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ANASAZI (PRE-COLUMBIAN NATIVE-AMERICAN) MIGRATIONS DURING THE MIDDLE-12TH AND LATE-13TH CENTURIES – WERE THEY DROUGHT INDUCED?

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Abstract. Severe droughts in the middle-12th and late-13th centuries appear to have affected Anasazi (pre-Columbian Native American) populations. During the first drought most of the great houses in the central San Juan Basin were vacated; the second drought resulted in the abandonment of the Four Corners region. During the first drought, villages may not have been completely abandoned. The multi-year drought periods probably were characterized by reductions in both winter and summer precipitation. Maize is dependent on winter precipitation for its germination and initial growth and on summer (monsoonal) precipitation for its continued growth. Reductions in precipitation are hypothesized to have resulted in low yields of maize, the dietary staple of the Anasazi. A comparison of historic climate data and tree-ring-based reconstructions of precipitation in the Four Corners region with tree-ring-based reconstructions of the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) indicate that severe and persistent drought in the Four Corners region occurs when the PDO is negative and the AMO is positive. Historic climate data from the greater San Juan Basin indicate that a negative PDO is characterized by reductions in both water-year and summer precipitation, reinforcing the concept that at least some multi-year droughts involved weakening of the summer monsoon with attendant decreases in the yields of maize.

1. Introduction

Anasazi is the term applied to a distinctive pre-Columbian archeological tradition of the Four Corners region. As such, the term has no prehistorical political, cultural, or linguistic connotation. Between 850 and A.D. 1300 the Anasazi constructed multistory masonry buildings called great houses. The great houses often contained large rooms with high ceilings, enclosed plazas, and one or more large circular semi-subterranean rooms known as great kivas (Figure 1).

The Anasazi population expanded and contracted many times during their occupation of the Four Corners region. However two contractions are of special interest. By A.D. ~1150 the Anasazi appear to have vacated most of their great houses in the heart of the San Juan Basin and by A.D. ~1300 they had abandoned the Four Corners region (Figure 2). The times of abandonment of most San Juan Basin greathouses are based on potsherd dates and are only accurate to a few to several decades. Therefore the abandonment of many greathouses can be argued to have occurred as early as A.D. 1130 Construction and remodeling of 12 great houses



Figure 1. The Chaco Canyon Pueblo Bonito great house which at one time contained ~800 rooms and was four stories tall. Circular structures are kivas; the center of the structure is a courtyard. Photo courtesy of the National Park Service.

in the Chaco Canyon core area, which had accelerated at A.D. ~1050, abruptly terminated at A.D. ~1130 (Lekson, 1984). The initial construction phase of Aztec West (24 km upstream from the confluence of the Animas and San Juan rivers, Figure 3) also ended at A.D. 1130 although most construction was completed by A.D. 1121.

The father of dendrochronology, Andrew E. Douglass, was one of the first to suggest that the abandonment of the Four Corners region in the late 13th century was due to a persistent and intense drought that occurred between A.D. 1276 and 1299 (Douglass, 1929). Douglass suggested that the Anasazi were heavily dependent on agriculture and would have had to abandon their homes and move to better-watered areas to survive what later became known as the “Great Drought”.

Robinson and Rose’s (1979) preliminary reconstruction of seasonal precipitation for the northwestern plateau area of New Mexico indicated that an intense summer drought occurred between A.D. 1135 and 1180. The evidence of this drought was used by several authors (e.g. Gillespie, 1984; Judge, 1989) to argue that it was partly responsible for the disintegration of the Chacoan regional system at A.D. 1150 and the migration of the Anasazi out of the central San Juan Basin.

Two studies have thrown doubt on the two droughts as major “push” factors in Anasazi migrations. As Dean (1992) points out “statistical tests failed to verify Robinson and Rose’s (1979) preliminary summer-precipitation reconstruction and it was dropped from their final report (Rose et al., 1982).” More recently, Van West (1994), in a study of prehistoric agricultural productivity in southwestern Colorado,

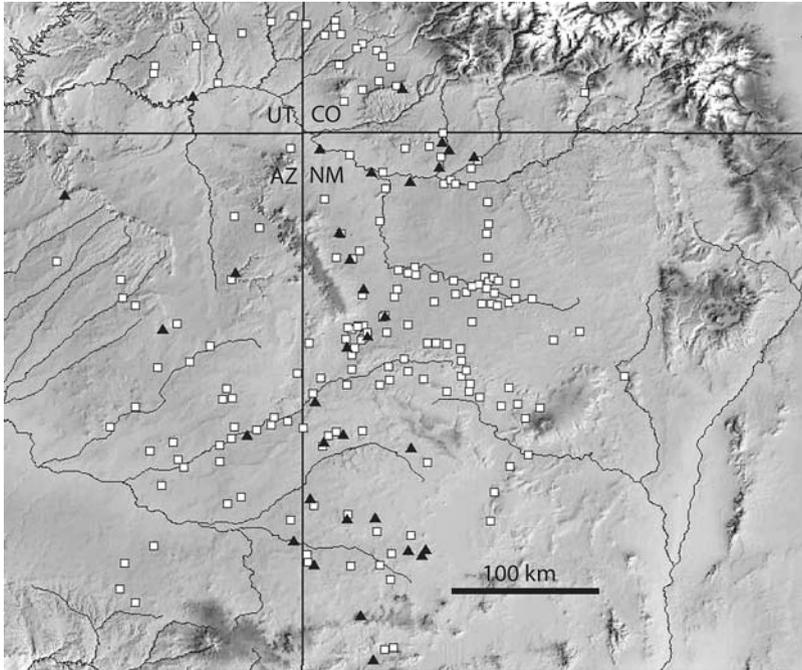


Figure 2. Anasazi great houses in the Four Corners region. The white squares indicate great-house communities that were abandoned by A.D. 1130/1150; the black triangles indicate great-house communities that persisted until A.D. 1300. Information portrayed on the map was taken from Fowler and Stein (1992); additional unpublished data on great-house locations in the southwestern and western San Juan Basin were compiled by Rich Friedman and John Stein based on fieldwork conducted between 1984 and 2004. See Figure 3 for names of rivers. All sites shown in this figure belong to the Chacoan great house tradition.

has suggested that “there *always* was enough productive land to produce enough maize to support a very large population [in the Northern San Juan region]¹. . . even in the relatively dry times of the middle-twelfth and late-thirteenth centuries.” Partly in response to the latter study, some archeologists have suggested that drought was not a major push factor in Anasazi migrations from the Four Corners region. For example, on August 20, 1996, George Johnson authored a *New York Times* article in which one prominent American archeologist was quoted as saying “Nobody is talking about great droughts anymore”. However, other scholars have pointed out that the influence of drought on prehistoric Southwestern populations should not be so quickly dismissed (e.g., Larson et al., 1996).

In this paper we examine both published and new data that reinforce the concept that climate change including drought was a primary push factor in the reduction or migration of Anasazi populations during the middle-12th and late-13th centuries. We suggest that droughts occurring during these time periods may have involved weakening or failure of the North American summer monsoon, which, in turn,

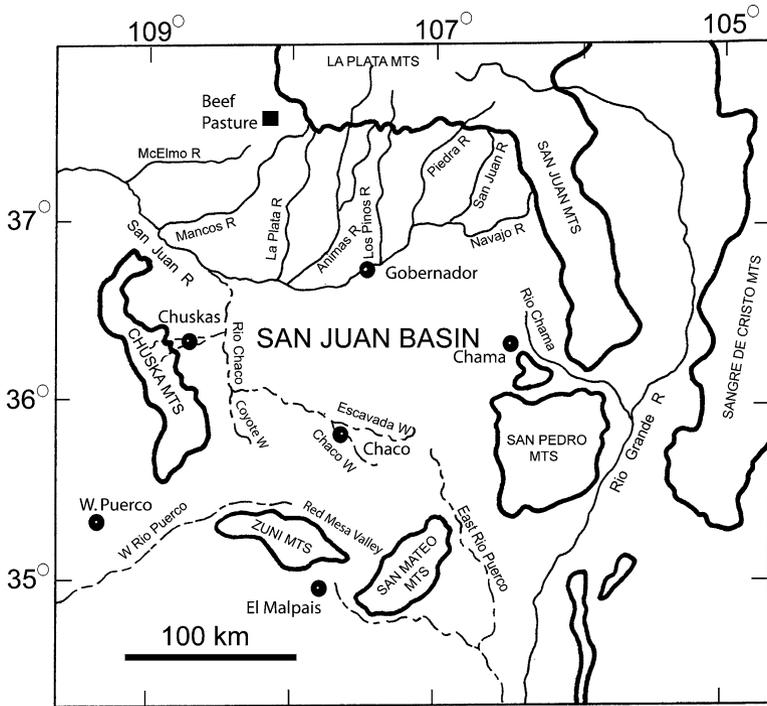


Figure 3. Pollen (filled square) and tree-ring (filled circle) sites in and around the San Juan Basin of northwestern New Mexico. Ephemeral streams are indicated by dashed lines.

resulted in sharp decreases in maize yields, causing the Anasazi to migrate to areas that had more available water. We also reiterate the suggestion of other researchers (e.g., Dean et al., 2000; Axtell et al., 2002) that environmental conditions during the Great Drought of the late-13th century were probably not sufficient to have caused the total abandonment of the Four Corners area; i.e., there were some areas that could have continued to be agriculturally productive during the Great Drought. This implies that push or pull factors other than drought contributed to the complete abandonment of the region.

2. Climate Records from the Four Corners Region

Tree-ring reconstructions of annual precipitation from sites within and at the periphery of the San Juan Basin (Figure 3) indicate that precipitation minima (droughts) have been nearly synchronous across the region since A.D. 1125 (Figure 4). Droughts centered at A.D. ~1090, 1150 and 1280 are apparent in the records as is the 16th century megadrought that severely impacted North America (Stahle et al., 2000). However, it should be noted that some droughts nearly as severe

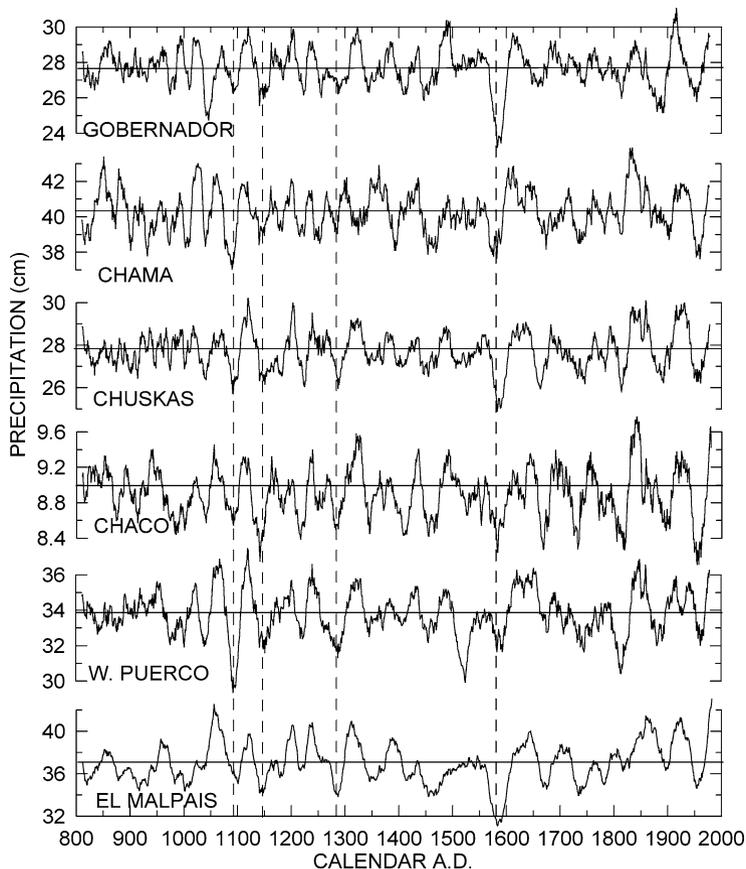


Figure 4. Tree-ring-based reconstructions of annual precipitation from the greater San Juan Basin for the period A.D. 800 to 2000. The El Malpais data came from Grissino-Mayer (1996); Chaco Canyon data are from Dean and Funkhouser (2004); all other data came from the University of Arizona Tree-Ring Laboratory. Horizontal lines are averages of the time series. All records have been subjected to a 21-year running average. Dashed vertical lines indicate specific droughts discussed in the text. The El Malpais precipitation year (previous July through current July) is slightly different than the other precipitation years (previous August through current July).

and persistent as the A.D. 1150 and 1280 droughts have not been associated with Anasazi migration (e.g., the drought centered on A.D. 1225).

The A.D. 1150 and 1280 droughts are somewhat unique in that they impacted much of the western United States (US). Both droughts have been observed in tree-ring-based reconstructions of precipitation in the southern Sierra Nevada (Graumlich, 1993; Figure 5a), in the tree-stump record of Mono Lake, California (Stine, 1994), and in the continuous $\delta^{18}\text{O}$ record from Pyramid Lake, Nevada (Benson et al., 2002). In addition, a recent tree-ring based reconstruction of summer Palmer Drought Severity Index (PDSI) by Cook et al. (2004) indicates that $\sim 55\%$ of

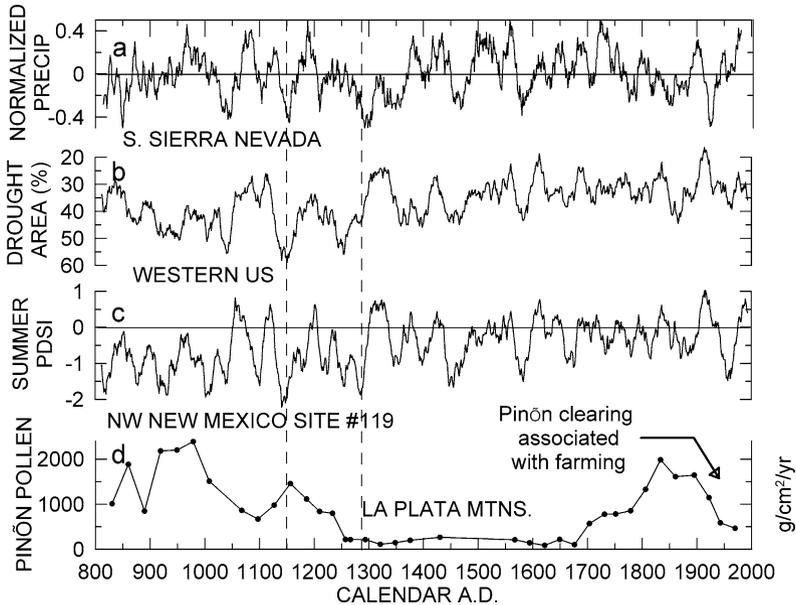


Figure 5. (a) Normalized annual precipitation record for the southern Sierra Nevada (Graumlich, 1993); (b) drought area in the western US (Cook et al., 2004); (c) summer (June, July, August) PDSI for northwestern New Mexico site #119 (Cook et al., 2004), and (d) piñon pollen counts for the southern La Plata Mountains (Petersen, 1994) for the period A.D. 800 to 2000. The three tree-ring records are presented as 21-year running averages. Vertical lines indicate two droughts that occurred at the same time as Anasazi migrations. Note how the PDSI overemphasizes the occurrence and frequency of drought.

the western US suffered drought during the A.D. 1150 event and ~40% of the western US suffered drought during the early part of the A.D. 1280 event (Figure 5b).

It is possible that both droughts were associated with the failure of or at least the weakening of the summer monsoon. The only available tree-ring record that may, in part, proxy for monsoonal strength in the Four Corners region is the June, July, and August PDSI record developed by Cook et al. (2004) for northwestern New Mexico (Figure 5c). Guttman (1998) has demonstrated that the PDSI has an inherent fixed time scale of ~9 to 12 months where. Thus the summer PDSI records of Cook et al. (2004) are influenced by the soil-water balance in previous months. To the limited extent that the summer PDSI reconstructions of Cook et al. (2004) indicate the strength of the monsoon, summer drought may have been associated with the A.D. 1150 and 1280 droughts in northwestern New Mexico (Figure 5c). This suggestion is reinforced by a piñon pollen record from Beef Pasture in the La Plata Mountains of southwest Colorado (Petersen, 1994; Figure 5d). Whereas winter precipitation plays a large part in the growth of piñon, Petersen (1994 and references therein) has argued that summer precipitation is critical for the establishment of piñon seedlings and that there is a coincidence between the region of summer rainfall in the western

US and the area populated by piñon. Petersen (1988) demonstrated that piñon (*Pinus edulis*) establishment in the Four Corners region in the 1920s and 1930s occurred during a peak in summer precipitation. In addition, piñon trees have shallow roots that are able to intercept summer precipitation (Fritts et al., 1965), illustrating the dependency of piñon on both winter and summer precipitation.

We fit a new calibrated age model using the ^{14}C dates obtained on the upper 1.2 m of the Beef Pasture core (Stuiver et al., 1998). The errors in the age calibration of the sediment core are such that the minimum in piñon pollen at 1090 and its near disappearance at A.D. 1270 can be argued to have occurred, respectively, during the middle-12th century Anasazi abandonment of great houses in the central San Juan Basin and during the late-13th century Anasazi abandonment of the Four Corners region (Figure 6). Therefore, we reiterate the hypothesis, suggested by previous authors, that failure of the summer monsoon was associated with great-house abandonment and the migration of the Anasazi.

During the early part (A.D. 1250–1450) of the *Pinus edulis* “plateau” (Figure 5d), the bimodal (summer-winter) precipitation pattern of the San Juan Basin gave way to a mixture of rainfall regimes (Dean, 1996) which is not interpretable in terms of modern climate analogs. Although we cannot specify the nature of the climate during this period, it indicates a major disruption of the long-term climatic pattern upon which Anasazi agriculture was based.

People from Chaco Canyon are thought to have constructed the Salmon great house (Larry Baker, personal communication). Initial construction of a few rooms occurred in A.D. 1068, during an early phase of the A.D. 1090 drought, and accelerated construction activities began in A.D. 1088, during another severe drought

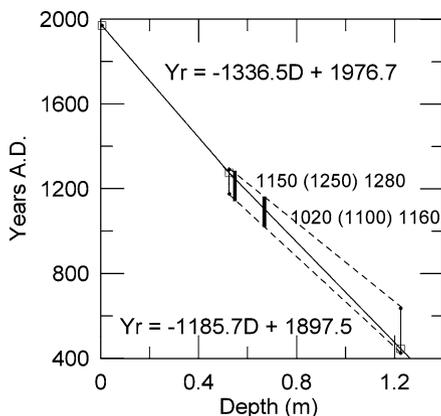


Figure 6. Age model for the Beef Pasture pollen core. Two linear regression lines have been fit to the centers of mass of the ^{14}C dates. The thin vertical lines indicate the error in the age calibration. The dashed lines indicate the estimated error range between the two oldest calibrated ^{14}C dates, and the two thick vertical lines indicate the estimated age range at A.D. 1090 and 1250. The minima and maxima of the age range estimates are listed on either side of the most probable date in parentheses.

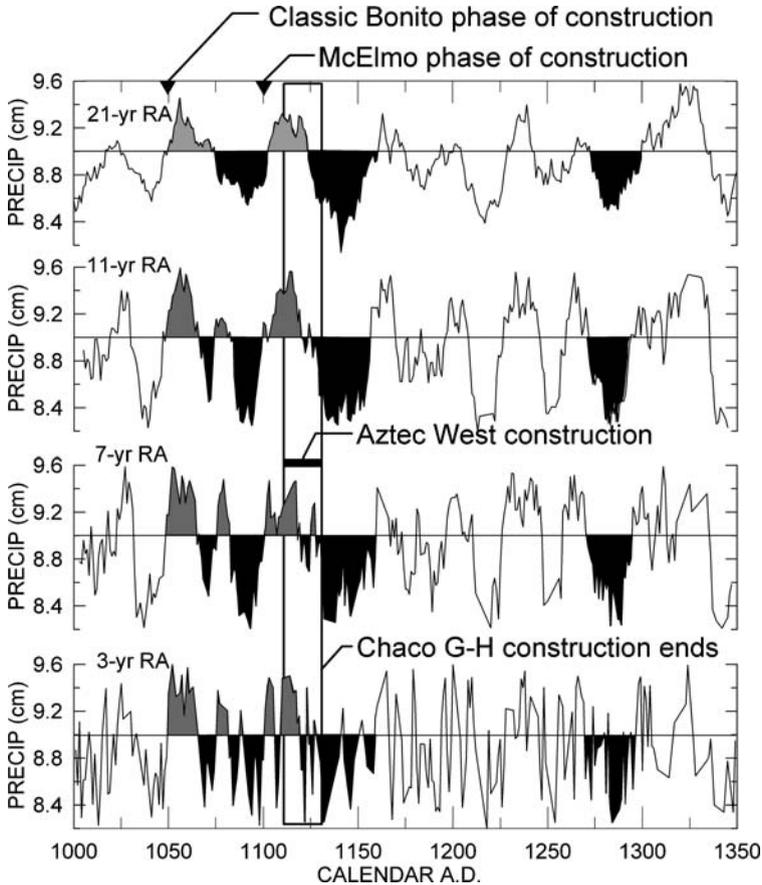


Figure 7. Tree-ring-based precipitation record for Chaco Canyon shown as a set of different running averages (RA) (Dean and Funkhouser, 2004). Droughts discussed in text are filled with black solid pattern and wet periods discussed in text are filled with a grey solid pattern. The Classic Bonito and McElmo (Late Bonito) phases of great-house construction occurred during two wet periods beginning, respectively, at A.D. 1050 and 1100. Aztec West construction (bracketed by vertical rectangle) was initiated during the latter wet period and great-house (G-H) construction at Chaco and Aztec West terminated during the initial phase of the A.D. 1150 drought. Construction of Salmon (bracketed by a dashed vertical rectangle) began in a drought (A.D. 1068) and accelerated in another drought (A.D. 1088) (Larry Baker, personal communication).

(Figure 7). In addition, Aztec North (24 km upstream from the confluence of the Animas and San Juan rivers, Figure 3) could have been constructed in the late-11th century (Tom Windes, personal communication). This suggests that some of the inhabitants of Chaco Canyon were migrating in response to drought to the better-watered Totah area where the San Juan and Animas Rivers meet.

Figure 7 illustrates the probable effect of climate change on Anasazi construction activities. In this figure the tree-ring-based record of annual precipitation for Chaco Canyon is depicted as a series of running averages, ranging from a

high-frequency 3-year running average to a low-frequency 21-year running average. Both the Classic Bonito and Late Bonito (McElmo) phases of great-house construction in Chaco Canyon were initiated during anomalously wet periods, and great-house construction at Chaco and Aztec was terminated by drought at A.D. 1130. In Chaco canyon, the drought intervals centered on A.D. ~ 1090 and ~ 1150 appear to have lasted longer and have been more severe than the Great Drought centered on A.D. ~ 1280 .

3. Maize and Migration

The link that connects monsoon failure and Anasazi migration is maize. Bruce Huckell and colleagues have discovered archeological maize in McEuen Cave, northeast of Tucson Arizona, that dates to ~ 3800 ^{14}C yr B.P. (~ 2240 B.C.), indicating that maize was introduced to the Southwest more than 4000 years ago (B. Huckell, personal communication). Over time, maize became the dietary staple of the Anasazi inhabiting the Four Corners region. In the early historical period, the Hopi and the Zuni attempted to keep a second year's supply of maize in reserve (Stevenson, 1904; Hough, 1915; Cushing, 1920; Forde, 1931; Titiev, 1944; Brown et al., 1952). However, such a reserve would not have been sufficient to last through a multi-year drought. Annual consumption by the Hopi was ~ 12 bushels per person (Stephen, 1936) and the maize yield in a good year was ~ 12 bushels per acre. Thus, a Hopi family of 6 would have to cultivate ~ 12 acres to provide enough maize for the following year's consumption and another year's storage. Farming of 12 acres represents a substantial investment in time, and although excess maize could have accumulated over a period exceeding one year, maize would not have kept indefinitely, given insect and animal predation.

Maize yields are a function of climate and the properties of the soil in which the maize grows. We do not know the environmental requirements of maize grown by the Anasazi; therefore, we must rely on the requirements of modern forage corn and maize grown by present-day Pueblo people as a proxy. We suggest that Zuni and Hopi agricultural practices are good analogs for Anasazi practices. The Zuni mitochondrial DNA (mtDNA) haplogroup distribution is very similar to that of the Anasazi (Carlyle et al., 2000), indicating that the Zuni are descended from one of the Anasazi groups.

Most soils in the semi-arid Southwest are nutrient poor and the raising of maize leads to nutrient depletion. Nutrient (e.g., N and P) loss necessitates that soil be left fallow until the nutrient balance is restored (Stewart, 1940). The bioavailability of N and P is pH dependent with a pH range of 5.5 to 7.0 being optimal (Olson and Sander, 1988). Zuni fields have a pH range of 6.6 to 8.0, are usually cropped from 2 to 3 years, and then left fallow for 1 to 4 or more years (Muenchrath et al., 2002). For modern forage corn, yield begins to decrease at a salinity (conductivity) threshold of 1.8 deciSiemens per meter (dS/m) (Ayers and Westcot, 1976).

Maize is produced in areas that receive 25 centimeters (cm) of annual precipitation or 15 cm of growing season precipitation (Shaw, 1988); however, optimum maize yields occur where growing season precipitation ranges from 40 to 60 cm (Minnis, 1981) and where the freeze-free period exceeds 120 days (Shaw, 1988).

At Zuni, May-through-September rainfall averages 15.8 cm and there is a 90% probability that a period of 112 days will be frost-free (Western Regional Climate Center, Desert Research Institute, 2004). Zuni maize cultivars take ~ 125 days to mature (Muenchrath et al., 2002), and Hopi blue corn requires 115 to 130 frost-free days (Bradfield, 1971).

Nutrient, pH, and salinity data are not available for most of the soils in the Four Corners region; however, freeze-free probabilities and precipitation data exist for 66 sites in the region. To determine the best areas for dry-land farming of maize, we assumed that 90 freeze-free days and 30 cm of annual precipitation must be equaled or exceeded. Growing season precipitation averages $\sim 50\%$ of the minimum annual precipitation in the 66 sites². Twelve of the 66 sites have precipitation and freeze-free conditions that permit dry-land farming of maize (Figure 8); the 12 sites lie on the periphery of the San Juan Basin (Figure 9).

A comparison of the locations of the 12 sites with locations of great houses occupied after the drought of A.D. 1150 (Figures 2 and 9) indicates a measure of congruency, suggesting that some Anasazi may have been forced to leave the relatively cold and dry central San Juan Basin during the drought because that area was no longer able to support dry-land farming. If village population can be assumed

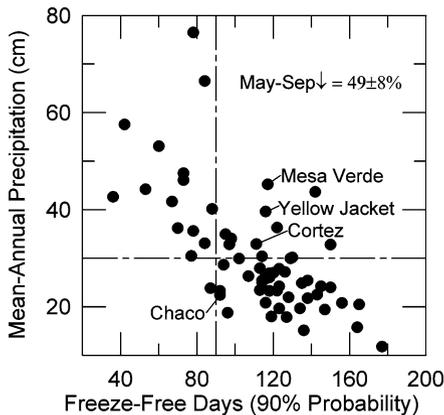


Figure 8. Plot of mean-annual precipitation versus freeze-free-day probabilities for 66 weather stations in the Four Corners region. Summer precipitation (May–Sep ↓) at the sites makes up $49 \pm 8\%$ of the mean-annual precipitation. The 12 sites in the upper right quadrant of the diagram have precipitation and freeze-free values that allow at least minimal dry-land agriculture. The Mesa Verde, Yellow Jacket, and Cortez sites fall within or close to the area studied by Van West (1994).



Figure 9. Locations of the 12 sites in the Four Corners region that currently can support dry-land farming of maize.

to be linked to greathouse occupation, the Anasazi appear to have remained in areas in which dry-land farming was possible and in areas located along perennial river systems. However, abandonment of great houses does not necessarily indicate complete abandonment of the villages in which they were located; i.e., village populations simply may have decreased in response to environmental deterioration. In this case, great-house abandonment may be hypothesized to represent dissatisfaction of the outlying villages with the Chacoan socio-political system inasmuch as Chaco was considered responsible for their welfare. Given the impact of a multi-year drought on both canyon and outlier village agriculture, many residents of the San Juan Basin may have decided the existing socio-political system was bankrupt and it was time for a change.

Evidence for the A.D. 1150 drought comes from two other areas. The Virgin River Anasazi abandoned their settlements in southwestern Utah at about A.D. 1150, presumably in response to drought (Larson and Michaelsen, 1990; Lyneis, 1996). The Fremont, living along the eastern shore of Great Salt Lake, Utah, incorporated maize in their diets beginning A.D. ~500; however, they ceased

consumption of maize after A.D. 1150 (Coltrain and Leavitt, 2002). There also was a widespread abandonment of Fremont farming sites between 1150 and A.D. 1350. Some authors have argued that the abandonment of farming was in response to a deterioration of climate (e.g., Hunt, 1953; Rudy, 1953). Lindsay (1986) and Newman (1996) suggested that reduced summer moisture and a shortened growing season (e.g., Salzer, 2000) were the specific causes of agricultural failure, and that the change in climate was due to a shift in the northern boundary of the summer monsoon which today reaches only into southeastern Utah (Mitchell, 1976). This concept is consistent with Petersen's (1994) suggestion that the expansion of piñon in southwestern Colorado during the 10th and 11th centuries (Figure 5) was due to an increase in summer moisture. These studies imply that prior to A.D. 1130 the summer monsoon was stronger and its boundary lay north of its present-day position, allowing the Anasazi to expand their territory and increase their population, during a time when maize yields were relatively high.

These results contradict Van West's (1994) conclusion that in the northern San Juan region of southwestern Colorado "there *always* was enough productive land to produce enough maize to support a very large population." Van West's study was ground breaking for its time and utilized the best available data; however, she never claimed that her study was applicable to the entire Four Corners region. Indeed, the climate of the northern San Juan region is demonstrably warmer and wetter than the climate of the central San Juan Basin and is, therefore, more reliable in terms of its agricultural productivity (see Figures 8 and 9 which show precipitation and freeze-free days for the Yellow Jacket, Cortez, and Mesa Verde sites in the northern San Juan Basin as well as other sites in the Four Corners region).

In addition, Van West's estimates of archeological maize yields are not sufficiently accurate to demonstrate that the agricultural productivity of the northern San Juan region was always able to withstand the effects of severe drought (see Appendix I).

The studies of Dean et al. (2000) and Axtell et al. (2002) shed some light on problems of applying maize yields derived by Van West (1994). Dean et al. (2000) estimated Long House Valley maize yields by adopting Van West's (1994) derived relationships between soil PDSI and maize production for southwestern Colorado. This was accomplished by matching the specific water-holding attributes of Long House Valley soils to southwestern Colorado soils. The Dean et al. (2000) simulation of the population of Long House Valley between A.D. 800 and 1360 was, however, ~6 times greater than the archeologically estimated population, suggesting that maize yields may have been overestimated in the model. Axtell et al. (2002) were able to accurately simulate the total number of households in Long House Valley between A.D. 800 and 1300. However, this was accomplished by optimizing the model with respect to eight adjustable parameters, including the average harvest per acre and the variance in this harvest. Thus, maize yields had to be treated as an adjustable parameter to accurately estimate population change through time in Long House Valley.

4. Culture and Migration

Drought by itself probably can never totally account for the migration of an entire group that occupied a particular geographic area. There always will be some part of the land that remains sufficiently productive to raise crops or that is adequate for some level of hunting and gathering. The relative importance of environmental deterioration, including drought, as a push factor has recently been explored by Dean et al. (2000) and Axtell et al. (2002) who applied agent-based modeling to the Kayenta Anasazi. This group of Anasazi occupied Long House Valley in north-eastern Arizona from ~1800 B.C. until A.D. 1300. The Anasazi totally abandoned the valley by A.D. 1300; however, model simulations indicate that the valley could have continued to support 35 to 40% of its peak population during the 40 years following the A.D. 1300 exodus. In the words of Axtell et al. (2002), "The fact that in the real world of Long House Valley, the supportable population chose not to stay behind but to participate in the exodus from the valley indicates the magnitude of sociocultural "push" or "pull" factors that induced them to move", a conclusion previously reached by Dean et al. (2000).

It takes a minimum number of individuals to fill the roles assigned to a "viable" Anasazi society, a concept that can be illustrated using examples from early-historic Pueblo cultures. Contemporary Pueblo people have social systems comprised of socialities, including clans, moieties, feast groups, religious societies, healing groups, war societies, village governments, and winter and summer governments, each of which exerts a sociocultural pull (George Gumerman, personal communication). Sociocultural pull also can be illustrated using the Zuni organizational structure. When Cushing (1896) intruded on the Zuni in 1879, there were 19 kinship groups (clans). The clans bore totemic names and were grouped in threes, except for one clan. Six groups of three clans were associated with the four cardinal points of the compass, the zenith and the nadir; the single clan was associated with the midpoint of this constellation of clans and was considered to be the mother clan from which the priesthood arose. The seven groups represented the original Zuni subtribes which had occupied the seven cities of Cibola noted by early Spanish explorers. Each of the totems were, in essence, god beings associated with their particular region; e.g., the evergreen oak totem of the north is as green in the winter as other trees in the spring and summer, indicating its unusual and unique quality.

To quote Cushing (1896) "By this arrangement of the world. . .into several worlds corresponding to the four quarters and the zenith and the nadir, and by this grouping of the (original) towns. . .according to such mythical division of the world, and finally the grouping of the totems in turn within the divisions thus made, *not only the ceremonial life of the people, but all their governmental arrangements as well, are completely systematized.*"³ If in the past, Anasazi villages or multi-village entities were as culturally and politically interconnected as the early-historic Zuni, then it would be logical for the group to migrate as a unit in response to one or more forms of environmental deterioration.

However, this degree of cultural interconnectivity does not always occur in Pueblo society, implying that migration need not always involve the entire group. At Orayvi, Hopi clans were assigned fields by the village chief. Some clans were assigned excellent fields; however, other clans were assigned fields of lesser value or not assigned fields at all; and, in general, the clans that controlled good lands also controlled the most important ceremonies (Levy, 1992). Thus, the Hopis were roughly divided into two classes as a result of the inequitable distribution of agricultural land. In times of drought, it was survival of the fittest, for “In case of drought, all resources are concentrated for the preservation of the central clan core, and other clansmen may be forced to migrate or starve. As conditions improve, they may return. . .” Eggan (1966). A major “sloughing off” of Hopi clans during environmental stress occurred in Orayvi in 1906 when a prolonged drought led to loss of half the village population (Levy, 1992). At that time the “Hostile” faction, consisting mostly of lower class Hopi, were expelled from Orayvi and were not allowed to return. This suggests that sociocultural push or pull factors may have differed in both character and strength during the heyday of Anasazi groups.

Other forms of resource depletion also may have contributed to Anasazi migration; e.g., fuel wood may have become limited in some areas (Dean, 2004; Kohler, 2004; Johnson et al., 2005), and a decline in protein availability may have stressed already limited agricultural resources (Kohler, 2002; Varien et al., 2000).

5. Drought and its Relation to the Pacific Decadal and Atlantic Multidecadal Oscillations

Drought in the Four Corners region, during the past 300 years, can be associated with two climate indices: the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO).

The PDO has a spatial pattern similar to the El Niño Southern Oscillation (ENSO) (Mantua et al., 1997); i.e., during positive phases of the PDO, the southwestern US tends to be wetter than average and during negative phases of the PDO, the southwest tends to be dry. However, the PDO has a very different time signature, having a pseudo-cyclicity ranging from 50 to 70 years (MacDonald and Case, 2005), whereas typical ENSO events occur every 4 to 7 years and persist from 6 to 18 months. A positive PDO phase is associated with warmer-than-normal temperatures in the eastern equatorial Pacific Ocean and cooler-than-normal temperatures in the northwest Pacific Ocean.

The AMO is an index of detrended sea-surface temperature (SST) anomalies that are averaged over the North Atlantic Ocean from 0 to 70°N (Kerr, 2000). The detrended AMO index has been associated with multi-year precipitation anomalies over North America and it has been shown to influence summer precipitation over the US (Enfield et al., 2001). During the instrumental period (1856–2005) it has exhibited a 65-to-80-year pseudo cycle.

Atmospheric modeling has demonstrated that the drought of the 1930s, which affected approximately two thirds of the contiguous US, was associated with warmer-than-normal North Atlantic (positive AMO) SSTs and colder-than-normal equatorial Pacific (negative PDO) SSTs (Schubert et al., 2004).

McCabe et al. (2004), using drought-frequency climate data for the period 1900 to 1999, have demonstrated that the southern part of the western US tends to experience drought when the AMO is positive and the PDO is negative. Brown and Comrie (2002) and Ni et al. (2002) have shown that winter precipitation in New Mexico is positively correlated with the PDO, and Fye et al. (2003) have shown that times of positive AMO and negative PDO produce western droughts that are spatially similar to the 1950s drought. The 1950s drought occurred between 1946 and 1956 and was especially severe in the Four Corners Region. During the 1950s drought, both winter and summer precipitation regimes declined dramatically.

In northwestern New Mexico's Climate Division 1 (San Juan Basin), between 1944 and 1976 (negative PDO), it was dry (10% below normal precipitation) 55% of the time and wet (10% above normal precipitation) 15% of the time; however, between 1977 and 1997 (positive PDO), it was wet 62% of the time and dry only 14% of the time in New Mexico Division 1 (Charles Liles, National Weather Service, personal communication). Thus, in the historical period, a negative PDO and a positive AMO are nominally associated with drought in the Four Corners Region. To determine the relation of water-year (October 1 through September 31) and summer (July, August, September) precipitation in the greater San Juan Basin during negative and positive PDO intervals, we analyzed historical climate records from 15 sites in New Mexico and Colorado. The data (Table I) indicate that a negative PDO interval is characterized by reduced water-year (October 1–September 31) and summer (June, July, August) precipitation. Note that water-year precipitation is driven more by winter precipitation ($64 \pm 6\%$ of annual) and its difference during positive and negative phases of the PDO ($11 \pm 4\%$ and $-8 \pm 3\%$ respectively).

In order to look back in time, we must turn to proxies for the PDO, AMO, and drought. Tree-ring (D'arrigo et al., 2001; Gray et al., 2004) and coral-chemistry (Linsley et al., 2000) records have been used to reconstruct fluctuations in the PDO and AMO for about the past 300 years. The use of different proxies for the PDO strengthens the reliability of its reconstruction. Plots of these climate indices versus tree-ring based reconstructions of summer PDSI for northwestern New Mexico site #119 (Cook et al., 2004) and annual precipitation for Chaco Canyon in the central San Juan Basin indicate that drought in the Four Corners region is generally associated with a positive AMO and a negative PDO (Figure 10). Note, however, that the maxima and minima in the records are not always synchronous and that the reconstructed summer PDSI record for northwestern New Mexico appears to overemphasize the frequency and persistence of drought.

TABLE I

Water-year and summer (July, August, September) precipitation in and around the San Juan Basin, New Mexico Values listed in Negative and Positive PDO columns are departures from the 1944–1997 mean value

Site	Water-year precipitation (cm)			Summer precipitation (cm)		
	Negative PDO (1944–1976)	Mean value (1944–1997)	Positive PDO (1977–1997)	Negative PDO (1944–1976)	Mean value (1944–1997)	Positive PDO (1977–1997)
Aztec, NM	–2.21	25.25	3.51	–0.41	7.95	0.66
Bloomfield, NM	–1.91	21.49	2.69	–0.36	7.77	0.53
Chaco Canyon, NM	–1.68	22.48	2.64	–0.13	8.99	0.22
Chama, NM	–5.87	52.88	8.41	–1.02	16.97	1.47
Dulce, NM	–2.24	43.26	3.33	–0.05	14.94	0.10
El Morro, NM	–3.48	35.00	5.44	–0.41	15.37	0.64
El Vado, NM	–2.06	36.40	3.20	–0.43	14.38	0.71
Jemez Spgs, NM	–3.40	41.99	5.38	–0.51	18.06	0.81
Laguna, NM	–2.62	24.08	3.35	–1.09	12.40	1.42
McGaffey, NM	–5.33	47.40	6.60	–0.28	17.15	0.36
Shiprock, NM	–2.21	17.09	3.05	–0.84	5.64	1.19
Cortez, CO	–1.37	32.94	2.34	–0.41	9.70	0.61
Fort Lewis, CO	–2.64	46.96	3.53	–1.12	15.29	1.50
Mesa Verde, CO	–2.08	46.25	2.79	–0.28	13.46	0.38
Northdale, CO	–0.76	31.27	1.07	–0.46	9.98	0.61

Recently a much longer (A.D. 993 to 1996) PDO record has been constructed by MacDonald and Case (2005). A comparison of this record with tree-ring-based records of precipitation at Chaco, the Chuskas, and northwestern New Mexico summer PDSI (Figure 11) indicates that negative oscillations in the PDO are associated with the A.D. 1150 and 1280 droughts but not the A.D. ~1090 drought, suggesting that monsoon failure did not occur at A.D. ~1090. The PDO index between 1000 and 1300 is negative and corresponds with largely negative values of summer PDSI during the same time period (Figure 11a, d). This suggests that summer drought was common during much of the time interval (A.D. 850 to 1300) that witnessed the florescence of the Anasazi.

The droughts of the middle-12th and late-13th centuries were associated with a negative PDO that, on average, involved both winter and summer drought. This is consistent with the tree-ring study of Fritts et al. (1965) who found that the Great Drought was associated with reduced winter and summer precipitation and elevated summer and autumn temperatures. The middle-12th and late-13th century droughts occurred after population expansions, during a time when people were living at the limit of their environmental and agricultural support systems (Dean et al., 1985; Dean, 1988). Some of the droughts

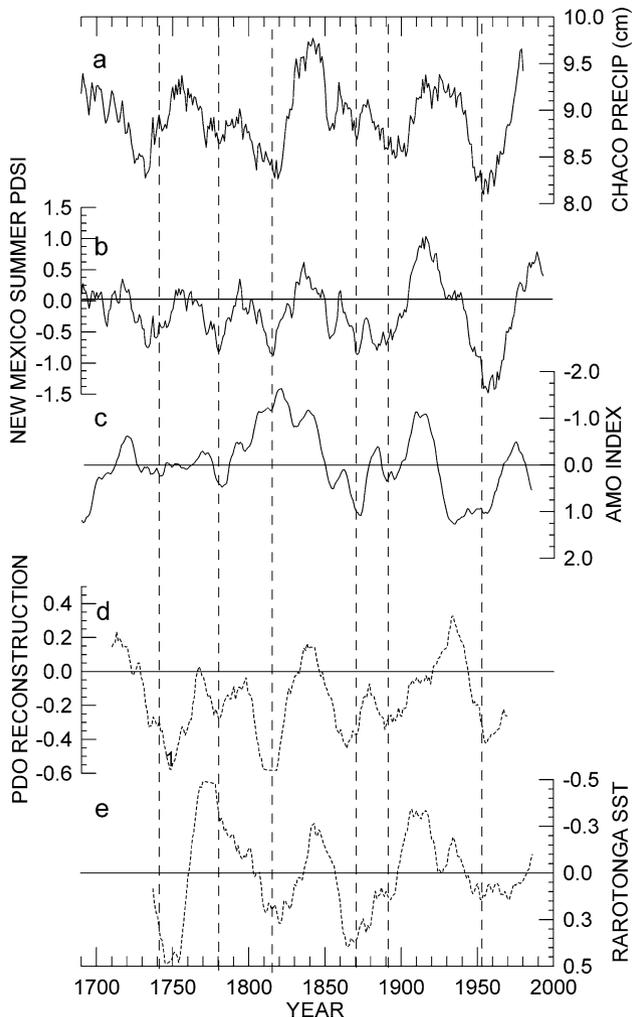


Figure 10. Plots of (a) tree-ring-based annual precipitation values for Chaco Canyon, New Mexico (Dean and Funkhouser, 2004), (b) tree-ring-based summer PDSI values for northwestern New Mexico (essentially the San Juan Basin) (Cook et al., 2004), versus (c) the tree-ring-based reconstruction of the AMO index (Gray et al., 2004), (d) the tree-ring-based reconstruction of the detrended PDO index (D'arrigo et al., 2001), and (e) the subtropical, coral-based, detrended Rorotonga sea-surface temperature (SST) proxy of the PDO (Linsley et al., 2000) for the past 300 years. When the SST is positive the PDO is negative. Vertical dashed lines indicate the essential co-occurrence of AMO maxima, PDO minima, and drought in northwestern New Mexico with the exception of the AMO value at 1815. The records are presented as 21-year running averages.

persisted for several years and would have caused all surplus maize to be consumed, thereby forcing the Anasazi to migrate to more agriculturally productive areas.

This concept is reinforced by the work of Burns (1983) who reconstructed maize and bean yields in southwestern Colorado using tree-ring records. Burns (1983)

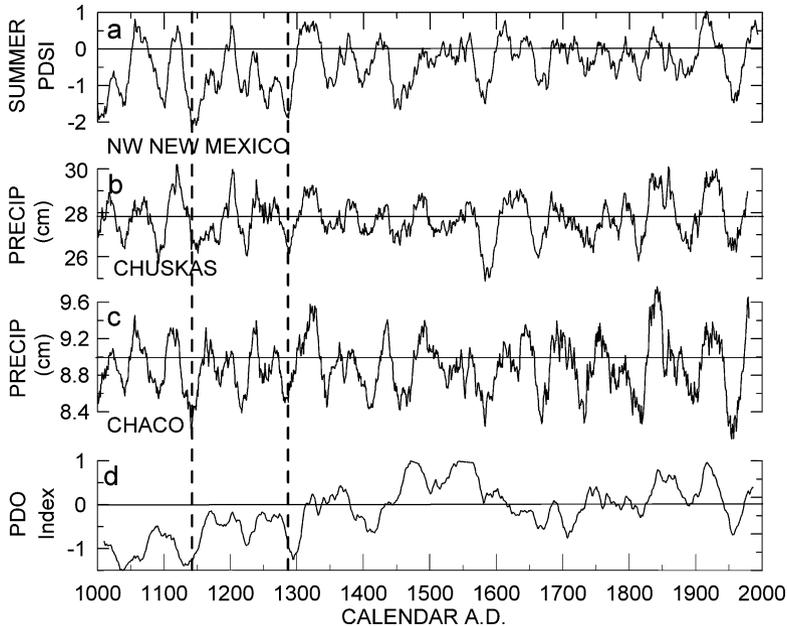


Figure 11. Plots of (a) tree-ring-based summer PDSI values for northwestern New Mexico (Cook et al., 2004), (b) tree-ring based annual precipitation for the Chuskas (Jeff Dean, personal communication), (c) tree-ring-based annual precipitation values for Chaco Canyon, New Mexico (Dean and Funkhouser, 2004), and (d) tree-ring-based reconstruction of the PDO (MacDonald and Case, 2005). The A.D. 1150 and 1280 droughts are shown with a dashed line. The records are presented as 21-year running averages.

showed that, given a 1.5-year storage capacity, the harshest famines endured by the Anasazi occurred during the middle-12th and late-13th centuries.

6. Summary and Conclusions

Many of the Anasazi may have left the relatively cold and dry central San Juan Basin during the middle-12th century and they abandoned the entire Four Corners region in the late-13th century. Tree-ring based reconstructions of precipitation and soil moisture indicate that both migrations occurred during intense multi-year drought intervals. During the middle-12th century, the Virgin River Anasazi abandoned their settlements in southwestern Utah and the Fremont, living along the eastern shore of Great Salt Lake, Utah, ceased their consumption of maize. Great-house construction and renovation at Chaco and at Aztec which had accelerated during wet periods terminated near the beginning of the middle-12th century drought. These data suggest that a persistent and intense drought impacted the Southwest in the middle-12th century, and supports the concept of a migration from the central San

Juan Basin and/or a reduction in community populations. Migration from Chaco Canyon to the Salmon great-house site occurred in 1068 during a decade-long drought. This suggests that climate deterioration impacted the fragile agronomic base of Chaco, causing some of its inhabitants to seek areas with a more reliable water supply.

Pollen data from the northern San Juan Basin indicate that the middle-12th and late-13th century droughts involved a weakening or failure of the summer monsoon. Tree-ring-based reconstructions of annual precipitation imply that both droughts also were associated with reductions in winter moisture. Comparison of tree-ring-based reconstructions of precipitation and soil moisture with tree-ring-based reconstructions of the PDO and AMO for the past 300 years indicate that drought in the Four Corners region occurs when the PDO is negative and the AMO is positive. Historic climate data indicate that reductions in both water-year and summer precipitation occur when the PDO is negative, and a long proxy record of the PDO indicates that the middle-12th and late-13th century droughts were associated with major negative excursions in the PDO. Reconstruction of summer drought for the past 800 years may be ultimately improved using tree-ring latewood width as an indicator of southwestern summer precipitation (Meko and Baisan, 2001).

We suggest that Anasazi populations declined and that the Anasazi sometimes migrated in response to droughts characterized by a weakening or failure of the summer monsoon. The loss of summer moisture is hypothesized to have resulted in reduced yields of maize, the dietary staple of the Anasazi, forcing them to abandon areas that were marginal for dry-land farming and migrate to better-watered areas. The drought of the middle-12th century may not have resulted in the complete abandonment of the central San Juan Basin. The middle-12th century drought may have occurred at a time of Anasazi population expansion, rendering the San Juan Basin population sensitive to the effects of agricultural failure.

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Appendix I

Van West's correlations of calculated and tree-ring-based June PDSI values with historic maize yields tabulated by Burns (1983) are not robust. These correlations were performed in order to demonstrate a linkage between yields and PDSI. However, linear regression of maize yields versus calculated and tree-ring-based June PDSI values for the most common soil for the period 1931 to 1960 yielded, respectively, R^2 values of 0.05 and 0.09 (Van West, 1994, p. 101). This, may in part, stem from the fact that the tree-ring-based June PDSI value integrates soil-moisture conditions over the previous several months but does not proxy well for the monsoonal (July, August, September) component of precipitation which is critical in determining maize yields. In addition, trees used to reconstruct historic PDSIs and historic cornfields are not located together. Given the patchiness of summer convective storms, a grove of trees may not experience the same precipitation events as a field of maize. Most importantly, improvements in technology after 1943 decoupled moisture from maize yields. Thus, ring width in the historic period may not always have been representative of maize yields.

Van West attempted to improve the correlation of maize yields to soil PDSI values by including time as an independent variable that proxied for the effects of technological change on yield since 1930. Burns (1983) had previously used Colorado fertilizer usage as a technological proxy; Van West made the assumption that the dependence of yields on technology was a linear function of time since 1930. The inclusion of time, which is assumed to proxy for the effect of technology on agricultural yields, improved the correlation of maize yields with soil PDSI; however, the technological effect actually was minimal prior to 1944 (see below).

Plots of unadjusted maize yields from five Colorado counties (Burns, 1983), together with the weighted average of those yields and water-year precipitation recorded at Durango and Cortez, Colorado for the period 1919 to 1960, indicate that decreases in maize yields were associated with particularly dry years prior to 1944; however, between 1944 and 1959, decreased yields are not associated with drought (Figure 12).

From 1926 until 1944, maize yields and precipitation are reasonably well correlated ($R^2 = 0.54$) (Figure 13); after 1944, the correlation significantly decreases ($R^2 = 0.05$). This suggests that technology was not playing an overwhelming role in maize yields until World War II, when fertilizer application increased and technologically advanced tractors were introduced into southwestern Colorado (Burns, 1983). Thus Van West's partial regression of yield versus time (technology) should probably have been done for the time period 1944 through 1960 (Figure 13). Or better yet, she should have regressed yield versus precipitation (or soil PDSI) for the 26 years preceding 1944.

In general, a regression of yield versus time represents a detrending of the yield data. However, such a detrending cannot be demonstrated to be independent of

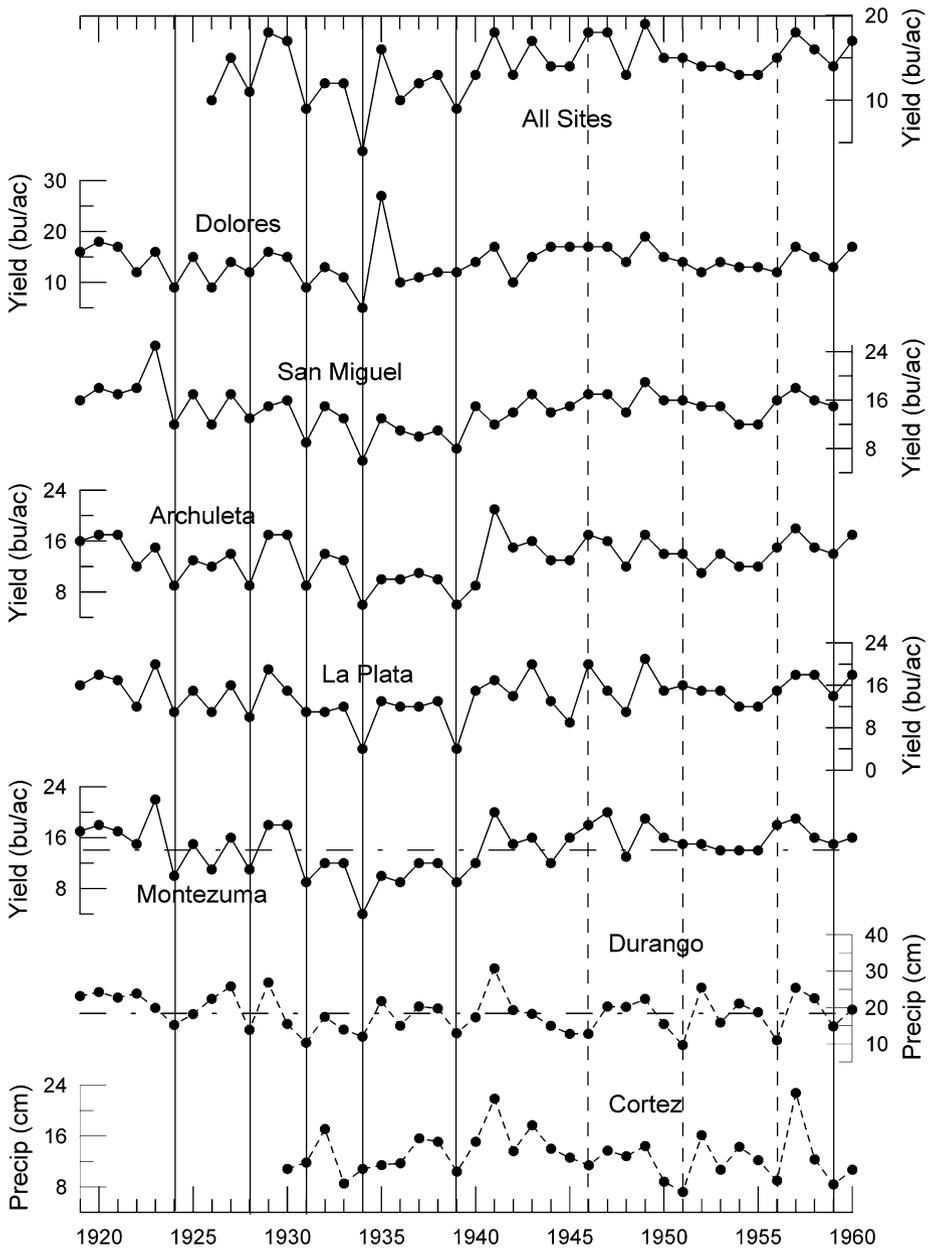


Figure 12. Trends in maize yields in southwestern Colorado between 1919 and 1960 (Burns, 1983) compared to precipitation (water-year) records from Durango and Cortez, Colorado. Solid vertical lines indicates times when drought and reduction in maize yields occurred at the same time. Dashed vertical lines indicate times of drought not accompanied by reductions in maize yields. Horizontal dashed-dotted lines indicate mean values for the period of record. Bushels per acre are denoted by bu/ac.

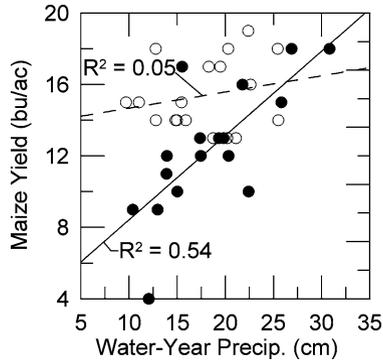


Figure 13. Linear regression of southwestern Colorado maize yields versus water-year precipitation at Durango, Colorado. Solid dots indicate data for 1926 to 1944. Open circles indicate data for 1945 to 1960.

other variables such as precipitation, temperature, and wind speed (the latter two variables affect evaporation rate) which also may be time dependent.

Although Van West correlated historic maize yields with calculated and reconstructed soil-PDSI values in an attempt to demonstrate a relation between the PDSI and maize yields, her actual calculation of prehistoric maize yields was less straightforward and more subjective.

The types of soils on which maize was grown are unknown; however, historic bean fields can be associated with 44 out of 98 soil-map units found in the study area. A linear-regression equation was derived between mean-historic bean yields for the 44 soils and their mean natural-plant productivities as assigned by the US Department of Agriculture's Soil Conservation Service. The regression equation was then used to calculate mean-bean yields for the other 54 soils. Bean yields also were estimated for favorable, unfavorable, and intermediate conditions using natural plant productivities. The 11 wetness classes of the PDSI were then subjectively assigned to the five bean-yield classes; e.g. PDSI categories I and II (extreme and severe drought) were assigned to the lowest bean-yield category (unfavorable growing conditions). Lastly, the mean-historic maize yield for Montezuma and Dolores counties was divided by the mean-historic bean yield for those counties and multiplied by tree-ring-based reconstructed bean yields to estimate prehistoric maize yields for each soil type.

The assignment of bean yields to PDSI classes is somewhat arbitrary and the correlations of bean yields to a lumped PDSI value ($R^2 = 0.14$) and to the PDSI of the most common soil ($R^2 = 0.26$) indicate a tenuous link between crop yields and soil PDSI for the calibration period (1931 to 1960). For example, it would probably have been better to correlate soil PDSIs with bean yields for the period 1919 to 1944.

In addition, the mean-historic bean yield was averaged over a known set and fractional distribution of soil types, whereas the mean-historic maize yield was

averaged over an unknown set and fractional distribution of soil types. The types and percentages of soils on which maize is presumed to have grown during the prehistoric period was not the same as during the historic period. Thus, the mean maize-to-bean yield ratio for prehistoric times cannot be accurately estimated from the mean-historic maize-to-bean yield ratio.

If historic dry-land farming technologies differed substantially from pre-Columbian Native American practices, historic maize yields may not be a good proxy for archeological maize yields; e.g., the types of maize grown by southwestern Colorado farmers in the early- and middle-20th century were not the same types grown by the Anasazi.

Notes

¹Insertion of geographical area by authors for clarity

²In this instance we have used May-to-September precipitation to represent growing season precipitation. This differs from our proxy for monsoonal summer precipitation which includes the months June, July, and August. Growing season precipitation was calculated for the period of record of each weather station and not for a particular time interval.

³Italics added by authors for emphasis

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