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Climate Change and Cultural Response In The Prehistoric American Southwest

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CLIMATE CHANGE AND CULTURAL RESPONSE IN THE PREHISTORIC AMERICAN SOUTHWEST

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ABSTRACT

Comparison of regional tree-ring cutting-date distributions from the southern Colorado Plateau and the Rio Grande region with tree-ring-based reconstructions of the Palmer Drought Severity Index (PDSI) and with the timing of archaeological stage transitions indicates that Southwestern Native American cultures were periodically impacted by major climatic oscillations between A.D. 860 and 1600. Site-specific information indicates that aggregation, abandonment, and out-migration from many archaeological regions occurred during several widespread mega-droughts, including the well-documented middle-twelfth- and late-thirteenth-century droughts. We suggest that the demographic response of southwestern Native Americans to climate variability primarily reflects their dependence on an inordinately maize-based subsistence regimen within a region in which agriculture was highly sensitive to climate change.

RESUMEN

La comparación entre las distribuciones de anillos de árboles con fecha de corte de la zona sur de la Colorado Plateau y la región del Río Grande con reconstrucciones basadas en anillos de árboles del Índice Severo de Deficiencia Palmer (PDSI, por sus siglas en Inglés) y con el momento del período de transición arqueológica, indica que las culturas Nativas Americanas del Suroeste fueron periódicamente impactadas por oscilaciones climáticas entre 860 y 1600 A.D. Información específica del sitio indica que violencia, agregación, abandono y migración de varias regiones arqueológicas ocurrieron durante varias deficiencias generalizadas, incluyendo las bien documentadas ocurridas a mediados del siglo 12 y fines del siglo 13. Sugerimos que la respuesta demográfica de los Nativos Americanos del suroeste a la variabilidad climática, refleja la tremenda dependencia basada en un régimen de subsistencia en el maíz, en una región en donde la agricultura en tierra firme era muy sensible al cambio climático.

INTRODUCTION

The degree and nature of prehistoric cultural response to climate instability remain debatable and certainly varied over space and time; however, recent publications

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(e.g., Benson et al. 2007; Dean and Van West 2002; Gill 2000; Jones et al. 1999; Kennett and Kennett 2006; Staubwasser and Weiss 2006) indicate renewed support for climate forcing of population movement and consequent cultural change.

Approximately 30 years ago Euler et al. (1979), using a variety of available climate-proxy records, showed that environmental change in the southern Colorado Plateau was accompanied by cultural and demographic responses during the past 2,300 years. One of the measures of cultural change they invoked was the distribution of tree-ring cutting dates over time, and one of the measures of climate change they employed was normalized tree-ring widths (principally a measure of annual precipitation). Since that time, the quality and quantity of Southwestern tree-ring-based records of climate change and timber harvesting have greatly increased. In the following, we compare a climate index (the PDSI) with tree-ring-date distributions (a qualitative proxy of population density) from several Southwestern archaeological regions, noting critical points of transition, marked by times of accelerated cultural change and decline. We show that dryland and floodplain farming within the southern Colorado Plateau, Mogollon Highlands and the Rio Grande region (hereafter referred to as the study area) (Figure 1) was a "risky business." We also show that between A.D. 600 and 1600, increases in population density in the study area occurred during anomalously wet periods that temporarily increased the carrying capacity of this semi-arid environment and, thus, set the stage for a series of economic collapses that occurred during periods of intense and persistent drought. These collapses were accompanied by well-documented occurrences of aggregation and eventually migration, resulting in the disappearance of some cultures from the archaeological record.

The main point of this paper is the correlation of climate change records with the timber cutting record in the study area. This correlation supports our argument that population change in the study area, as indicated by construction activity, varied coherently with climate change. The length of this paper does not allow a comprehensive treatment of demographic and cultural response to climate change; however, we have attempted to provide some examples of migration and abandonment in specific regions of the southern Colorado Plateau that illustrate the main features of our argument.

MAIZE AGRICULTURE—THE LINK BETWEEN CLIMATE CHANGE AND CULTURAL RESPONSE

Maize has been cultivated in the American Southwest since at least 2900 B.C. (Huckell 2006).[1] Coltrain et al. (2007) have recently demonstrated, using $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen, that Basketmaker II people were heavily dependent on maize agriculture by 400 B.C. and that their degree of dependence was similar to Pueblo II and III peoples of the Four Corners area. In addition, Coltrain et al. (2006) have shown that eastern Basketmaker groups in southwestern Colo-

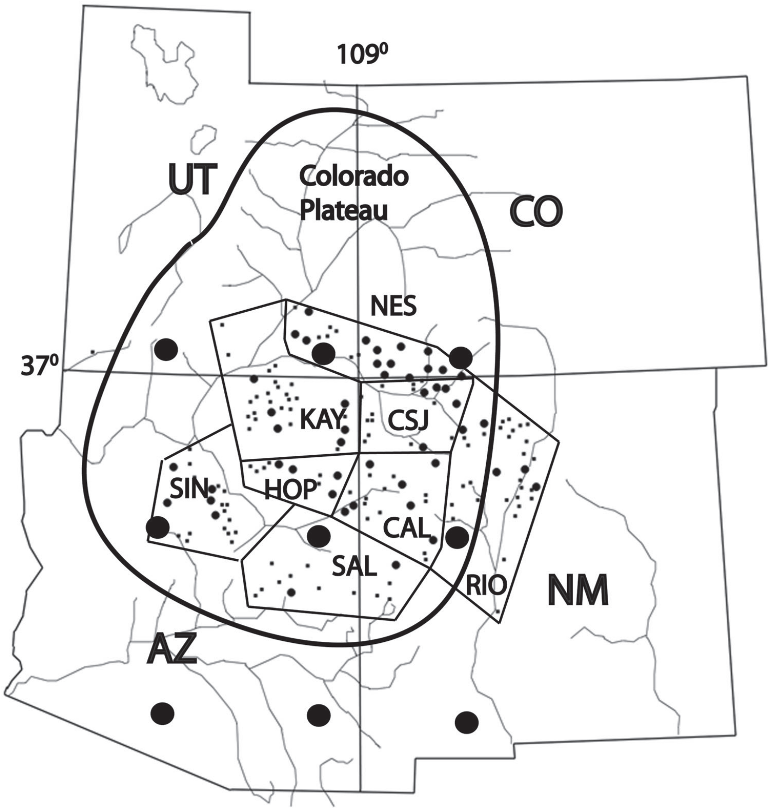


FIGURE 1. Map showing location of cutting-date sites and archaeological regions within the study area. KAY = Kayenta region, NES = northeastern San Juan Basin, CSJ = central San Juan Basin, SIN = Sinagua region, HOP = Hopi region, CAL = Cibola-Acoma-Laguna region, RIO = Rio Grande region, SAL = Salt River region. Large black circles indicate locations of PDSI nodes; medium black circles indicate cutting-date site clusters; small black circles indicate single cutting-date sites. Heavy black line outlines the Colorado Plateau.

rado were strongly reliant on maize from 500 B.C. until the region was abandoned at ~A.D. 1300. These studies demonstrate that prehistoric Native Americans, in at least part of the southern Colorado Plateau, were heavily dependent on maize for the past 2,500 years. This dependency on an exotic cultigen artificially inflated the carrying capacity of the arid Southwest. Hunter-gatherers in the southern Colorado Plateau, at the time of European contact, had a population density of roughly one person per twenty-five square miles (Steward 1938). While population

density for agriculturalists is very difficult to estimate, it is clear that population densities of several regions within the study area were several orders of magnitude greater than that of the hunter-gatherer precursors and post-abandonment groups.

Overall population density must be near carrying capacity for climate deterioration to have its greatest impact on a culture. As shown in the "Tree Ring Dates and Climate Change" section which follows, two relatively wet periods that occurred between A.D. 1045–1129 and A.D. 1193–1269 probably allowed Native Americans to exploit environmental settings in the study area that under normal (long-term mean) climate conditions were marginal in terms of agricultural productivity.

In the southern Colorado Plateau, several environmental factors make the cultivation of maize a potentially perilous means of subsistence. Meteorological and soil parameters that impacted maize agriculture include the following: annual precipitation, summer rainfall, freeze-free days (FFD), corn-growing degree (°C) days (CGDD), soil pH, soil total organic carbon (TOC), and soil total organic nitrogen (TON).

A summer rainfall of 15 cm and an annual precipitation of 30 cm represent, approximately, the lower limits for maize production (Shaw 1988). Most varieties of corn, including Southwest Native American landraces such as Hopi blue corn, require about 120 FFD (Bradfield 1971). In a recent experimental maize grow-out in the Durango District of southwestern Colorado, Bellorado (2007) showed that five southwestern Native American maize varieties reached maturity within 1055 to 1110 CGDD. CGDD are calculated using the following formula

$$CGDD = \sum_{i=m}^{n} (T_a - T_b)\Delta t$$

where T_a is the average daily temperature in °C; T_b is a base temperature (10°C) below which development is assumed to cease; m is the date of the first freeze-free day after planting; n is the date of the last freeze-free day; and t is a time step in days. If $T_a > 30$°C, its value is set to 30°C. For the purposes of this paper, we use 1,000 CGDD as the value below which maize yields cease to be optimal.

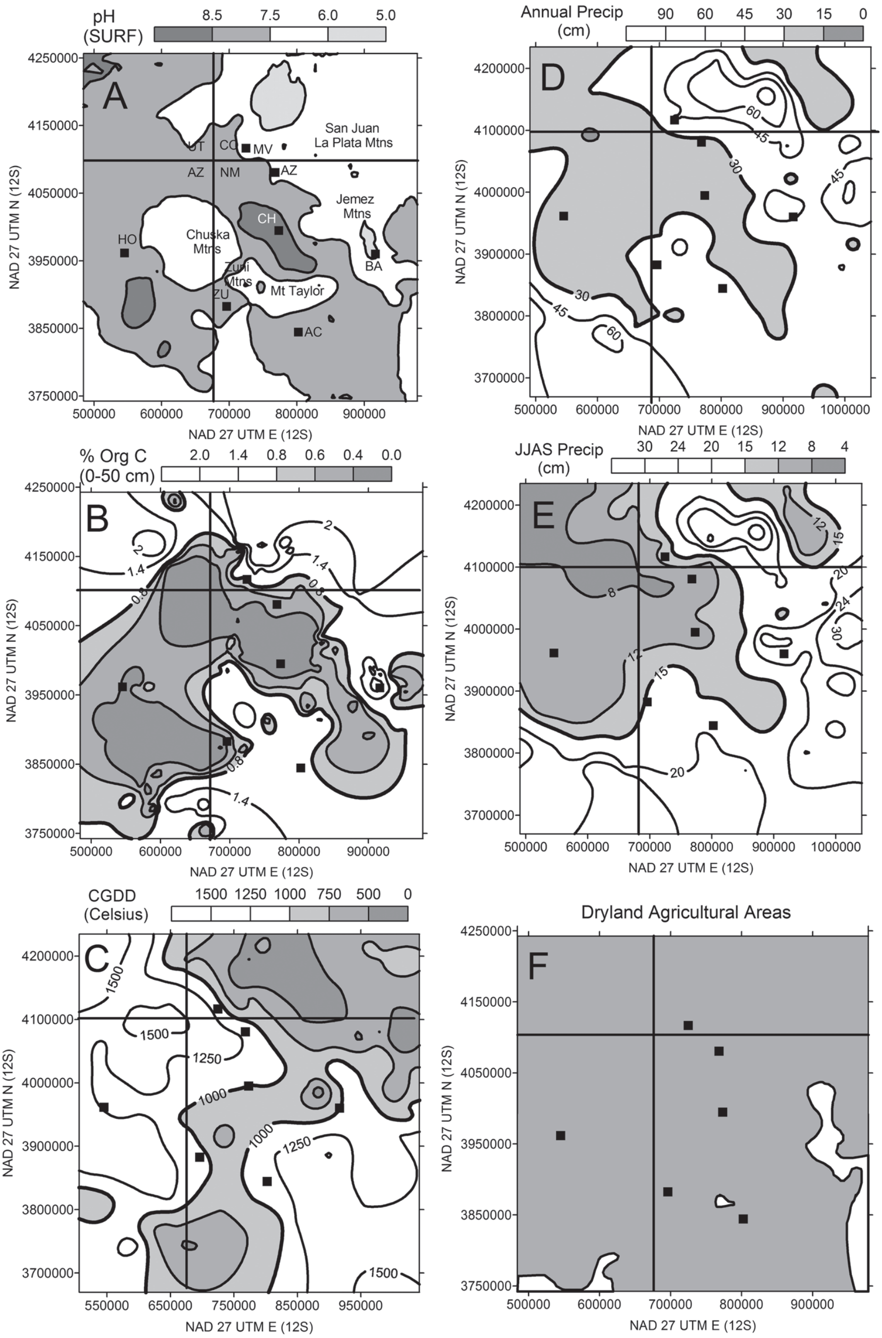
The above-ground maize plant contains about 3.3 g nitrogen (N) (calculation using data on mean grain, cob, and stover weights from Shinners and Binversie [2007] and mean N concentrations in grain, cob, and stover from Sawyer and Mallarino [2007]). Thus, an early historical Southwestern Native American corn field having a plant density of 2100 plants/acre (see, e.g., Bradfield 1971) would remove slightly less than 7 kg of N per year. Maize uses nitrate nitrogen (NO_3-N), which is produced by the mineralization of TON. Rates of TON mineralization range from 1.5 to 3.5% per year, with the higher rates occurring in warm and humid environments (Waksman and Gerretsen 1931).

With respect to TOC and TON, Zuni agricultural fields are still viable with respect to the growing of maize (Homburg 2000) , and we use soil-chemistry data from Zuni fields to set the minimum TON limit for reliable maize production in the southern Colorado Plateau. The top 1 m of soil in uncultivated Zuni fields contains 0.076% TON (Homburg 2000) , and the mean TOC/TON ratio in soils throughout the southern Colorado Plateau is 10.6 ± 4.5 (670 samples from 166 soil pedons[2]) (USDA Soils Data). Herrmann (2003) has noted that "Gross nitrogen mineralization is proportional to C mineralization in soils, so that C mineralization may be used as a predictor for gross N mineralization." Because pedon-based TOC values are more commonly measured than TON values, we converted existing TOC values from 192 pedons to TON values using the mean TOC/TON ratio. Thus, on average, a 0.076% TON value is equivalent to a TOC value of 0.81%, the value we used to determine whether dryland farming of maize is feasible from a nitrogen standpoint.

The negative log of the hydrogen ion concentration (pH) affects the availability of both N and phosphorous (P). Transformation of ammonia N (NH_3-N) to NO_3-N is favored by soil-water pH values <7.1, and volatilization of N occurs at high pH values; e.g., Rao and Batra (1983) observed that 62% of applied NH_3-N was lost in 10 days when applied to an alkali soil with a pH of 10.2. With respect to P, Olson and Sander (1988) have shown that a majority of calcareous soils with pHs in the range of 7.5–8.5 are deficient in P for optimum corn production because at pHs >7, phosphate minerals with extremely low phosphate (PO_4^{3-}) solubilities form. Therefore, we will assume that pH values >7.5 are non-optimal for growing corn in the southern Colorado Plateau.

Contour plots of pH, TOC, CGDD, and annual and summer precipitation (Figure 2A–E) demonstrate the difficulty of dryland maize farming within the study area if water is not concentrated. We plotted CGDD instead of the FFD because the calculation of CGDD included the length of the freeze-free period and also because both plots yield nearly identical results in terms of areas where maize cultivation is risky. In general, throughout the study area, where it is warm enough to grow maize, precipitation tends to be low and the soil tends to be depleted in TOC—our proxy for TON. pH tends to be appropriate for farming in and at the edge of high-elevation areas (e.g., the San Juan LaPlata Mountains) where, unfortunately, the growing season is short (compare Figure 2A and C).

Superposition of the five plots (Figure 2F) indicates that only a small part of the study area is suitable for dryland farming under present-day (1970–2000) climatic conditions, which are relatively warm and wet compared to mean conditions that typified the past two millennia (see Figure 4 in Salzer and Kipfmueller 2005 and Figure 2 in Cook et al. 2004). The climate data portrayed in Figure 2 indicate that dryland farming is problematic within the study area; however, Figure 2C–E indicates average climatic conditions only for the period 1970–2000. In


pH (SURF)
8.5 7.5 6.0 5.0
A
San Juan La Plata Mtns
UT CO MV
AZ NM AZ
Jemez Mtns
CH
HO
Chuska Mtns
Zuni Mtns
Mt Taylor
ZU
BA
AC
Annual Precip (cm)
90 60 45 30 15 0
D
% Org C (0-50 cm)
2.0 1.4 0.8 0.6 0.4 0.0
B
JJAS Precip (cm)
30 24 20 15 12 8 4
E
CGDD (Celsius)
1500 1250 1000 750 500 0
C
Dryland Agricultural Areas
F
NAD 27 UTM N (12S)
NAD 27 UTM E (12S)

the past, when the climate was warmer and wetter, dryland farming would have been feasible in parts of the study area. In addition, maize could have also been grown in settings where surface-water could be concentrated, e.g., within side-valley tributary and alluvial fan settings (ak-chin and check dam farming). Even if dryland farming is problematic over much of the region, there have always been some areas where maize usually could be raised; e.g., the Zuni and their ancestors have relied on localized thunderstorms to supply water and nutrients to fields located on side-valley alluvial fans for most of the past 2,000 years (Muenchrath et al. 2002). Bellorado (2007) has recently demonstrated that high yields of maize can be realized today in the Durango District of southwestern Colorado. However, during intense and persistent drought periods, there is little overland flow that can be concentrated and applied to fields, and if winter storms fail to provide sufficient soil moisture, seeds fail to germinate and sprout. Thus, maize will not be produced no matter the amount of summer precipitation.

The Pacific Decadal Oscillation (PDO) has a spatial pattern similar to the El Nino Southern Oscillation (ENSO); i.e., during a La Nina period or negative PDO period, the Southwest tends to experience relatively dry winters. However, the PDO has a very different duration, having a pseudo-cyclicity ranging from 50 to 70 years (MacDonald and Case 2005) when the pseudo-cyclicity of ENSO ranges from 4 to 7 years. Benson et al. (2007) compared historical water-year (October 1 through September 30) precipitation with the PDO in the greater San Juan Basin, New Mexico and Colorado, and showed that negative PDO conditions were accompanied by reduced precipitation. Benson et al. (2007) also compared tree-ring-based reconstructions of the PDSI with coral and tree-ring-based reconstructions of the PDO and showed that drought in the San Juan Basin is generally associated with a negative PDO. Winter drought is frequently accompanied by drought during the following summer; e.g., if we define drought as occurring when annual precipitation is one standard deviation or more less than the long-term average, summers (May, June, July, August) were drier than average during eight out of nine drought years in Mesa Verde between 1924 and 2008 and also were drier than average during 14 out of 14 drought years in Chaco Canyon between 1933 and 2008. We suggest that the megadroughts discussed in following sections of this paper were associated with negative values

FIGURE 2. Contour plots of A. soil-surface pH (298 sites), B. organic carbon in top 50-cm of soil (235 sites), C. corn-growing degree days (125 weather stations), D. annual precipitation (140 weather stations), and E. summer precipitation (140 weather stations). Dark areas in the contour plots are areas in which a particular parameter is non-optimum for the production of maize. White area in F. indicates areas where dryland (rain-fed) farming of maize is feasible; this plot results from the superposition of A–E. Filled rectangles indicate archaeological sites/areas; i.e., MV = Mesa Verde; AZ = Aztec Ruin; CH = Chaco Canyon, BA = Bandelier; ZU = Zuni; AC = Acoma, and HO = Hohokam region.

of the PDO which were and are characterized by substantial decreases in winter precipitation.

Floodplain irrigation via canal systems or ditches was implemented in a major way by the Hohokam culture (e.g., Wilcox and Shenk 1977; Masse 1991); however, evidence for widespread floodplain agriculture (including irrigation) in the Southwest outside the Hohokam region is extremely limited. In part, this may be due to the difficulty of preserving irrigation features in active floodplains. In the Totah area, Newberry (1876) documented two irrigation ditches at Aztec, and Earl Morris identified an irrigation ditch that followed the Animas River from its confluence with the San Juan River to Aztec (Reed 2008). In addition, Vivian (1974) has documented irrigation features located on the north side of Chaco Wash in Chaco Canyon, New Mexico; however, we do not know how effective or long-lived such attempts at irrigation were.

Whereas some authors have attributed the continued existence of Rio Grande Pueblos to the implementation of irrigated farming, archaeological survey and excavation data have demonstrated that large ancient agricultural areas in the Rio Grande area were most often associated with rainfall-fed field systems (Cordell 1997). Three factors weigh against floodplain agriculture, not only in the Rio Grande surface-water system, but also in areas drained by the San Juan and Little Colorado rivers. First, these rivers and their tributaries have highly variable flow regimes; second, their floodplain soils can become too salty to raise corn, and third, floodplain incision can prevent both irrigation and farming on floodplain surfaces.

The discharges of small ephemeral tributaries such as the Rio Chaco and the Rio Puerco of the East are especially hazardous to crops because summer monsoon convective events can lead to extreme discharge events. During such events, crops planted in the floodplain will be eradicated and maize planted after such floods face a much abbreviated growing season.

Although the large snowpack-fed rivers of the Southwest are less variable, their flow regimes certainly complicate the raising of maize, e.g., early historic farming of the San Juan River proved extremely difficult. Bluff, Utah, was settled by Mormons in 1880 and a ditch from the San Juan River was excavated to facilitate farming. By August 1880, water had broken out of the ditch and by 1881 a new ditch was required (McPherson 1995). In May 1882, the ditch washed out beyond repair and the community excavated another ditch five miles upstream (Hurst 1979). In 1883, the community had problems with the new ditch, and during the flood of 1884 the ditch and headgate were destroyed (McPherson 1995). To complicate matters even further, in 1896 the San Juan River carried no water during the irrigation season (Hurst 1979). In response, many of the early settlers gave up agricultural pursuits and became cattlemen.

The floodplains of these rivers also tend to accumulate salts when the shallow groundwater beneath the floodplain is subjected to evaporation and evapo-

transpiration. In a recent study, three soil samples from the San Juan floodplain immediately south of Salmon Ruin, Bloomfield, New Mexico, were found to have conductivities ranging from 7.7 to 19.5 dS/m (deciSiemens/meter) (supplementary Table 1 in Benson et al. 2009). Maize is sensitive to salinity, and yields of modern irrigated crops begin to decline when conductivity exceeds ~1.7 dS/m. At a conductivity of ~6.5 dS/m, maize yields approach zero (Maas and Hoffman, 1977); thus, San Juan River floodplain soils in the vicinity of Salmon Ruin are today too saline to grow maize. With respect to the Rio Grande floodplain, Fossberg (1979) found that during the fourteenth and fifteenth centuries, agricultural soils near the Cochiti Pueblo developed heavy concentrations of salt, suggesting that this land would have been removed from cultivation.

Arroyos are incised ephemeral-stream channels in the American Southwest that form during periods of erosion and aggrade during periods of sediment deposition (Elliot et al. 1990). Bryan (1941) and Hack (1942) were among the first geologists to document numerous incision and aggradation cycles in the Southwest. Elliot et al. (1990) have shown that, during the Holocene, many channels did not incise or aggrade isochronously with other channels in the Southwest. Drought which reduces vegetative cover that armors a floodplain combined with a major flood event can lead to incision (e.g., Bryan 1941; Hack 1942). A post-incision valley floor initially may lie several meters below the pre-incision valley floor, thus isolating the pre-incision valley floor from all but the most catastrophic flood events. Farming the post-incision valley floor is risky given that the reduced valley width increases water velocity and level such that "normal" summer convective events will often result in flooded crops. Therefore, farming the pre-incision valley floor is generally impossible until aggradation has raised the post-incision valley floor to near the elevation of the pre-incision valley floor. The complete aggradation of an incised arroyo can take a few to several hundred years to complete (Elliot et al. 1990). For example, since 1936, about 27% of the cross-section of the incised Rio Puerco of the East has filled with sediment (Friedman et al. 2005); if filling continues at this rate, it will take about 240 years for the Rio Puerco to completely aggrade.

Obviously there were times and places in the Southwest when floodplain farming was tenable; however, incision events that lasted for hundreds of years, frequent summer flooding, and gradual increases in the salinities of floodplain soils were sources of agricultural instability in the prehistoric Southwest. These observations reinforce our argument that it was inherently difficult to produce a reliable maize crop from year to year in the Southwest, whether farming occurred by strictly dry-land methods (rainfall-fed farming), whether it involved the diversion and concentration of overland flow (e.g., ak-chin, check dam, and earth-berm farming), or whether it involved the farming of floodplains.

In order to deal with environmental risk, prehistoric Southwestern Native Americans employed a diverse set of agricultural strategies that were designed to

counter most forms of environmental stress (see, e.g., Travis, 1990). This strategy allowed for the successful cultivation of maize in some agricultural niches that were relatively free of environmental stress; however, we suggest that few large agricultural niches persisted during the multidecadal megadroughts that occurred in the study area over the past two millennia (see, e.g., Cook et al. 2004).

TREE-RING DATES AND DEMOGRAPHIC CHANGE IN THE AMERICAN SOUTHWEST

In general, when we speak of "demographic change" we are referring to fluctuations of size, settlement aggregation, and movement of human populations.

Within the southern Colorado Plateau, only a fraction of the huge number of sites (and their timbers) has been sampled; nevertheless, a large number of tree-ring dates exist and cutting-date accuracy permits an almost annual resolution of timber harvesting and construction histories. On the other hand, timber sampling has not been done in a random or regular fashion; thus, the sampling of timber is biased towards those sites that exhibit sample preservation and those on which archaeologists have chosen to focus. Most of the tree-ring dates obtained during the past few decades have come from sites that were excavated because they were going to be destroyed by highway, pipeline, or reservoir construction. Many tree-ring dates have also been obtained on large extant structures such as great houses and cliff-house dwellings.

Although the tree-ring dates on which this study is based were not randomly obtained, few if any of the sites were selected based on whether they dated to a particular wet or dry period. As such, the process of site selection does not prejudice our comparison of changes in the intensity of timber cutting with records of climate change discussed in a later section of this paper.

Tree-ring dates are qualitative indicators of population change. Although it is impossible to equate the number of people inhabiting a structure with the number of dendrochronologically dated timbers from that structure, maxima in regional-scale cutting distributions should indicate times of accelerated tree harvesting and construction. It is reasonable to assume that population increases accompanied increases in construction although the relation between the two parameters cannot be quantitatively linked with any degree of certainty.

Prehistoric Southwestern pit houses and most small surface structures were occupied for only a few decades. With respect to repair or abandonment of Southwestern Native American structures, Cordell (1997) has stated that Hohokam pit houses were used for about 15 years, and Schlanger (1988) has shown that pit structures in the Dolores area also had average life spans of about 15 years. In addition, Crown (1991) showed that adobe rooms at Pot Creek Pueblo (Figure 3) had a mean repair interval of 19 years and suggested that this interval represented the use life of those rooms. At the Sand Canyon locality (Figure 3) in the Mesa

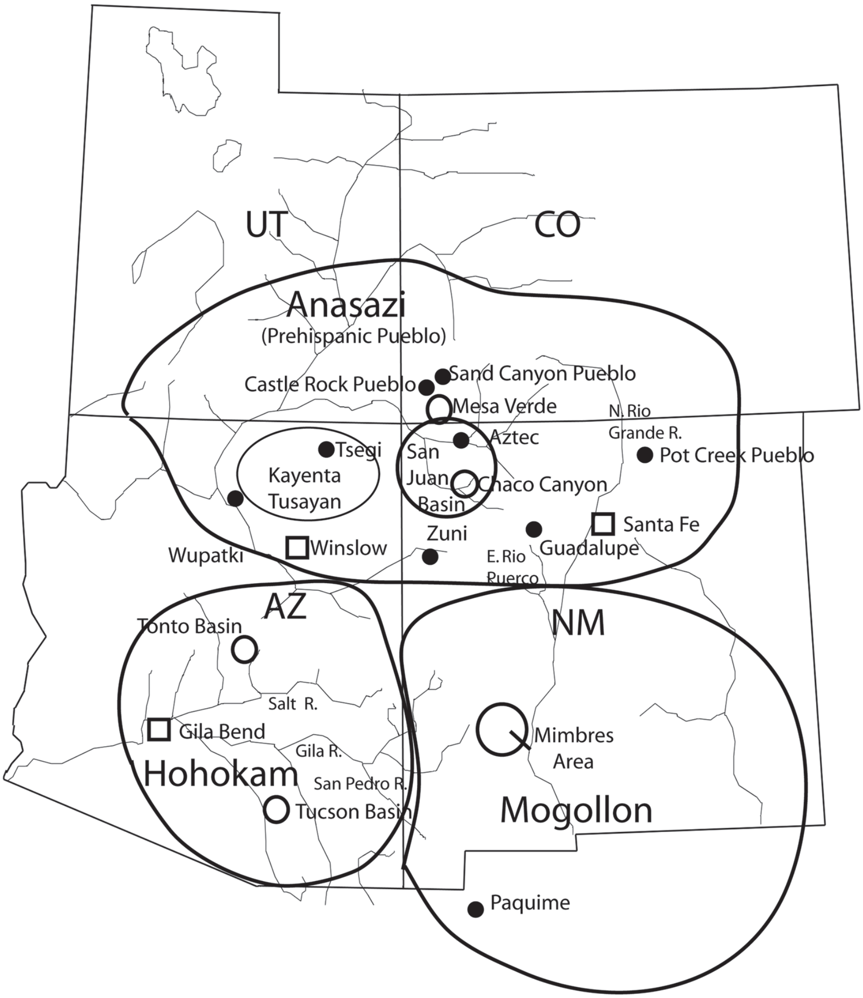


FIGURE 3. Locations of cultural traditions (Anasazi, Hohokam, and Mogollon), archaeological areas (empty circles), archaeological sites (small filled circles) and present-day cities (empty squares) mentioned in the text.

Verde region, Pueblo II sites were occupied for ~20 years and Pueblo III sites for ~40 years (Varien 1999). If very large pueblos are excluded from dated sites on the Colorado Plateau, the mean occupation of small sites (<10 rooms) is ~34 years (Hantman 1983).

Even during times of environmental and cultural stress, population aggregation involves construction activities. This implies that timber harvesting and

construction should have persisted even when populations were static or decreasing and that minima in cutting-date distributions indicate times of population decline. However, the rate of decline in cutting dates does not necessarily indicate the rate of population decline.

Approximately 24,000 tree-ring dates are available from prehistoric structures in the eight archaeological regions considered herein (Figure 1); 8,606 of these dates are tree "death" dates and another 3,095 are "v" dates accurate to within a few years of the timber harvest date. In the following, we rely on "death" and "v" dates (hereafter referred to collectively as tree-ring dates) for interpretation, ignoring "vv" dates, the temporal placement of which is earlier than the construction event of interest by an unknown time span.

TREE-RING DATES AND CLIMATE CHANGE

In Figure 4, the pan-regional tree-ring-date distribution for the study area is compared with the mean PDSI of nine sites within the study area (site locations are shown as solid circles in Figure 1) and with the mean of six normalized tree-ring-based reconstructions of annual precipitation for sites within and on the edge of the San Juan Basin (data from Benson et al. 2007 and references therein) for the period A.D. 900 to A.D. 1400.

Cook et al. (2004) have published summer (June–July–August) PDSI values for gridded locations across much of North America. The PDSI value is a theoretical measure of available soil moisture calculated from monthly temperature and precipitation. This index was specifically designed to evaluate drought impacts on agriculture (Palmer 1965); PDSI values range from −6 (extreme drought) to +6 (extreme wet). It is not a measure of summer precipitation; it is a measure of accumulated soil moisture as of summer and may integrate several months of climate variability. The method used to calibrate the PDSI with historical tree-ring widths and the application of that calibration to long tree-ring records is detailed in Cook et al. (1999). Negative PDSI values indicate dry conditions, whereas positive values indicate wet conditions.

The drought contour reconstructions are based on a 286-point grid of instrumental PDSIs. The tree-ring network used for PDSI reconstruction over North America originally was composed of 835 annually resolved records. A revised network containing 1,825 records is now available (Cook personal communication 2009) and has been used in this paper.

Of particular interest are two megadroughts (D3 and D4) that occurred between A.D. 1130–1177 and A.D. 1273–1297, respectively, separated by two overall wet periods (W1 and W2) that occurred between A.D. 1040–1129 and A.D. 1193–1269. For the purposes of this paper, a megadrought is defined as a dry period that spans more than 20 years, that has PDSI values ≤−1 for at least 60% of the years within the dry period, and that contains at least two >3 consecu-

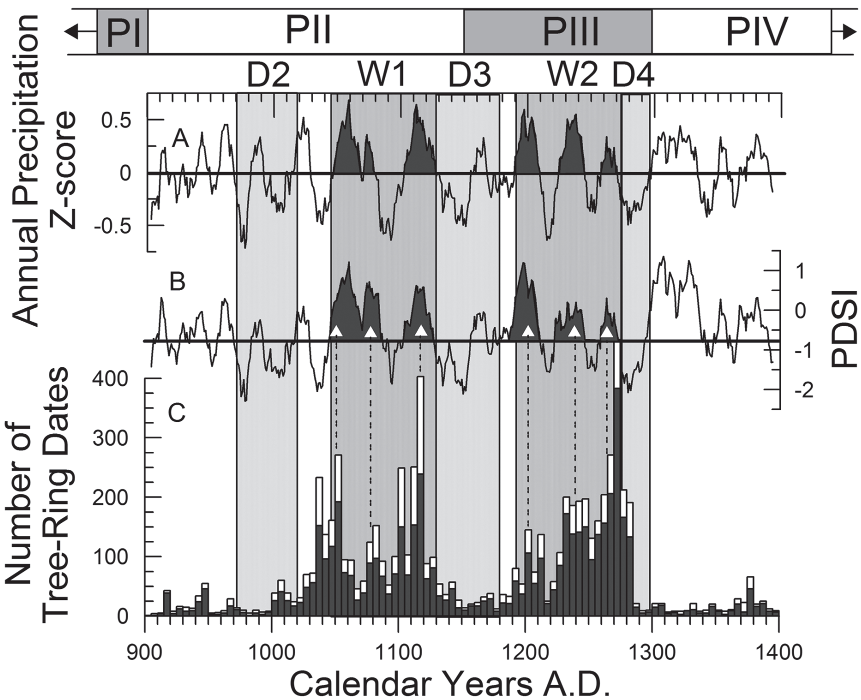


FIGURE 4. Comparison of pan-regional tree-cutting-date distribution with two climate indices and archaeological stage boundaries. A. Mean of six normalized tree-ring-based precipitation records from sites within and at the edge of the San Juan Basin. B. Mean of nine PDSI records from the southern Colorado Plateau. Baseline has been set at a PDSI of –0.5, the mean value for the past 2,000 years. PDSI and precipitation values have been smoothed with an 11-year running average. C. Distribution of tree-ring dates for the period A.D. 900–1400. Black values indicate "death" dates and white values indicate "v" dates. Three megadroughts (D2–D4) have been colored light grey; two extended wet periods (W1–W2) have been colored dark grey. Dashed lines between cutting-date distribution and PDSI curves during W1 and W2 indicate correlations of exceptionally wet times with intense tree harvesting and construction. BM indicates Basketmaker and P indicates Pueblo cultural stages.

tive-year droughts with PDSI values ≤–1. Megadroughts depicted in Figure 4 include the well-known middle-twelfth- and late-thirteenth-century droughts (D3 and D4) discussed most recently in Benson et al. (2007).

Berry (1982), building on the tree-ring-date record of Euler et al. (1979), showed that Southwestern cutting-date distributions could be used to estimate major punctuated changes in population and further suggested that those changes

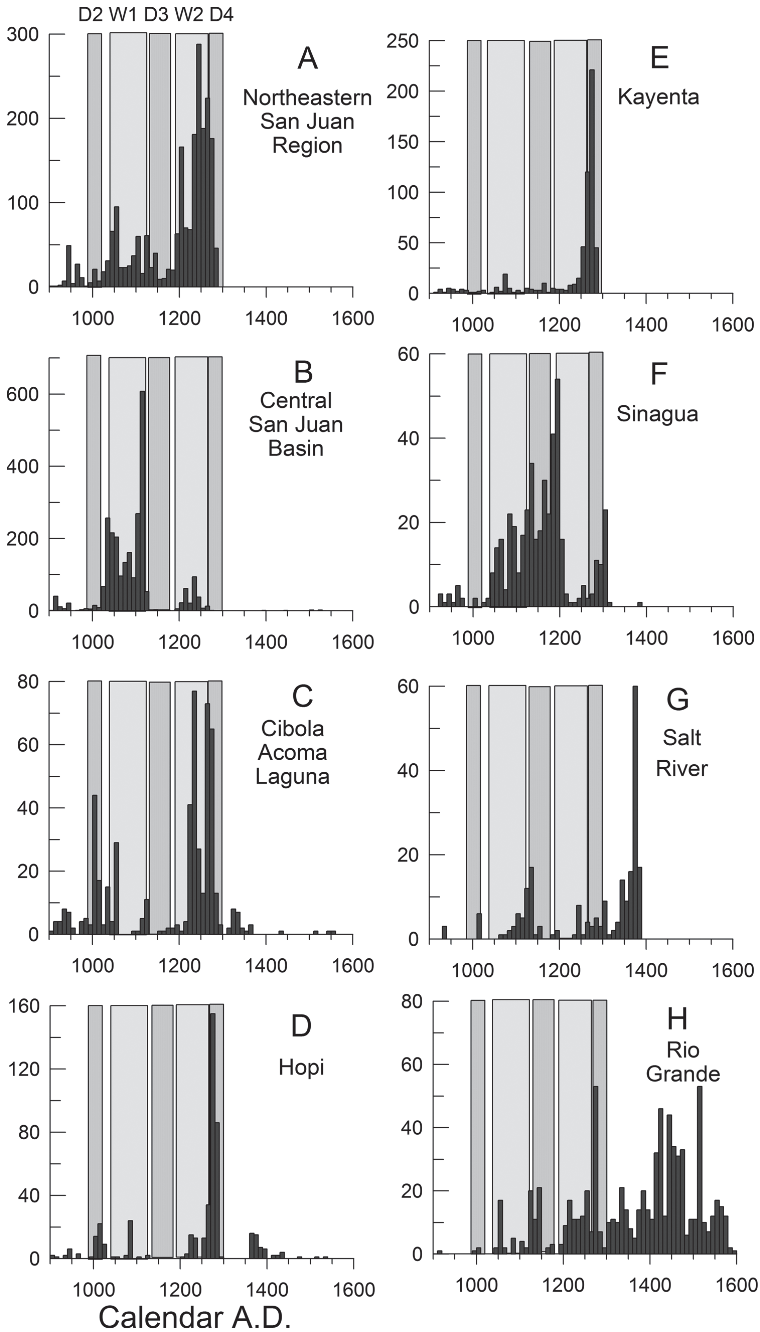
resulted from climate cycling. He used cutting dates from ~700 sites to create a tree-ring-date distribution from A.D. 600 to 1600, which is almost identical in overall shape to the one featured in this paper based on 11,701 dates, indicating the overall stability of the form of the pan-regional cutting-date distribution.

The climate and cutting records for the overall study area depicted in Figure 4 indicate a strong correlation between annual precipitation and construction; e.g., the two generally wet intervals correlate with times of increased construction and the three dry periods correlate with times of reduced construction. Even decadal-scale changes in the intensity of construction activity correlate with changes in the PDSI (dashed lines linking Figure 4B and 4C).

Regional timber harvesting, building construction, and changes in population density between A.D. 860 and 1600 in each of eight archaeological regions can also be related to climate change (Figure 5). Most of the regions (with the exception of the Sinagua and Salt River regions, Figure 5F, G) exhibit cutting-date minima during the three megadroughts. The Sinagua region, in the Wupatki Basin of northern Arizona, appears to have acted as a refugium during D3. Three of the regions (the northeastern San Juan Basin, the central San Juan Basin and the Sinagua) exhibit accelerated tree harvesting during W1 (Figure 5A, B, F). Regional increases in tree harvesting also occurred during W2 (except in the Salt River region, Figure 5G). Construction in the Cibola-Acoma-Laguna, Hopi, Salt River, and Rio Grande regions continued through the late-thirteenth-century megadrought and increased after the drought (Figure 5C, D, G, H). These data suggest that population fluctuations and the redistribution of humans across most of the study area between A.D. 975 and 1297 were associated with multi-decadal megadroughts and anomalous wet periods.

Tree-ring-date distributions for the five most thoroughly sampled great houses in the Chaco Canyon and Totah regions of the central San Juan Basin are shown in Figure 6. The distributions indicate that most of the construction of the three Chaco Canyon (Figure 3) great houses (Pueblo Bonito, Chetro Ketl, Pueblo del Arroyo) occurred during the A.D. 1045–1130 wet period and was terminated by initiation of the middle-twelfth-century megadrought (D3) (Figure 6A–C). In the Totah region, construction of Aztec West (Figure 3) peaked during the latter part of the W1 wet period and was terminated by D3 (Figure 6D). Construction of Aztec East also began during the W1 wet period but slowed markedly during D3; construction then peaked during W2 and was terminated by the onset of the late-thirteenth-century megadrought (D4) (Figure 6E).

FIGURE 5. Tree-cutting-date distributions for the eight archaeological regions depicted in Figure 1. Dark-grey vertical rectangles indicate times of megadrought (D2–D4); light-grey vertical rectangles indicate anomalously wet periods (W1–W2). The numbers in the parentheses indicate how many tree-ring-dates were used in each plot.


D2 W1 D3 W2 D4
A
Northeastern San Juan Region
B
Central San Juan Basin
C
Cibola Acoma Laguna
D
Hopi
E
Kayenta
F
Sinagua
G
Salt River
H
Rio Grande
Calendar A.D.

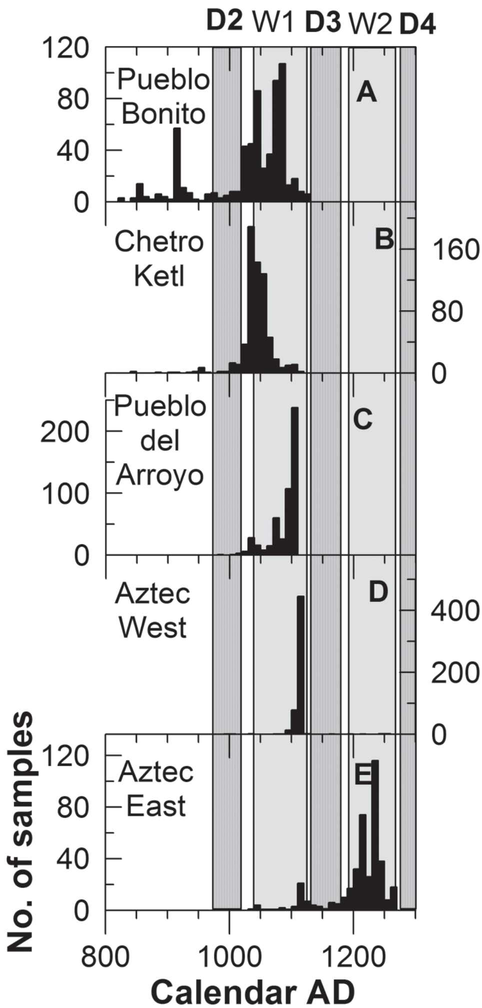


FIGURE 6. Cutting-date distributions for (A–C) three Chaco Canyon and (D–E) two Totah great houses compared with megadroughts D2–D4 and anomalously wet W1–W2 periods. Note that cutting-date minima occur during times of megadrought and cutting-date maxima occur during wet periods.

CLIMATE CHANGE AND POPULATION RESPONSE IN THE STUDY AREA

In the following, we focus on the A.D. 1045–1130 wet period (W1) and megadroughts D3–D6 depicted in Figure 7. As defined below, W1 witnessed accelerated building activity in the central San Juan Basin, including the construction and remodeling of 13 great houses in Chaco Canyon, New Mexico (Lekson 1986), as well as the construction of numerous great houses across the entire Four Corners area (Fowler and Stein 1992; Judge 1989; Stein and Fowler 1996). At the same time, a shift to above-ground structures and population expansion into agriculturally marginal areas occurred in the Mimbres area (Figure 3) of southwestern New Mexico (LeBlanc 1989). During W1, western Anasazi populations filled nuclear areas in Kayenta, Tusayan, and Winslow (Figure 3) and then expanded outward, attaining their greatest geographical distribution.

Most of the Anasazi great houses were vacated during the middle-twelfth-century megadrought (D3) (Marshall et al. 1979). In the northern San Juan Basin, Brown et al. (2008) have attributed the slow and intermittent construction of the Aztec East great house during D3 to "a sustained period of hardship associated with epic drought." During W1, the Mimbres valley reached its carrying capacity with a few large villages present along major drainages; however, during D3 the Mimbres area underwent a cultural reorganization. The large villages in the eastern region were abandoned, the population dispersed, and field houses were remodeled into small hamlets (Hegmon et al. 1998). During D3, western Anasazi

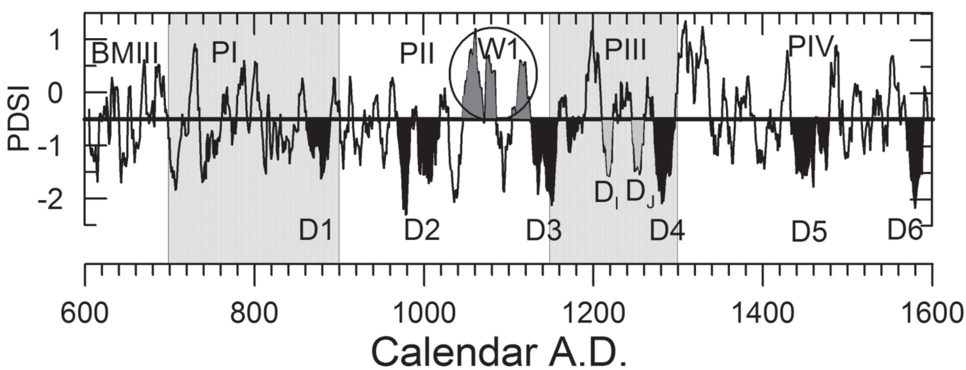


FIGURE 7. Comparison of the timing of megadroughts (defined in text) within the study area with the timing of archaeological stage boundaries. BM indicates Basketmaker; P indicates Pueblo cultural stages. PDSI values have been fit with an 11-year running average. PDSI baseline has been set at a PDSI of –0.5, the mean value for the past 2,000 years. Six megadroughts (D1–D6) have been colored black; two non-megadroughts (DI and DJ) have been colored light grey; and one extended wet period (W1) has been enclosed within an ellipse and colored dark grey.

settlement changed rapidly, with populations withdrawing from peripheral areas and returning to nuclear areas (see, e.g., Gumerman and Dean 1989). In the Zuni region, substantial in-migration began about the time of the Chacoan collapse (which occurred in the early part of D3). In the Sinagua region, substantial populations persisted during D3, suggesting that this area acted as a refugium (Berry 1982; Plog 1989; Stanislawski 1963).

In the Four Corners area, the last Anasazi great houses were abandoned during the late-thirteenth-century megadrought (D4) (see Figure 2 in Benson et al. 2007). In the Mogollon region, population aggregation occurred in or before D4 with the majority of the people living in pueblos having 100 to 800 rooms (Reid 1989). In Zuni, small pueblos were abandoned when the occupants presumably moved to a very large newly constructed Pueblo (Heshot uta), having ~870 rooms (Kintigh et al. 2004). During D4, population aggregation and movement to the upper reaches of the western Anasazi drainage systems occurred (Gumerman and Dean 1989) and most of the Sinagua region was abandoned (Plog 1989).

During the early part of the late-thirteenth-century megadrought (D4), other large areas in the study area were abandoned. The Kayenta region in northeastern Arizona/southeastern Utah was abandoned by the late A.D. 1280s/early A.D. 1290s, and the Mesa Verde area in southwestern Colorado was abandoned in the early/mid A.D. 1280s (Dean et al. 1994; Varien et al. 2007). At Guadalupe Ruin, along the Rio Puerco of the East (Figure 3), Pippin (1987) documented a site-unit intrusion from the Mesa Verde or Totah areas that occurred during D4. At the same time, many of the southern Hohokam villages were abandoned and settlement shifted north to the confluence of the San Pedro and Gila rivers (Figure 3). In some northern Rio Grande districts (e.g., Taos, Jemez, Pajarito, and Santa Fe), population increased during D4, possibly in response to in-migration of groups from other archaeological regions (Crown et al. 1996).

Sites established by Kayenta migrants during D4 have been recognized in the Mogollon Highlands (Dean 1996) and in the Hohokam area of southern Arizona (Clark 2001). At the same time, demographic change occurred throughout much of the Hohokam region; e.g., the Tonto Basin (Figure 3) experienced a substantial reduction in population, and the northern Tucson Basin and Gila Bend areas (Figure 3) were abandoned (Hill et al. 2004). Shortly after D4 ended (the early A.D. 1300s), most of the Southwest's population had aggregated in about 120 compact pueblos clustered in 27 groups, suggesting a defensive posture (Adler et al. 1996; Cameron and Duff 2008; LeBlanc 1999).

Important abandonments that occurred during the A.D. 1435–1475 megadrought (D5) include the Mogollon Mountains in central Arizona (Dean et al. 1994) and the Hohokam area in southern Arizona (Hill et al. 2004; Dean 1991). Dean and Ravesloot's (1993) tree-ring-based dating of the Paquimé population center in northern Chihuahua (Figure 3) indicates that construction began there

during D4 (presumably in response to in-migration) and ended with its destruction and abandonment (DiPeso 1974) during D5. In the Southwest and northern Mexico, the abandonment of almost a dozen pueblos between A.D. 1540 and 1598 has been attributed to the D6 drought's effect on dryland farming (Schroeder 1968).

TREE-RING DATES AND ANASAZI ARCHAEOLOGICAL CULTURAL-STAGE BOUNDARIES

Six intense multidecadal megadroughts (D1–D6) occurred between A.D. 860 and 1600 (Figure 7). The pan-regional tree-ring-date distribution between A.D. 900 and 1400 consists of two sawtooth-shaped segments, each of which terminates on or slightly before an archaeological cultural-stage boundary and each of which is associated with a megadrought (Figure 4). Archaeological stages are defined by diagnostic sets of traits that suggest cultural transformation and, in the Anasazi-occupied Southwest, ceramics and architecture were first used to define the archaeological stages of the Pecos classification (Kidder 1927). That these initial formulations retain their essential validity 80 years later may now be attributed to the punctuated temporal pattern of the Basketmaker-Puebloan occupation of the Southwest.

The termination of each Pueblo stage also is associated with a megadrought, although not all megadroughts are associated with archaeological-stage transitions (Figure 7). We suggest that expanding populations declined precipitously during megadroughts, causing culturally diverse groups within the study area to aggregate in drought-survivable refugia. Aggregation further resulted in alterations of material culture that proved sufficient to define archaeological-stage transitions. The dates assigned to archaeological-stage transitions have evolved over time and represent a somewhat subjective consensus of Southwestern scholars; thus, they lack the precision of the tree-ring-based climate and timber-harvesting reconstructions presented herein. It seems clear, given the data now available, that the correlation of the tree-ring-based data sets with the stage boundaries is meaningful.

DIFFERENCES IN THE INTENSITIES AND DURATIONS OF PREHISTORIC SOUTHWESTERN DROUGHTS

One criticism frequently leveled at correlations between drought and demographic change is that not all droughts are associated with demographic change; e.g., "why did this particular drought cause the Shmoo to vacate Dogpatch but the previous drought had little discernable effect on Shmoo movement?"

It has been previously pointed out that "prolonged droughts exhibit different annual attributes" (Dean and Van West 2002), which are due to the nonstationary nature of climate change. In Figure 8A, B we have plotted parameters

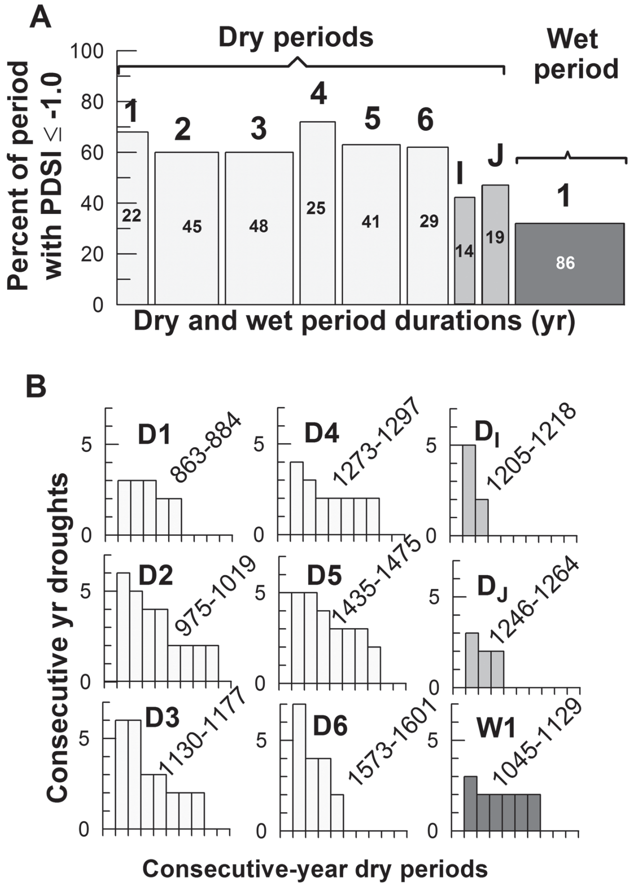


FIGURE 8. Duration and intensity of megadroughts, two non-megadroughts, and one anomalously wet period. The dry and wet periods are shown in the PDSI plot in Figure 7. A. Duration of megadroughts (light-grey rectangles), typical non-megadroughts (medium-grey rectangles), and one wet period (dark-grey rectangle). Labels within rectangles indicate length (years) of wet and dry periods. Height of rectangles indicates percent of years with PDSI of <–1. B. Number of ≥2-consecutive-year droughts during wet and dry periods. The height of each rectangle is equivalent to the number of consecutive years that the PDSI was <–1; e.g., megadrought D1 lasted 22 years; 64% of those years were characterized by PDSI values that were <–1; the overall drought contained three 3-consecutive-year droughts, and two 2-consecutive-year droughts.

relating to the duration and the intensity of the six megadroughts and contrasted them with two non-megadroughts (D_I and D_J) that occurred between megadroughts D3 and D4 (Figure 7). Also shown are the climatic characteristics of the W1 wet period.

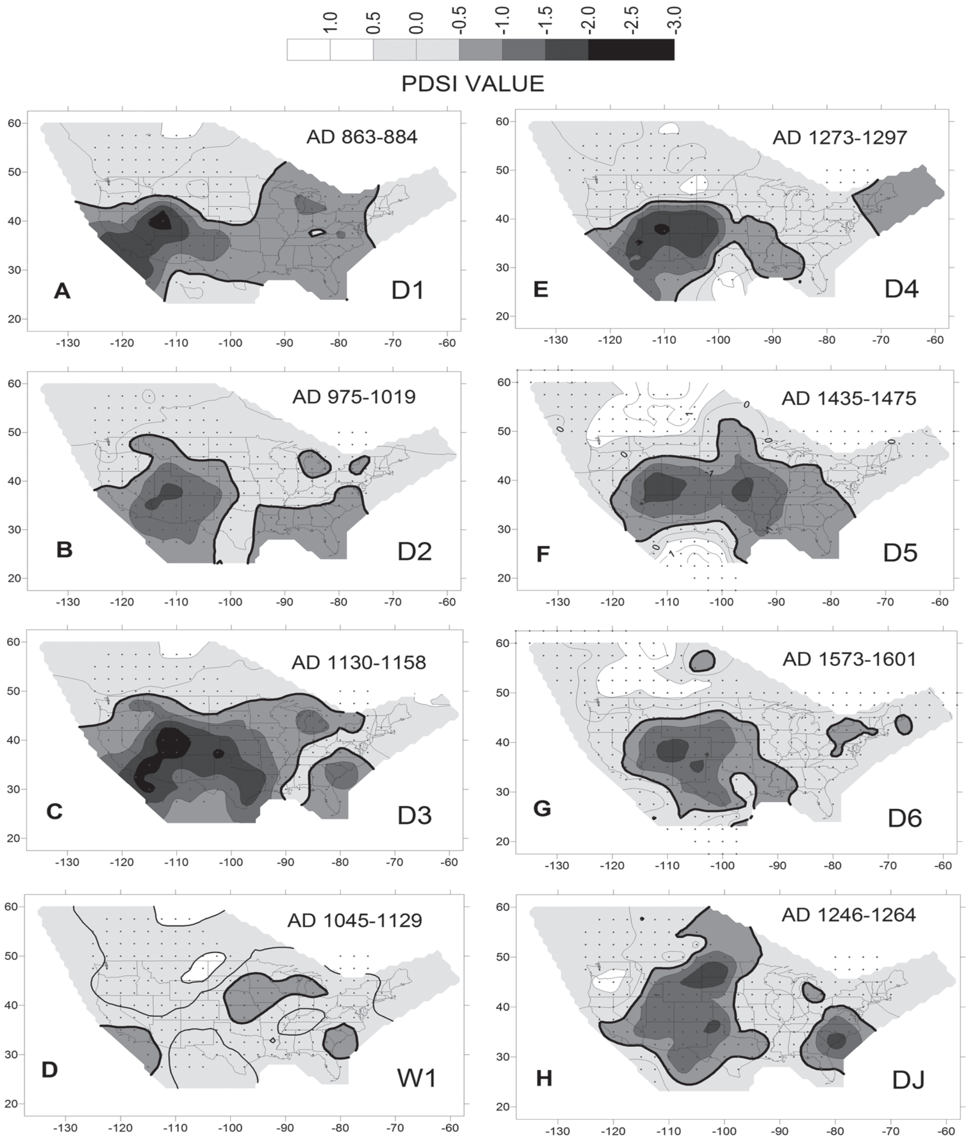
The six archaeological megadroughts lasted from 22 to 48 years, during which time PDSI values of <–1 occur 60–72% of the time (Figure 8A). Each of the six megadroughts contained several consecutive-year drought periods (each year having a PDSI of <–1) ranging from two to six years (Figure 8B). In contrast, the two non-megadroughts lasted only 14 and 19 years, respectively, and had PDSI values of <–1 42–47% of the time. In addition, these two periods contained far fewer and shorter-duration consecutive-year drought periods compared with the megadroughts (Figure 8B).

Ethnographic data indicate that the historic Pueblos attempted to store enough food to sustain themselves through 2–3 years of drought (Burns 1983). We suggest that the six multidecadal megadroughts, which hosted several successive-year intervals having PDSI values of <–1, strongly impacted both prehistoric Native American agriculture and wild food resources and that the non-megadroughts (e.g., D_I and D_J) were not sufficiently intense and persistent to elicit marked human response. In addition, the successive-year drought intervals may have caused prehistoric Native Americans to consume the corn kernels they normally kept for future plantings.

The spatial natures of the six megadroughts (D1–D6), the A.D. 1045–1129 wet period (W1), and the A.D. 1246–1264 non-megadrought (D_J) are illustrated in Figure 9. During a megadrought, most of the Four Corners states have mean PDSI values of <–1 and there exist regions within the Four Corners states that have PDSI values between –1.5 and –2.0, indicating severe drought. During a non-megadrought such as D_J, the PDSI value does not reach –1.5. For the Four Corners states, the 86-year W1 wet period is characterized by a mean PDSI value of >–0.5—the mean PDSI value for the past 2,000 years—suggesting a time when agriculture was feasible over much of the study area.

CONSEQUENCES OF MEGADROUGHT: AGGREGATION, POPULATION DECLINE, AND MIGRATION

We also suggest that climate deterioration at archaeological-stage transitions led to competition for scarce resources. Drought negatively impacted dryland farming of crops in regions of high population density where some natural resources (e.g., large game) had already been depleted by human exploitation (Adams and Bowyer 2002). In the northern San Juan region, Muir and Driver (2002) showed that during Pueblo III, when densely settled areas were experiencing declines in artiodactyl populations, protein-based diets were supplemented with domestic turkey.


1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
PDSI VALUE
AD 863-884
A
D1
AD 1273-1297
E
D4
AD 975-1019
B
D2
AD 1435-1475
F
D5
AD 1130-1158
C
D3
AD 1573-1601
G
D6
AD 1045-1129
D
W1
AD 1246-1264
H
DJ
60
50
40
30
20
-130
-120
-110
-100
-90
-80
-70
-60

Scudder (1993) has shown that present-day relocated populations are open to accelerated economic and social changes. In order to protect human life and vital resources, culturally diverse groups in the study area aggregated and cultural exchange ensued; e.g., the abandonment of the Tusayan and Kayenta regions (Figure 3) during D4 led to mixing of previously distinct cultures (Hill et al. 2004). Transformation of material cultural variants could occur at these stress-laden times with the most successful variants appearing on the other side of the stage boundary, a process which accounts for the correlation of some megadroughts with archaeological stage boundaries.

Aggregation also leads to disease and increased mortality (e.g., LeBlanc 1999 and references therein; Martin 1994). In addition, mortality may have been exacerbated by increased violence; e.g., numerous individuals died violently at Castle Rock and Sand Canyon Pueblos (Figure 3) in the Mesa Verde region during the late A.D. 1280s (Kuckelman et al. 2002).

The presence of cutting-date minima over a broad region of the Southwest during D2, D3, and D4 (Figure 4) suggests that the phenomena (droughts) that lead to population decline were operating on a very large spatial scale (Figure 9). When an environmental support system continues to degrade, people may be forced to migrate to existing higher-elevation (wetter and cooler) regions (Berry 1982; Adams and Duff 2004) or to regions outside the impacted area where unused arable land exists (e.g. irrigated lands could be expanded during D4 in the Hohokam region, Figure 3). This concept is consistent with the findings of Euler et al. (1979) who argued that "Population increases associated with wetter periods generally occurred in areas now characterized by scant surface water supplies, drier weather, and longer growing seasons . . . past environmental changes may have triggered population displacements toward wetter and cooler localities during the major droughts."

During and after the late-thirteenth-century drought, farmers in the northern Rio Grande region had access to a wider range of agricultural options than did Mesa Verde farmers (Ahlstrom et al. 1995). However, tree-cutting minima associated with D4 occur in nearly every other archaeological region within the

FIGURE 9. PDSI contour maps for six megadroughts (A, B, C, E, F, G), one wet period (D), and one non-megadrought (H) shown in Figure 7. The early and most severe part of the middle-twelfth-century megadrought is shown in C. A PDSI value of –0.5 (the mean value in the Southwest for the past 2,000 years and shown as a thick black line in the eight panels) serves to divide relatively wet (white and light-grey) regions from relatively dry (medium-grey to black). Data used to construct these maps were taken from Cook et al. 2004. Note that the PDSI values of >–1.5 characterize the non-megadrought in the Four Corners states shown in H. The small black dots in each plot indicate locations of PDSI nodes used in construction of the contours. Note the exceptionally large areas of continental North America that experienced drought during the megadroughts.

study area, suggesting that the areal extent and intensity of D4 (Figures 6, 9E) may have led to many Native Americans simply dying in place (see, e.g., Figure 4 in Cordell et al. 2007, which shows that the late-thirteenth-century drought impacted Santa Fe as well as Mesa Verde and Tsegi). Small residual groups, moving in a piecemeal fashion, may not be able to maintain material culture diagnostics in a new cultural milieu; instead, they may be forced to adopt the culture of the preexisting population, making their cultural intrusion difficult to detect in the archaeological record. For example, virtually none of the Mesa Verde Anasazi traits show up in the northern Rio Grande region (Figure 3), the area to which they presumably moved (e.g., Cordell 1997:405; Wendorf and Reed 1955).

SUMMARY AND CONCLUSIONS

We conclude that Native Americans occupying the study area for at least the last two millennia were dependent on a maize-based economy. During relatively wet (and warm) periods, agriculture was introduced to areas that normally were unproductive. During these optimally productive periods, populations increased, expanding ever further into areas of marginal productivity. When dry (and cool) years occurred more frequently and drought set in, much of the dryland agricultural base vanished and wild-food sources were also negatively impacted, leaving a large number of people faced with a dwindling resource base. Extended drought also tended to eliminate vegetation that armored floodplains, permitting channel incision to occur, reducing floodplain-based agriculture practices. Boom gave way to bust.

In order to protect food supplies and lives from raiding parties, groups aggregated and populations declined. Aggregation provided a melting pot for diverse cultures, and the new cultural norms which evolved during these times were later used by archaeologists to define archaeological stage boundaries. Consecutive-year drought intervals, within the six megadroughts discussed in this paper, exceeded maize storage limits. When this occurred, people had to move, either laterally outside the drought-stricken region or vertically to wetter and cooler elevations. However, each of the megadroughts covered a very large part of the Southwest, making it extremely difficult to relocate to an agriculturally productive area. We believe that many Native Americans died in place or in transit, which in part explains the general lack of detectable intrusive sites established during megadrought and the small number of tree-ring dates documented for the A.D. 1130–1177 and post–A.D. 1300 periods.

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NOTES

1. This date was obtained by calibrating a 4300 B.P. ^{14}C date from Table 7-1 in Huckell (2006) using CALIB rev5.01 (Stuiver et al. 2005) after assignment of a one-sigma value of 60 years.
2. A soil pedon (pit) is the smallest unit of land surface that can be used to study a characteristic soil profile.

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