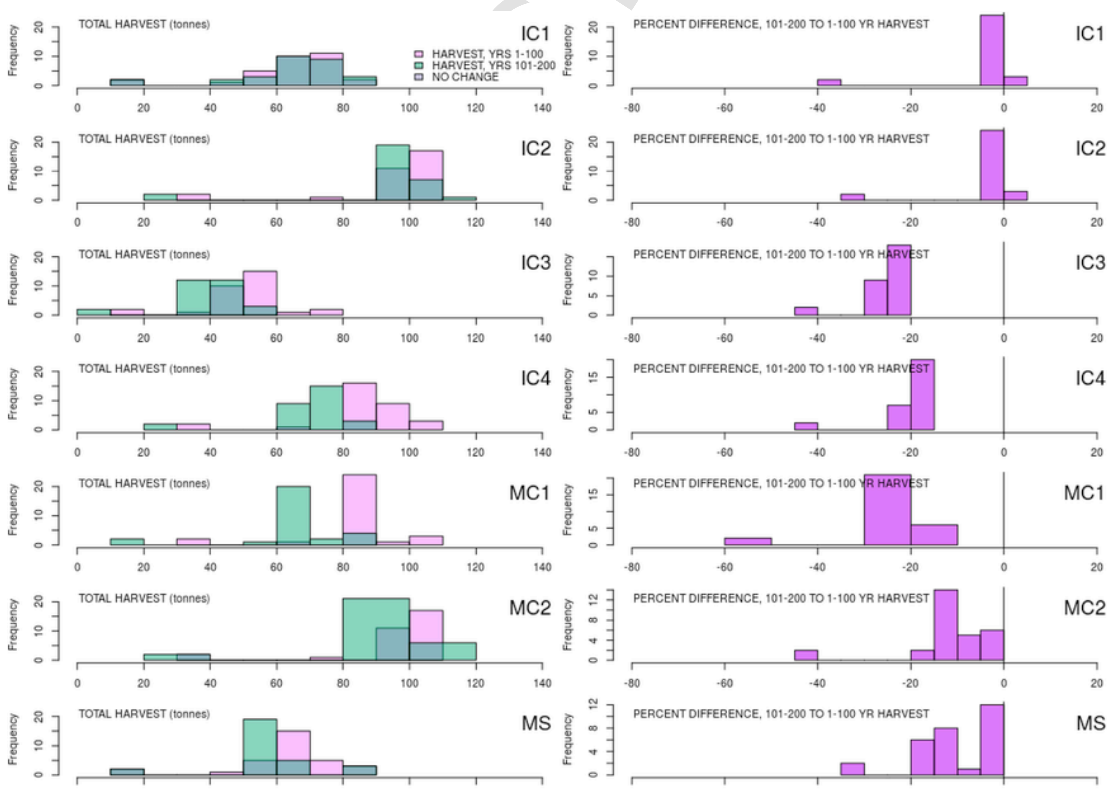

Fig. 5. Irrigated consecutive centennial harvests, GSL Fremont sites. Comparison of average irrigated ("wet") 100-year harvest return rates for the first and second centuries of potential farming, with percent differences for each strategy given in the neighbouring column.

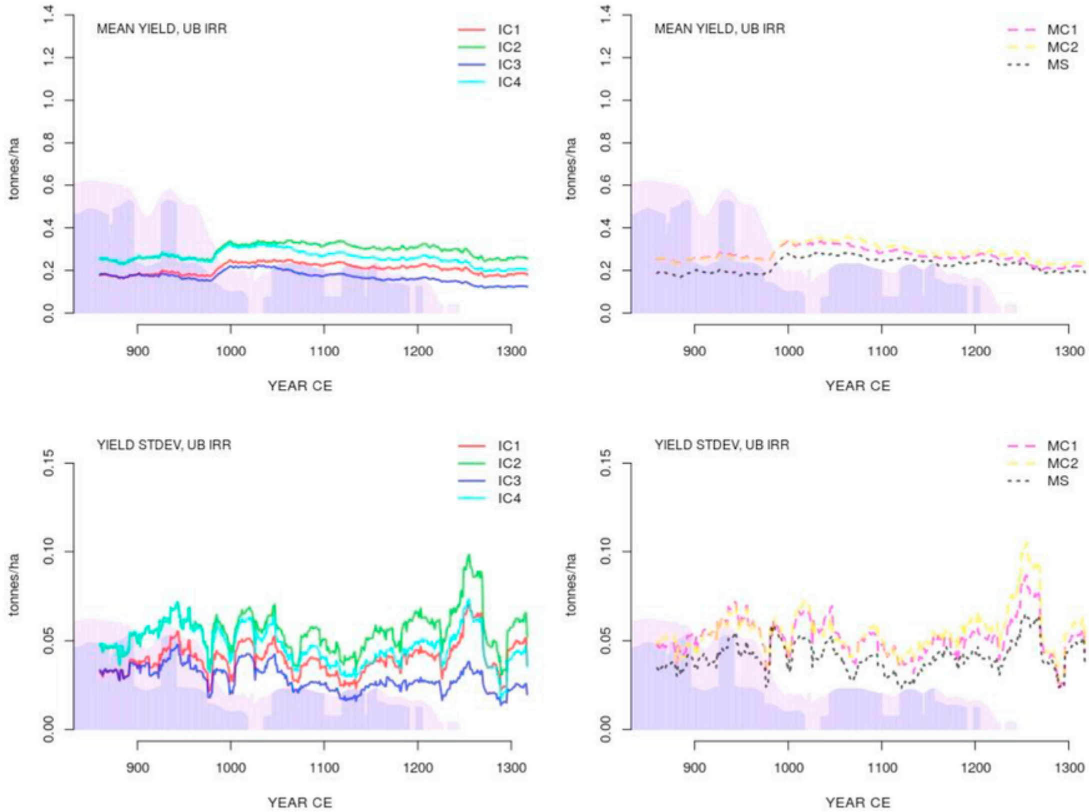

Fig. 6. Combined cropping-occupation plot for UB Fremont, IRR. Mean yield and 21-yr rolling standard deviation ("volatility") of yield from all "wet" simulations in the ensemble for seven management strategies, averaged over all UB sites. Yield curves overly cumulative $SPD_{1\sigma}$ and $SPD_{2\sigma}$ for all UB sites, which are arbitrarily rescaled for the purposes of comparison.

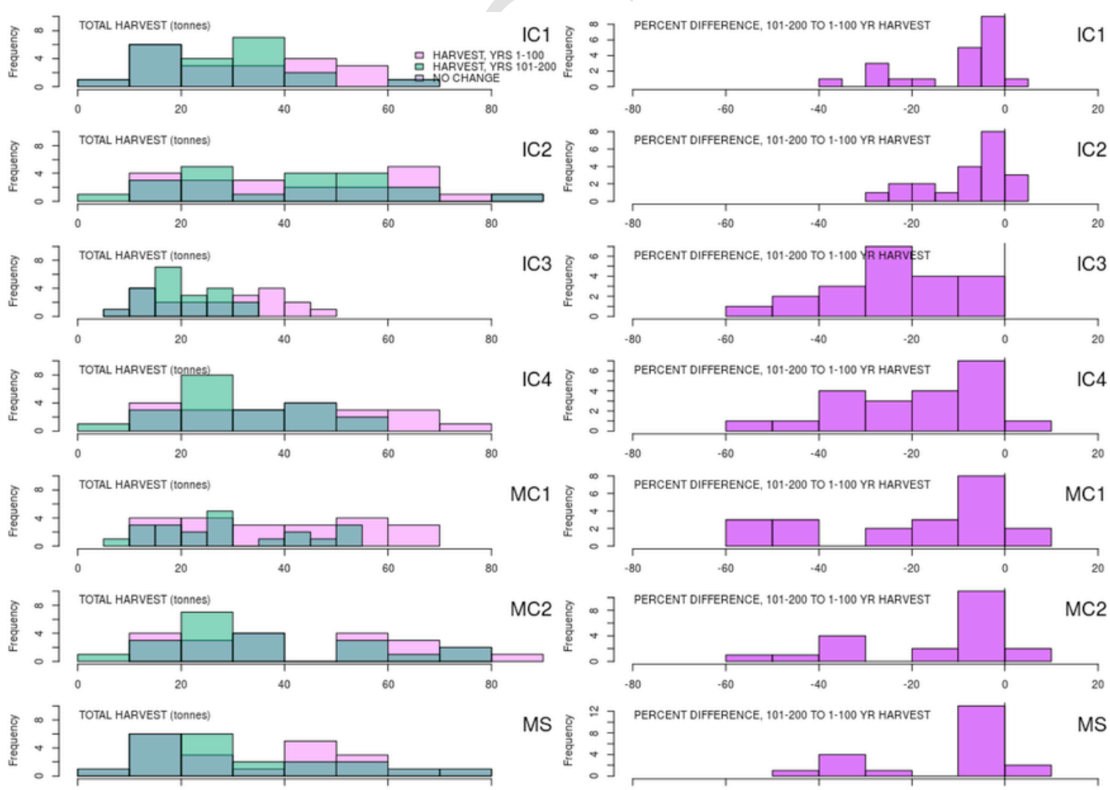

Fig. 7. Consecutive centennial harvests, UB Fremont sites, IRR. Comparison of average irrigated ("wet") 100-year harvest return rates for the first and second centuries of potential farming, with percent differences for each strategy given in the neighbouring column.

RC Fremont artifacts from to make our own determination, but archaeologists have previously stated that they observe an early to late-occupation progression of high to low elevation, or more mesic to more xeric, sites in Range Creek (Boomgarden, 2015). However, evidence of increased flood frequency in the late-stage RC occupation suggests that relocating to lower elevation occupation sites would carry increased flood risk (Rittenour et al., 2015). We have included our "dry" simulation output and SPD for the upper RC site (Fig. 8) to show the performance of the model under restricted hydro-climatology.

Lacking precise radiocarbon date provenience data, we selected three sites from a transect along the RC reach to capture different hydro-climatic zones. Since we only compare the cumulative mean yield of the upper-elevation site to itself for subsequent centuries, the data for both "dry" and "wet" simulations is presented as paired bar graphs in Fig. 9.

4.2. Correspondence testing

We used a moving-window Spearman rank correlation test, reasoning that the rank coefficient (ρ) would increase positively as the simulated yield and SPD became more tightly coupled. That is, we tested the constraint of maize productivity on occupation through the hypotheses that the goodness-of-fit of the yield, or yield volatility, curves to their associated SPD will improve over the time-series. Ensemble means of rank correlation tests of mean yield to all SPDs in each of the GSL, UB, and RC subregions from "wet" simulations is shown in Fig. 10; and for yield volatility in Fig. 11. We found yield-SPD coupling increased for all management strategies across all subregions examined; but the combined cropping-occupation plots from Fig. 11 in particular, showed strong negative correlation between yield volatility and SPDs. This suggests that populations grew during periods of reduced maize yield volatility, itself a consequence of climatic variability. Further, rank correlation "flipped" from relatively uncorrelated to correlated between ~925 and 1100 CE, first for the UB sites, then for the GSL sites, and then for the RC sites. Finally, yield-SPD coupling diverged strongly in the UB between ~1000 and 1100 CE, when simulated maize yield increased while SPD declined, an anomaly which we explain in terms of increasing yield volatility. From Fig. 10, the general trend suggested that coupling is weak for GSL sites throughout the time-series; coupling was strong for RC; and the curves were erratically coupled, and generally uncorrelated, for the UB sites. (We have already noted the divergence of mean yield and SPD curves in Fig. 6 .) When yield volatility was considered instead, from Fig. 11, the response of the GSL sites is similar to that in Fig. 10 (i.e., the GSL sites are similarly unconstrained by changes in yield or its variability); coupling for the RC sites is enhanced; and the coupling of the UB sites becomes much more erratic, with the "flip" at ~1000 CE noted where yield volatility rapidly increased in Fig. 6 .

5. Discussion

Like other APs, Fremont occupations likely had complex dependencies on many variables not limited to local maize yield or yield variability. Nevertheless, we expect that SPDs, as representations of local occupations, were constrained by the quality and predictability of local maize harvests; that is, their shapes express, to varying degrees, the combined effects of population growth and decline, and crop productivity. Across the subregions, we found shared sensitivity of occupation to yield variability, driven by exogenous climate-variability, and the potential for rapid decline of productivity over time under intensive

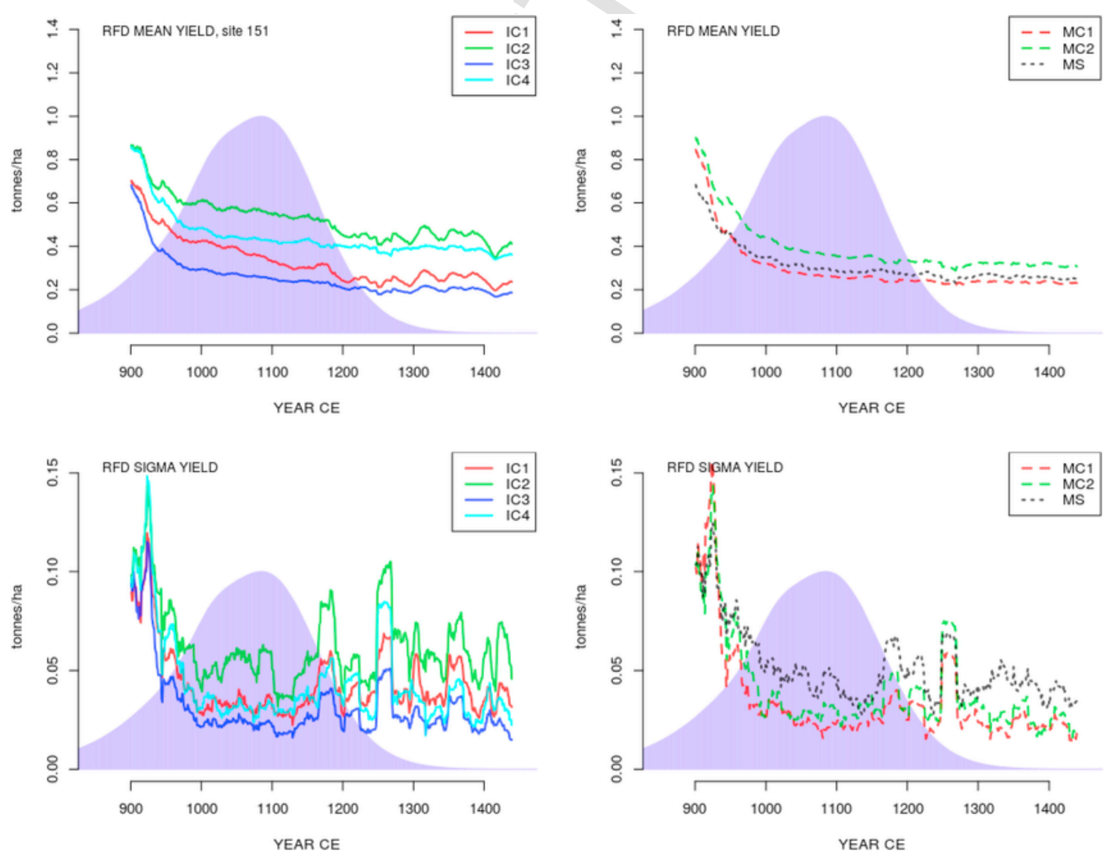

Fig. 8. Combined cropping-occupation plot for RC Fremont, RFD, high-elevation site. Mean yield and 21-yr rolling standard deviation ("volatility") of yield from all "dry" simulations in the ensemble for seven management strategies, for the high-elevation RC site only. Yield curves overly cumulative SPD for all 21 calibrated radiocarbon dates from RC, arbitrarily rescaled for the purposes of comparison.

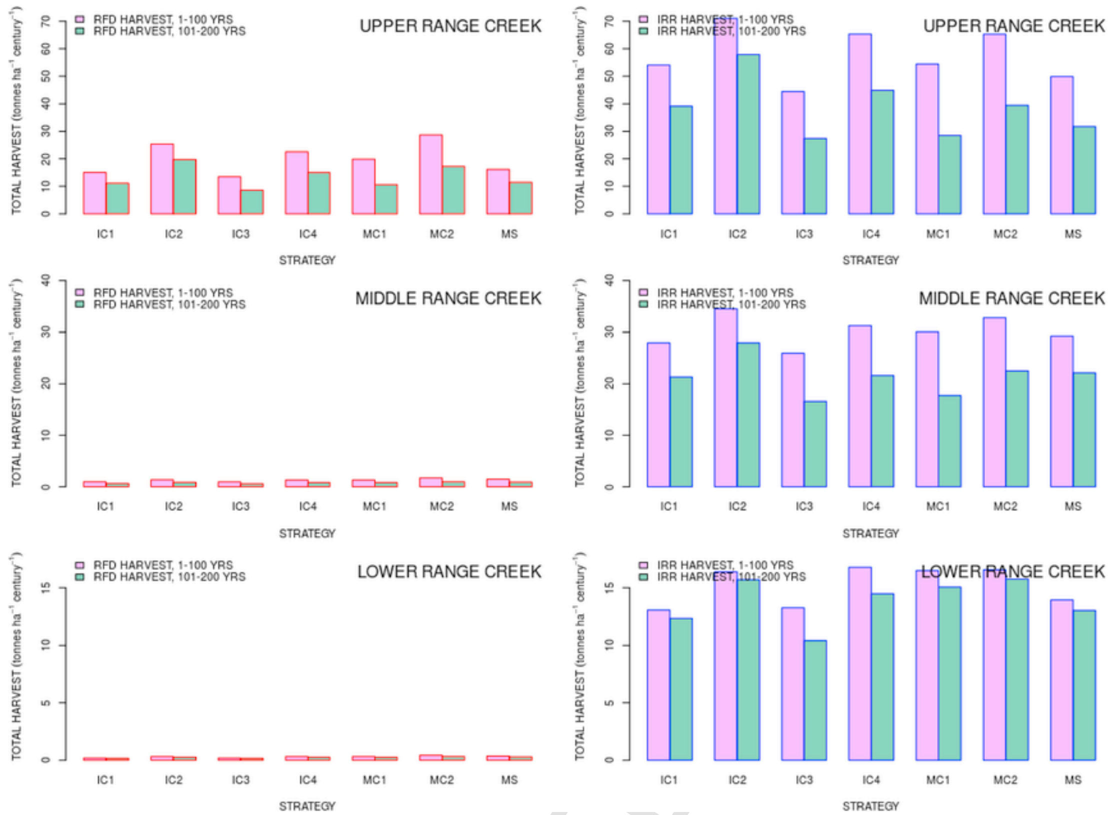

Fig. 9. Maize crop mean centennial harvests for each management strategy for the "dry" (left column, bars outlined in red) and "wet" (right column, bars outlined in blue) cases. Results for all sites are shown; the top row corresponds to the site from Fig. 8. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

management strategies, particularly with the added burning of unharvested residue. Yield-resilient management strategies allowed for fallow periods or the planting of nitrogen-fixing legumes in alternative years. Consistent with proxy reconstructions of temperature, the climate model shows reduced mean annual temperatures during the middle 12th century. These result in very modest declines in yields (partly concealed by the rolling average in the mean plots, and exposed in the variability plots) between ~1100 and 1200 CE. For our downscaling method, we relied on interpolated climate-station temperature fields that have since been called into question for potentially overestimating high-elevation warming in the Western United States (Oyler et al., 2015). This may have caused an inflation of our yield estimates for higher elevation sites, particularly during the MCA.

The Great Salt Lake and Range Creek sites also show increasing coupling between SPDs and mean annual maize yields, after ~950 CE and ~1100 CE, respectively. Among the drivers of this relationship were likely endogenous population pressure, soil degradation, and exogenous general cooling and hydrological change at the MCA-LIA transition. That is, while variability exerted a continuous pressure on occupation intensity, the pressure from declining mean yields increased over time. Low and highly variable crop yields are especially risky for dryland farmers in general, and have been shown to coincide with transitions to lower occupation intensities at other AP sites (Kohler and Van West, 1996). Moreover, according to the simulations, long-term occupation at any site would be made especially challenging if the Fremont burned unharvested residue or grew maize in isolation.

GSL Fremont dietary regimes were detailed by a trove of isotopic data from bones exposed during an historic low-stand of the lake in the late-20th century: maize comprised a substantial part of the GSL Fremont diet prior to 850 CE; but between 850 and 1150 CE, they added substantial wild, non-C_4 plants to their diet; and calories from maize are probably absent after 1150 CE (Coltrain and Leavitt, 2002). The GSL Fremont presumably exploited a deep reservoir of resources, besides maize, provided by their environment (Scott Cummings, 2004), necessitating periods of relatively high mobility on the landscape (Barlow, 2002; Ruff, 1999). It may be that the increasing difficulty of growing maize crops of consistent quality induced a shift to more easily obtained, higher value wild foods (Winterhalder et al., 1999), or the maize-growers among them to migrate elsewhere. Unfortunately, we did not have the climatology data to begin our crop simulations prior to 850 CE, by which time the GSL and UB occupations were already on the decline; and we could not simulate soil salinization, which presumably also hindered productivity around the GSL in particular (Jennings, 1978).

Throughout the Uinta Basin, Fremont occupations were in decline well before 850 CE, the start-date for our earliest simulations. The UB Fremont SPDs are better represented by trends in the mean yield volatility than they yield itself. The negative correlation of SPDs with yield variability (Fig. 11) is strong and consistent; i.e., the high-elevation occupations were particularly sensitive to increased climate variability. These low-yield, high-yield-variability sites would have been the most high-risk for farmers with critical dependence on crop calories. Although generally warmer conditions during the MCA drew UB Fremont to higher elevations, it also increased their exposure to the risk of higher uncertainty in crop yields. (During the MCA, the Uinta Basin was characterized by a greater frequency of long growing season years that raised mean annual temperatures. The sudden jump in volatility across the ensemble member simulations was driven by an increase in the frequency of long to short growing seasons, not necessarily warmer winters.) Higher elevation maize-farming sites in the UB may have been short-lived experiments in agriculture. The APs who moved to higher elevation sites during the MCA may have counted

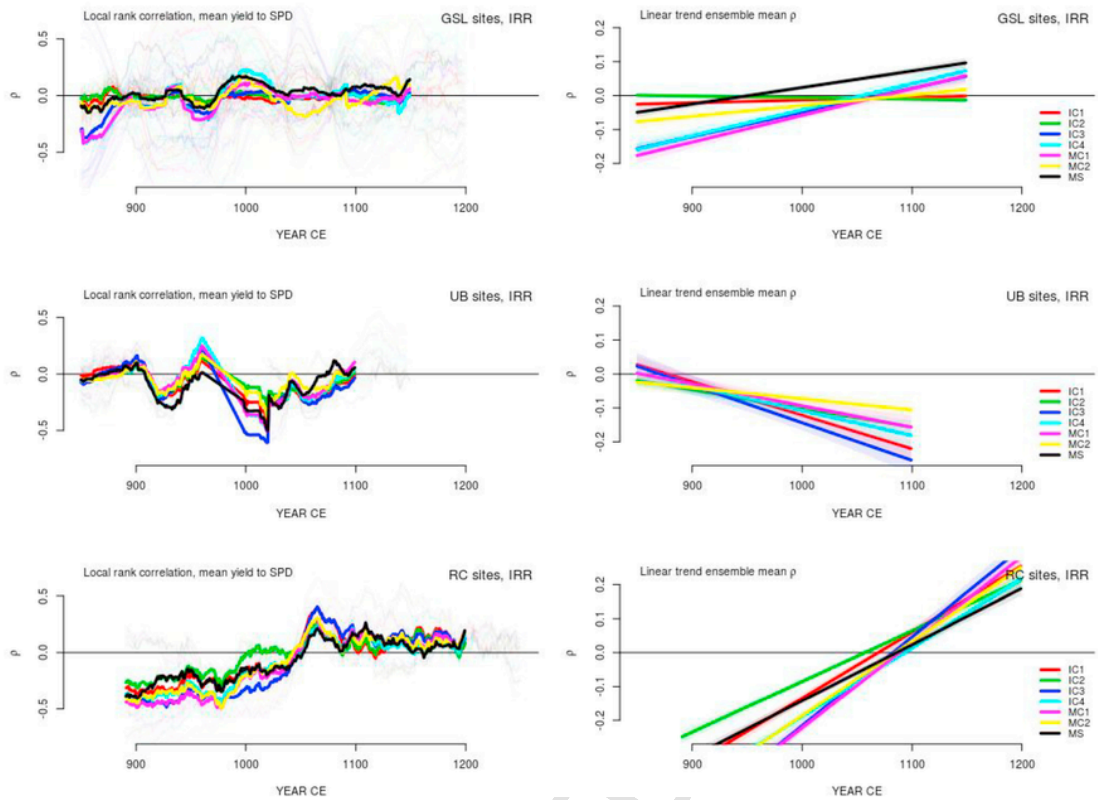

Fig. 10. Test of the correlation of the EPIC "wet" simulation yields and SPDs for sites within different subregions. In the left column are Spearman coefficients for subregions generated within a 75-year rolling window (ensemble means are highlighted in bold); in the right column are the associated trend lines for each.

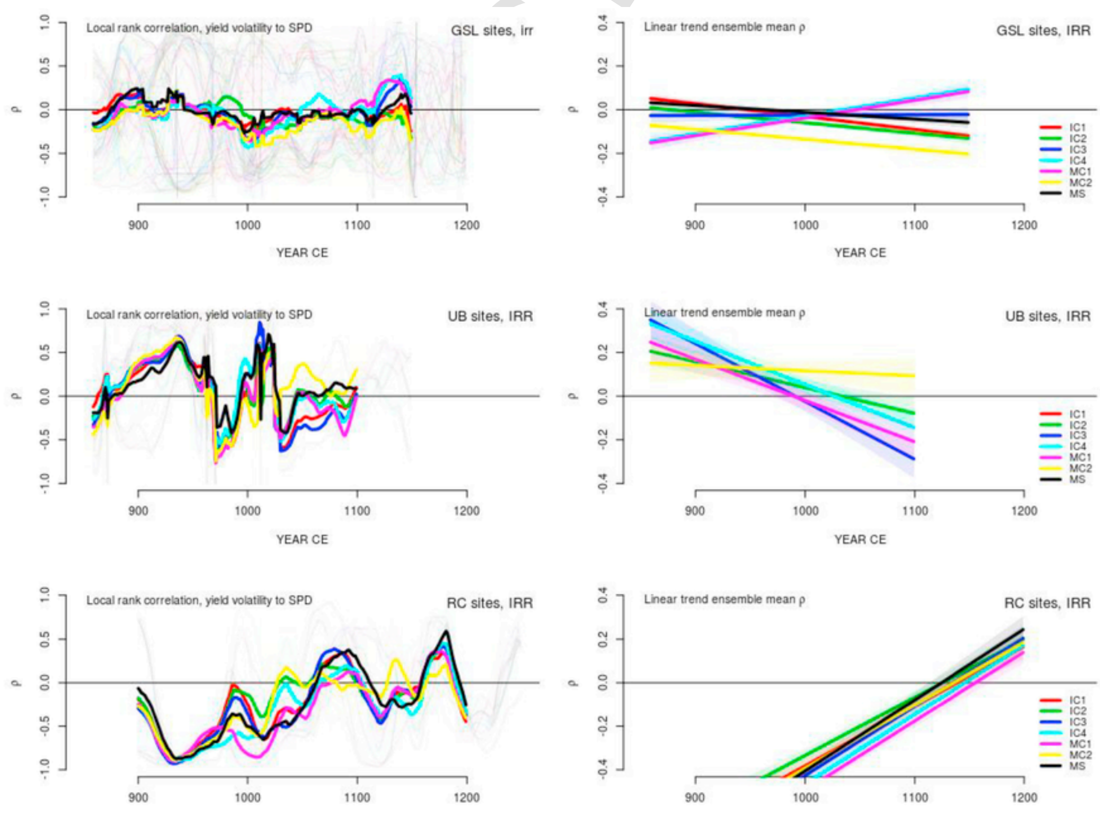

Fig. 11. Test of the correlation of the EPIC "wet" simulation yield standard deviation (volatility) and SPDs for sites within different subregions.

other farmers' risk-aversion among their assets: small groups of opportunistic foragers may have positioned themselves locally to grow maize when conditions permitted (Winterhalder, 1986). Other AP groups have been shown to have responded to ameliorating environmental conditions by exploring and expanding into regions that were otherwise marginal (Benson and Berry, 2009; Bocinsky et al., 2016).

Along Range Creek, our model shows that it was then, as it is now, simply too dry to grow maize without irrigation, which accords with field-experimental plotting (Boomgarden, 2015). Furthermore, doing so would also rapidly deplete the soil of nutrients, particularly if pursuing a mono-cropping and/or residue burning strategy. Nevertheless, it was possible to generate a modest maize crop in high-elevation, mesic sites; and the high variance of the ensemble members (before the mean is taken) indicates that some seasons may have been sufficiently wet to produce maize crops approaching those raise in Utah during the early historical period. We therefore expect that if dryland farming produce maize in Range Creek, it was in the upper reach of the catchment, following a strategy similar to IC2. But the SPD also clearly peaks during a period of relative climatic quiescence, and declines as variability increases after ~1150 CE. The last Fremont occupations in Range Creek occur on defensible promontories and in the context of greater fortifications of their food supply (e.g., numerous maize-store granaries camouflaged on vertiginous canyon walls), and even rock-falls over the approaches to their dwellings, suggesting increased value of maize, competition for resources and interpersonal violence. At other AP sites, it has been found that traumatic injury due to interpersonal violence rose when modelled maize yields were meagre and variable (Kohler et al., 2014). In addition, when we set up our simulation runs, raw radiocarbon dates for RC Fremont artifacts were not available. Once provenience data become available, the same procedure as we used to analyze the other Fremont sites may be carried out on the nineteen raw radiocarbon dates (Boomgarden et al., 2014).

Authors' contributions

CESM downscaling, EPIC modifications, analysis of results, and writing by MJT; EPIC modifications and simulations by JB; manuscript suggestions and consultation with analytics TK; manuscript assistance and funding support provided by GMM.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2018.09.031.

References

Adams, D.K., Comrie, A.C., 1997. The North American monsoon. Bull. Am. Meteorol. Soc. 78 (10), 2197–2214. https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.

Allison, J.R., 1996. Comments on the impacts of climatic variability and population growth on Virgin Anasazi cultural development. Am. Antiq. 61 (2), 414–418 https://doi.org/10.2307/282435.

Asmerom, Y., Polyak, V.J., Rasmussen, J.B., Burns, S.J., Lachniet, M., 2013. Multidecadal to multicentury scale collapses of Northern Hemisphere monsoons over the past millennium. Proc. Natl. Acad. Sci. U. S. A. 110 (24), 9651–9656 https://doi.org/10.1073/pnas.1214870110.

Ault, T.R., St. George, S., Smerdon, J.E., Coats, S., Mankin, J.S., Carrillo, C.M., Stevenson, S., 2017. A robust null hypothesis for the potential causes of megadrought in western north America. J. Clim. 31 (1), 3–24 https://doi.org/10.1175/JCLI-D-17-0154.1.

Axtell, R.L., Epstein, J.M., Dean, J.S., Gumerman, G.J., Swedlund, A.C., Harburger, J., Parker, M., 2002. Population growth and collapse in a multiagent model of the kayenta Anasazi in long house valley. Proc. Natl. Acad. Sci. U. S. A. 99, 7275–7279 https://doi.org/10.1073/pnas.092080799.

Barlow, K.R., 2002. Predicting maize agriculture among the Fremont: an economic comparison of farming and foraging in the American southwest. Am. Antiq. 67 (1), 65–88 https://doi.org/10.2307/2694877.

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. J. Archaeol. Meth. Theor. 18 (1), 1–60 https://doi.org/10.1007/s10816-010-9082-z.

Benson, L.V., Berry, M.S., 2009. Climate change and cultural response in the prehistoric American southwest. KIVA 75 (1), 87–117 https://doi.org/10.1179/kiv.2009.75.1.005.

Bocinsky, R.K., Kohler, T.A., 2014. A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest. Nat. Commun. 5 (1) https://doi.org/10.1038/ncomms6618.

Bocinsky, R.K., Rush, J., Kintigh, K.W., Kohler, T.A., 2016. Exploration and exploitation in the macrohistory of the pre-Hispanic Pueblo Southwest. Sci. Adv. 2 (4), e1501532 https://doi.org/10.1126/sciadv.1501532.

Bocinsky, R.K., Varien, M., 2017. Comparing maize paleoproduction models with experimental data. J. Ethnobiol. 37, 282–307 https://doi.org/10.2993/0278-0771-37.2.282.

Boomgarden, S.A., 2015. Experimental Maize Farming in Range Creek Canyon, Utah. The University of Utah, Retrieved from: https://search.proquest.com/openview/adfa855464511448cd107e635a1df6ef/1?pq-origsite = gscholar&cbl = 18750&diss = y.

Boomgarden, S.A., Metcalfe, D., Springer, C., 2014. Prehistoric archaeology in range Creek canyon, Utah: a summary of the activities of the range Creek field station. Utah Archaeol. 27 (1), 9–32.

Bradley, R.S., Wanner, H., Diaz, H.F., 2016. The medieval quiet period. Holocene 26 (6), 990–993 https://doi.org/10.1177/0959683615622552.

Burnett Benjamin, N., Meyer Grant, A., McFadden Leslie, D., 2008. Aspect-related microclimatic influences on slope forms and processes, northeastern Arizona. J. Geophys. Res. Earth Surface 113 (F3) https://doi.org/10.1029/2007JF000789.

Burns, B.T., 1983. Simulated Anasazi Storage Behavior Using Crop Yields Reconstructed from Tree-rings: A.D. 652–1968. University of Arizona, Tucson, (Unpublished dissertation).

Christiansen, B., Ljungqvist, F., 2012. The extra-tropical NH temperature in the last two millennia: reconstructions of low-frequency variability. Clim. Past 8, 765–786 https://doi.org/10.5194/cpd-7-3991-2011.

Coltrain, J.B., 1993. Fremont corn agriculture: a pilot stable carbon isotope study. Utah Archaeol. 6 (1), 49–55.

Coltrain, J.B., Janetski, J.C., Carlyle, S.W., 2007. The stable- and radio-isotope chemistry of western basketmaker burials: implications for early puebloan diets and origins. Am. Antiq. 72 (2), 301–321 https://doi.org/10.2307/40035815.

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. Am. Antiq. 67 (3), 453–485 https://doi.org/10.2307/1593822.

Contreras, D., Guiot, J., Suarez, R., Kirman, A., 2018. Reaching the human scale: a spatial and temporal downscaling approach to the archaeological implications of paleoclimate data. J. Archaeol. Sci. 93, 54–67 https://doi.org/10.1016/j.jas.2018.02.013.

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 (5698), 1015–1018 https://doi.org/10.1126/science.1102586.

Cutler, H.C., 2001. In: Blake, L., Cutler, H.C. (Eds.), Plants from the Past: Works of Leonard W. Blake & Hugh C. Cutler. University of Alabama Press.

Diamond, J., 2005. Collapse: How Societies Choose to Fail or Succeed. Penguin.

Douglass, A.E., 1929. Secret of the southwest solved by talkative tree rings. Natl. Geogr. Mag. 56 (6), 736–770.

Douglass, A.E., 1935. Dating Pueblo Bonito and Other Ruins of the Southwest. National Geographic Society.

Ford, R.I., 1981. Gardening and farming before AD 1000: patterns of prehistoric cultivation north of Mexico. J. Ethnobiol. 1 (1), 6–27.

Graumlich, L.J., 1993. A 1000-year record of temperature and precipitation in the sierra Nevada. Quat. Res. 39 (2), 249–255 https://doi.org/10.1006/qres.1993.1029.

Griffin, D., Woodhouse, C.A., Meko, D.M., Stahle, D.W., Faulstich, H.L., Carrillo, C., Leavitt, S.W., 2013. North American monsoon precipitation reconstructed from tree-ring latewood. Geophys. Res. Lett. 40 (5), 954–958 https://doi.org/10.1002/grl.50184.

Harris, F.S., Jensen, I.J., Bracken, A.F., 1920. Sixteen Years of Dry Farm Experiments in Utah. Utah Agricultural College Experiment Station.

Hegmon, M., Peeples, M.A., Kinzig, A.P., Kulow, S., Meegan, C.M., Nelson, M.C., 2008. Social transformation and its human costs in the prehispanic U.S. Southwest. Am. Anthropol. 110 (3), 313–324 https://doi.org/10.1111/j.1548-1433.2008.00041.x.

Higgins, R.W., Yao, Y., Wang, X.L., 1997. Influence of the north American monsoon system on the U.S. Summer precipitation regime. J. Clim. 10 (10), 2600–2622 https://doi.org/10.1175/1520-0442.

Hockett, B., Morgenstein, M., 2003. Ceramic production, Fremont foragers, and the late archaic prehistory of the North-central Great Basin. Utah Archaeol. 16 (1), 1–36.

Janetski, J.C., 2002. Trade in Fremont society: contexts and contrasts. J. Anthropol. Archaeol. 21 (3), 344–370 https://doi.org/10.1016/S0278-4165(02)00003-X.

Jennings, J.D., 1978. Prehistory of Utah and the Eastern Great Basin. University of Utah Press.

Jones, M., Metcalfe, S., Davies, S., Noren, A., 2015. Late Holocene climate reorganisation and the north American monsoon. Quat. Sci. Rev. 124, https://doi.org/10.1016/j.quascirev.2015.07.004.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M., Potter, G.L., 2002. NCEP–DOE AMIP-II Reanalysis (R-2). Bull. Am. Meteorol. Soc. 83 (11), 1631–1644 https://doi.org/10.1175/BAMS-83-11-1631.

Kelly, R.L., 1997. Late Holocene Great Basin prehistory. J. World PreHistory 11 (1), 1–49 https://doi.org/10.1007/BF02221200.

Kohler, T.A., Bocinsky, R.K., Cockburn, D., Crabtree, S.A., Varien, M.D., Kolm, K.E., Kobti, Z., 2012. Modelling prehispanic Pueblo societies in their ecosystems. Ecol. Model. 241, 30–41 https://doi.org/10.1016/j.ecolmodel.2012.01.002.

Kohler, T.A., Kresl, J., Van West, C., Carr, E., Wilshusen, R.H., 2000. Be there then: a modeling approach to settlement determinants and spatial efficiency among late ancestral Pueblo populations of the Mesa Verde region, US Southwest. In: Kohler, T.A., Gumerman, G.G. (Eds.), Dynamics in Human and Primate Societies: Agent-based Modeling of Social and Spatial Processes. Oxford University Press, pp. 145–178.

Kohler, T.A., Ortman, S.G., Grundtisch, K.E., Fitzpatrick, C.M., Cole, S.M., 2014. The better angels of their nature: declining violence through time among prehispanic farmers of the pueblo southwest. Am. Antiq. 79 (3), 444–464 https://doi.org/10.7183/0002-7316.79.3.444.

Kohler, T.A., Van West, C.R., 1996. The calculus of self-interest in the development of cooperation: sociopolitical development and risk among the northern Anasazi. In: Tainter, J.A., Tainter, M.B. (Eds.), Evolving Complexity and Environmental Risk in the Prehistoric Southwest, first ed. CRC Press, pp. 169–196 https://doi.org/10.1201/9780429492587-7.

Lindsay, L.W., 1986. Fremont Fragmentation, vol. 110, University of Utah Anthropological Papers, 229–251.

Lo, F., Clark, M.P., 2002. Relationships between spring snow mass and summer precipitation in the southwestern United States associated with the north American monsoon system. J. Clim. 15 (11), 1378–1385. https://doi.org/10.1175/1520-0442(2002)015<1378:RBSSMA>2.0.CO;2.

Loisel, J., MacDonald, G.M., Thomson, M.J., 2017. Little Ice Age climatic erraticism as an analogue for future enhanced hydroclimatic variability across the American Southwest. PLoS One 12 (10), e0186282 https://doi.org/10.1371/journal.pone.0186282.

MacDonald, G.M., 2010. From the cover: climate change and water in southwestern north America special feature: water, climate change, and sustainability in the Southwest. Proc. Natl. Acad. Sci. Unit. States Am. 107 (50), 21256–21262 https://doi.org/10.1073/pnas.0909651107.

MacDonald Glen, M., Stahle David, W., Villanueva, Diaz Jose, Nicholas, Beer, Busby Simon, J., Julian, Cerano-Paredes, et al., 2008. Climate warming and 21st-century drought in southwestern north America. Eos, Trans. Am. Geophys. Union 89 (9), 82–82 https://doi.org/10.1029/2008EO090003.

MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., R, R., van Ommen, T., Elkins, J., 2006. Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP. Geophys. Res. Lett. 33 (14) https://doi.org/10.1029/2006GL026152.

Madsen, D.B., Simms, S.R., 1998. The Fremont complex: a behavioral perspective. J. World PreHistory 12 (3), 255–336 https://doi.org/10.1023/A:1022322619699.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392 (6678), 779–787 https://doi.org/10.1038/33859.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ni, F., 2009. Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science (New York, N.Y.) 326 (5957), 1256–1260 https://doi.org/10.1126/science.1177303.

Marwitt, J.P., 1973. Median Village and Fremont Culture Regional Variation. A M S Press, Incorporated.

McAnany, P.A., Yoffee, N., 2010. Questioning Collapse: Human Resilience, Ecological Vulnerability, and the Aftermath of Empire. Cambridge University Press.

Metcalfe, D., Larrabee, L.V., 1985. Fremont irrigation: evidence from gooseberry valley, central Utah. J. Calif. Great Basin Anthropol. 7 (2), 244–254.

Metcalfe, S.E., Barron, J.A., Davies, S.J., 2015. The Holocene History of the North American Monsoon: "known Knowns" and "known Unknowns" in Understanding its Spatial and Temporal Complexity. https://doi.org/10.1016/j.quascirev.2015.04.004.

Miller, D.M., Schmidt, K.M., Mahan, S.A., McGeehin, J.P., Owen, L.A., Barron, J.A., Löhrer, R., 2010. Holocene landscape response to seasonality of storms in the Mojave Desert. Quat. Int. 215 (1), 45–61 https://doi.org/10.1016/j.quaint.2009.10.001.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlén, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433 (7026), 613–617 https://doi.org/10.1038/nature03265.

Morss, N., 1931. The Ancient Culture of the Fremont River in Utah: Report on the Explorations under the Claflin-Emerson Fund, 1928-29. na.

Nachtergaele, F.O., Velthuizen, H. van, Verelst, L., Batjes, N.H., Djjkshoorn, J.A., van Engelen, V.W.P., Shi, X., 2008. Harmonized World Soil Database (Version 1.0). FAO/IIASA/ISRIC/ISSCAS/JRC, Retrieved from: https://www.isric.online/.

Otto-Bliesner, B.L., Brady, E.C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Strand, G., 2015. Climate variability and change since 850 CE: an ensemble approach with the community Earth system model. Bull. Am. Meteorol. Soc. 97 (5), 735–754 https://doi.org/10.1175/BAMS-D-14-00233.1.

Oyler, J.W., Dobrowski, S.Z., Ballantyne, A.P., Klene, A.E., Running, S.W., 2015. Artificial amplification of warming trends across the mountains of the western United States. Geophys. Res. Lett. 42 (1), 153–161 https://doi.org/10.1002/2014GL062803.

Parnell, A., 2018. Bchron: Radiocarbon Dating, Age-depth Modelling, Relative Sea Level Rate Estimation, and Non-parametric Phase Modelling (Version 4.2.7), Retrieved from: https://CRAN.R-project.org/package=Bchron.

PRISM Climate Group, 2004. PRISM. Oregon State University, Retrieved from: http://prism.oregonstate.edu.

R Core Team. (n.d.). R: The R Project for Statistical Computing. Vienna, Austria. Retrieved from https://www.r-project.org/.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Plicht, J. van der., 2013. IntCal13 and Marine 13 radiocarbon age calibration curves 0–50,000 Years cal BP. Radiocarbon 55 (4), 1869–1887 https://doi.org/10.2458/azu_js_rc.55.16947.

Reinemann, S.A., Porinchu, D.F., MacDonald, G.M., Mark, B.G., DeGrand, J.Q., 2014. A 2000-yr reconstruction of air temperature in the Great Basin of the United States with specific reference to the Medieval Climatic Anomaly. Quat. Res. 82 (2), 309–317 https://doi.org/10.1016/j.yqres.2014.06.002.

Rittenour, T.M., Coats, L.L., Metcalfe, D., 2015. Investigation of late and post-Fremont alluvial stratigraphy of Range Creek, east-central Utah: use of OSL when radiocarbon fails. Quat. Int. 362, 63–76.

Ronan, A.D., Prudic, D.E., Thodal, C.E., Constantz, J., 1998. Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath an ephemeral stream. Water Resour. Res. 34 (9), 2137–2153.

Ruff, C.B., 1999. Skeletal structure and behavioral patterns of prehistoric Great Basin populations. In: Hemphill, B.E., Larsen, C.S. (Eds.), Prehistoric Lifeways in the Great Basin Wetlands: Bioarchaeological Reconstruction and Interpretation. University of Utah Press, Retrieved from: https://ci.nii.ac.jp/naid/10018120432/.

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. Clim. Dynam. 42 (5–6), 1517–1526 https://doi.org/10.1007/s00382-013-1911-9.

Salzer, M.W., Kipfmueller, K.F., 2005. Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, U.S.A. Clim. Change 70 (3), 465–487 https://doi.org/10.1007/s10584-005-5922-3.

Scott Cummings, L., 2004. Great Basin paleoethnobotany. In: Minnis, P.E. (Ed.), People and Plants in Ancient Western North America. Smithsonian Books, Washington, D.C., pp. 205–277.

Simms, S.R., 1986. New evidence for Fremont adaptive diversity. J. Calif. Great Basin Anthropol. 8 (2), 204–216.

Simms, S.R., 2016. Ancient Peoples of the Great Basin and Colorado Plateau. Routledge.

Stine, S., 1994. Extreme and persistent drought in California and Patagonia during medieval time. Nature 369, 546–549.

Tainter, J., 1988. The Collapse of Complex Societies. Cambridge University Press.

Tainter, J.A., 2006. Archaeology of overshoot and collapse. Annu. Rev. Anthropol. 35 (1), 59–74 https://doi.org/10.1146/annurev.anthro.35.081705.123136.

Ugan, A., Coltrain, J., 2012. Stable isotopes, diet, and taphonomy: a look at using isotope-based dietary reconstructions to infer differential survivorship in zooarchaeological assemblages. J. Archaeol. Sci. 39 (5), 1401–1411 https://doi.org/10.1016/j.jas.2011.12.027.

Van West, C.R., 1994. Modeling Prehistoric Agricultural Productivity in Southwestern Colorado: a GIS Approach. Department of Anthropology, Washington State University, Pullman, WA and Crow Canyon Archaeological Center, Cortez, CO.

Walker, F.A., 1883. Report on the Productions of Agriculture as Returned at the Tenth Census (June 1, 1880). Government Printing Office, Washington DC.

Wenda, W.I., Hanks, R.J., 1981. Corn yield and evapotranspiration under simulated drought conditions. Irrigat. Sci. 2 (4), 193–204 https://doi.org/10.1007/BF00258373.

West, C.R.V., Dean, J.S., 2000. Environmental characteristics of the a.d. 900–1300 period in the central mesa Verde region. KIVA 66 (1), 19–44 https://doi.org/10.1080/00231940.2000.11758420.

Wheeler, G.M., Humphreys, A.A., Wright, H.G., 1875. Report upon United States Geographical Surveys West of the One Hundredth Meridian, vol. 6, US Government Printing Office.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE (Am. Soc. Agric. Eng.) 32 (2), 497–511.

Winterhalder, B., 1986. Diet choice, risk, and food sharing in a stochastic environment. J. Anthropol. Archaeol. 5 (4), 369–392 https://doi.org/10.1016/0278-4165(86)90017-6.

Winterhalder, B., Lu, F., Tucker, B., 1999. Risk-sensitive adaptive tactics: models and evidence from subsistence studies in biology and anthropology. J. Archaeol. Res. 7 (4), 301–348.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim. Change 62 (1–3), 189–216 https://doi.org/10.1023/B:CLIM.0000013685.99609.9e.

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W., Cook, E.R., 2010a. Climate change and water in southwestern north America special feature: a 1,200-year perspective of 21st century drought in southwestern north America. Proc. Natl. Acad. Sci. Unit. States Am. 107 (50), 21283–21288 https://doi.org/10.1073/pnas.0911197107.

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