

The Holocene

<http://hol.sagepub.com/>

The 5.1 ka aridization event, expansion of piñon-juniper woodlands, and the introduction of maize (*Zea mays*) in the American Southwest

Brandon L Drake, WH Wills and Erik B Erhardt

The Holocene 2012 22: 1353 originally published online 9 July 2012

DOI: 10.1177/0959683612449758

The online version of this article can be found at:

<http://hol.sagepub.com/content/22/12/1353>

Published by:



<http://www.sagepublications.com>

Additional services and information for *The Holocene* can be found at:

Email Alerts: <http://hol.sagepub.com/cgi/alerts>

Subscriptions: <http://hol.sagepub.com/subscriptions>

Reprints: <http://www.sagepub.com/journalsReprints.nav>

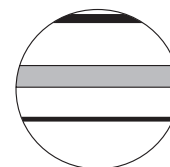
Permissions: <http://www.sagepub.com/journalsPermissions.nav>

Citations: <http://hol.sagepub.com/content/22/12/1353.refs.html>

>> [Version of Record](#) - Nov 22, 2012

[OnlineFirst Version of Record](#) - Jul 9, 2012

[What is This?](#)



The 5.1 ka aridization event, expansion of piñon-juniper woodlands, and the introduction of maize (*Zea mays*) in the American Southwest

The Holocene
22(12) 1353–1360
© The Author(s) 2012
Reprints and permission:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0959683612449758
hol.sagepub.com
SAGE

Brandon L Drake, WH Wills and Erik B Erhardt

Abstract

Pollen analysis is frequently used to build climate and environmental histories. A distinct Holocene pollen series exists for Chaco Canyon, New Mexico. This study reports linear modeling and hypothesis testing of long distance dispersal pollen from radiocarbon-dated packrat middens which reveal strong relationships between piñon pine (*Pinus edulis*) and ponderosa pine (*Pinus ponderosa*). Ponderosa pollen dominates midden pollen assemblages during the early Holocene, while a rapid shift to a much higher proportion of piñon to ponderosa pine pollen between c. 5440 and 5102 cal. yr BP points to an aridization episode. This shift is associated with higher $\delta^{18}\text{O}$ values in Southwest speleothem records relative to the preceding millennium. The period of aridization is followed by a sharp increase in El Niño/Southern Oscillation events that would have caused highly variable precipitation and lasted until c. 4200 cal. yr BP. Bayesian change-point analysis suggests that this aridization episode led to stable ecotonal boundaries for at least 3000 years. The piñon/ponderosa transition may have been caused by punctuated multiyear droughts, analogous to those in the 20th century. The earliest documented instance of *Zea mays* cultivation on the Colorado Plateau is around c. 3940 ^{14}C yr BP (c. 4364 cal. yr BP) (Hall SA (2010) Early maize pollen from Chaco Canyon, New Mexico, USA. *Palynology* 34(1): 125–137) in Chaco Canyon. The introduction of this labor-intensive cultigen from Mesoamerica may have been facilitated by changes in the regional ecosystems, specifically by an increase in piñon trees, that promoted increasing human territoriality. Linear modeling and hypothesis testing can complement traditional palynological techniques by adding greater resolution in vegetation patterning to climate/environmental histories.

Keywords

4.2 ka event, 5.1 ka event, Chaco Canyon, climate change, forest succession, Holocene, piñon pine, pollen, ponderosa pine

Received 8 September 2011; revised manuscript accepted 13 February 2012

Introduction

Chaco Canyon in northwestern New Mexico (Figure 1) is famous for the emergence around 1000 years ago of a complex prehistoric

society based on maize agriculture and long-distance movement of goods, including cacao (chocolate) from central America (Crown and Hurst, 2009; Wills, 2001). Chaco Culture National Historic Park is an UNESCO World Heritage site in recognition of the intrinsic importance associated with understanding the social and environmental conditions underlying this dramatic transformational process, during which dispersed hamlets of subsistence farmers coalesced rapidly around the construction of massive stone communal buildings called ‘great houses’, such as Pueblo Bonito. A long-standing interest among scientists in characterizing the environmental context for the appearance of Chaco great house communities has produced numerous studies of geological and biological data from the canyon dating to the last 12,000 years.

The present-day environment of the Chaco Canyon area is a mixed piñon-juniper woodland with some scrubland, while ponderosa forests are restricted to higher altitudes in nearby

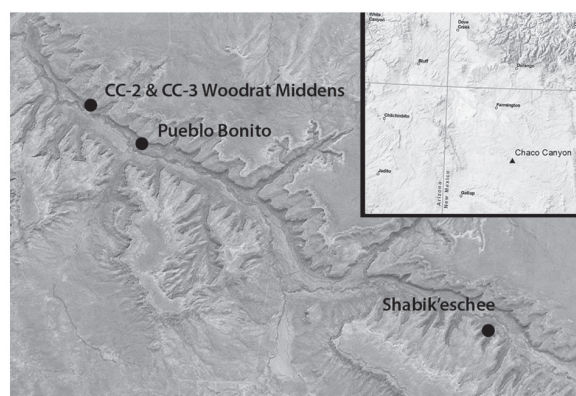


Figure 1. Map of Chaco Canyon. Packrat middens CC-2 and CC-3 provide the earliest palynological evidence for *Zea* maize occurrence in the Southwest at c. 3940 ^{14}C yr BP (c. 4364 cal. yr BP) (Hall, 2010). Shabik'eschee village (c. 1550–1200 cal. yr BP) is the oldest known agricultural settlement (Wills and Windes, 1989) in Chaco and Pueblo Bonito is the type site for the Bonito Phase (c. 1100–800 cal. yr BP).

University of New Mexico, USA

Corresponding author:

Brandon L Drake, MSC01, Department of Anthropology, University of New Mexico, 1 University of New Mexico, Albuquerque NM 87131, USA.
Email: b.lee.drake@gmail.com

mountain ranges (Figure 2). Combined pollen and macrobotanical evidence suggest a transition to increased aridity in the San Juan Basin in the mid Holocene. Pollen data from Chaco alluvium indicate this aridization occurred sometime before *c.* 5800 BP ¹⁴C yr BP (*c.* 6600 cal. yr BP) (Hall, 1977). Ponderosa pine macrofossils are found in middens dated to before *c.* 5550 ¹⁴C yr BP (6302 cal. yr BP), but disappear afterward, while piñon pine macrofossils increased in frequency from that point onwards (Betancourt and Van Devender, 1981). Total differentiated pollen from packrat midden pollen assemblages record an increase of piñon pollen and a decrease in ponderosa pollen that begins around *c.* 5550 ¹⁴C yr BP (6302 cal. yr BP) (Hall, 1988). Pine tree evidence is altogether lacking in packrat middens after *c.* 1202 cal. yr BP, possibly reflecting human depletion of local tree stands.

Historical changes in the piñon/ponderosa ecotone in New Mexico have been attributed to punctuated episodes of intensive drought (Allen and Breshears, 1998). Ponderosa is more drought sensitive than piñon and therefore tends to occupy higher elevations (Pearson, 1920), while in dry years low-elevation ponderosa trees exhibit reduced growth relative to piñon (Adams and Kolb, 2005). Ponderosa forests in northern New Mexico experienced large die offs after the 1950s droughts and were replaced by piñon (Allen and Breshears, 1998). One ecotonal shift covered 2 km in less than 5 years and has persisted for more than 50 years with an upward elevational shift from 1800 m to 2200 m. In addition, the spatial distribution of ponderosa in the ecotone has grown more fragmented with time. Recent droughts between 2000 and 2004 resulted in ponderosa die offs across the Southwest and researchers anticipate that continued aridity will further reduce the presence of ponderosa (Burkett et al. 2005; Gitlin et al., 2006; Negron et al., 2009). These historical observations suggest that it is possible to track the relationship between piñon and ponderosa during ecotonal transitions in the past.

A 12,000 year record of piñon and ponderosa pine pollen has been recovered from Chaco packrat middens (Betancourt and Van Devender, 1981; Hall, 1988). Packrat middens preserve a sequence of long-distance dispersal pollen that records floral change at the regional level. Midden pollen assemblages have been used to identify changes in piñon woodlands in Dutch John Mountain in Northeastern Utah, where multidecadal droughts and pluvial periods were related to the expansion of piñon at the

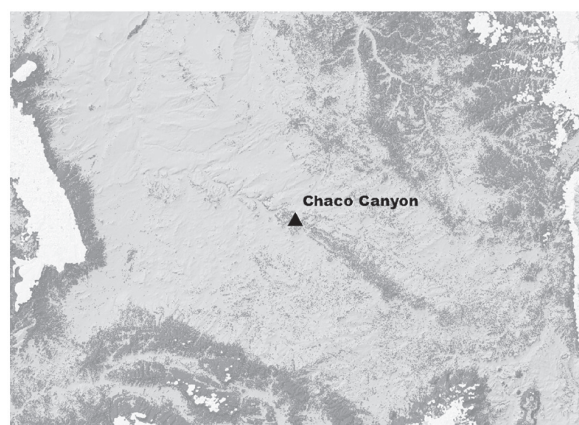


Figure 2. Distribution of ponderosa forests and piñon-juniper woodlands around Chaco Canyon, New Mexico (United States Geological Survey National Gap Analysis Program, 2004). Ponderosa pine (white) is mainly confined to higher elevations where interruptions in precipitation are less common, although small stands and isolated trees do occur in favorable settings at lower elevations. Piñon-juniper woodlands (dark grey) occur at lower elevations where precipitation is more variable.

expense of *Juniper* (genus) (Gray et al., 2006). There is debate as to what degree pollen in packrat middens reflects local versus regional (e.g. long distance dispersal) pollen (Davis and Anderson, 1987, 1988; Van Devender, 1988) but it seems clear that long-distance dispersal of pine pollen accounts for its presence in packrat middens when pine macrobotanical remains are absent (Hall, 1988). Packrat middens are a unique depositional environment allowing for rapid incorporation of pollen onto a sticky surface. The resulting sample should be reflective of long-distance dispersal pollen rain (Van Devender, 1988). Provided that pollen accumulation is a result of a random, gradual process. In an Arizona case study, local pine abundance had a significant weak relationship ($r^2 = 0.06$, $p < 0.001$) with pollen rain, suggesting that local pine only slightly augments a primarily regional pollen signal (Stuart et al., 2006). Although it is impossible to know the exact contribution of local versus regional sources in packrat midden pollen in Chaco over the past 12,000 years, linear modeling can help generate statements of significance as to the broader relationship between ponderosa and piñon abundance.

Palynologists traditionally calculate pollen spectral percentages to address variation between taxonomic abundance on regional and depositional scales in order to help resolve issues of over- and under-representation of taxa (Calcote, 1995; Davis et al., 1973). This calculation was developed by Lennart von Post in 1916 (Manten, 1966), and has remained the most consistent form of analyzing pollen data since its introduction. This metric is often used to report changes in frequency of taxa occurrence but it seldom tests specific hypotheses about environmental/climate change (Birks, 1993; Ritchie, 1995; Seppä and Bennett, 2003). Frequently the attribution of pollen changes to one or more factors is simply speculation (MacDonald, 1993). An alternate metric can correct for differences in sample size but retain information about their occurrence through time by summing each taxon from all pollen assemblages used in a given study and reporting the fraction of this number in each temporally defined assemblage. For the purpose of this paper, the term 'species occurrence' will refer to this calculation and 'pollen percentage' will reflect the traditional approach.

Materials and methods

We analyzed published packrat midden pollen data (Hall, 1988) using linear models with long-distance dispersal (LDD) taxa juniper, piñon pine, ponderosa pine, and limber pine. Simple linear regressions were run between each of the four tree types and sample size. In the combined set of linear models the variation in each species can be represented as a function of other taxa, or simply as a change in sample size. Species with clear relationships were then contrasted with other paleoclimate records that reflect Holocene changes in the San Juan Basin. The intent of this approach is to demonstrate that significance testing is both possible and helpful in understanding changes in plant species abundance. Additionally, comparison with other paleoclimate records helps better contextualize changes in species representation over time in pollen assemblages.

All radiocarbon dates were calibrated using Calib 6.0 software with intcal09 (Reimer et al., 2009; Stuiver and Reimer, 1993). Radiocarbon-dated material in middens were primarily macrobotanicals (Betancourt and Van Devender, 1981; Hall, 1988) and as such have calendrical dates BP. However, it is important to consider the ambiguity of pollen dates from packrat middens; material can be aggregated and mixed over hundreds and even thousands of years (Webb, 1986). For this reason, the time frame represented by pollen assemblages were broader than a specific calendrical date indicates. Pollen taxa data were and calculated as conventional pollen percentages displayed in spectra:

$$\text{Taxon}_{\text{sample}} = \text{Taxon}_{\text{count}} / \text{Sample}_{\text{count}} \quad (1)$$

This ratio expresses relative abundance but precludes linear modeling of relationships between taxa. A second calculation of pollen percentages was performed with juniper removed, following previous treatment (Hall, 1988).

A separate calculation for species occurrence still reports pollen as frequencies but preserves temporal variation independent of temporal assemblage sample size:

$$\text{Taxon}_{\text{total}} = \text{Taxon}_{\text{count}} / \text{Total}_{\text{taxon}} \quad (2)$$

Simple linear models were generated to examine long-distance dispersal species with known modern ecotonal boundaries (juniper, piñon, ponderosa and limber pine). These taxa were also tested against sample size. To show change in piñon over time, piñon pollen was divided by the sum of piñon and ponderosa pollen to show its proportional representation among long distance dispersal (LDD) pollen species. Juniper and limber pine were excluded from these calculations because of their significant relationships with sample size.

For comparison, an oxygen isotope record derived from a speleothem in Pink Panther Cave in the Guadalupe Mountains of New Mexico (Asmerom et al., 2007) was used to provide an independent measure of Holocene climate. To determine the relationship between climate near Carlsbad Caverns/Guadalupe Mountains and the San Juan Basin, a linear regression was run between monthly precipitation at the Carlsbad Caverns weather station and the National Oceanic and Atmospheric Association's (NOAA) New Mexico climate divisions 1, 2, and 4. All $\delta^{18}\text{O}$ values in the Pink Panther record that fell within the 1σ value of each packrat midden radiocarbon date were averaged to create representative values for the period of pollen accumulation.

Similarly, records of El Niño/Southern Oscillation (ENSO) events were utilized as an additional complementary source of regional climate change. ENSO data are reported from Laguna Palicachoa in southern Ecuador (Moy et al., 2002). Color intensity peaks (red) were gathered from clastic organic sediments deposited gradually over 13,000 years. All years with color intensity values at least 15 units above the mean were aggregated to produce a history of ENSO events for the Holocene.

For piñon pine proportions, a Bayesian change-point model was run using the Barry and Hartigan (Barry and Hartigan, 1993) algorithm to estimate two sets of quantities: the probability that each point in the time series partitions blocks with different means and those block means. The algorithm is initialized with no partition points. In each step of the Markov chain, partition points are drawn given the data and the current partition. At each point the odds ($p/(1-p)$) for a partition depends on the within and between block sums of squares obtained given the data and the updated partition. After each iteration, the posterior block means are updated conditional on the data and the updated partition. Repeated many times, this process converges to the posterior distributions of the partition probabilities and block means. Each model had a burn-in of 10,000 iterations and posterior probabilities were generated from 10,000 Markov-Chain Monte Carlo

simulations. These simulations were run in R using the bcp package with hyper parameter defaults recommended by Erdman and Emerson (2007).

Results

Ponderosa pine was common in Chaco Canyon packrat midden pollen assemblages during the early Holocene but declined sometime before c. 6302 cal. yr BP, after which piñon pine contribution increased, especially between c. 5440 and 5102 cal. yr BP. Piñon continued to be prevalent in Chaco assemblages until c. 1202 cal. yr BP but is absent thereafter. This decline may be related to hypothesized deforestation by local farmers (Betancourt and Van Devender, 1981), although piñon was used as fuel until at least c. 900 BP (Toll, 1983).

Piñon pine has a significant negative relationship with both ponderosa and limber pine (Table 1). The proportion of variation in limber pine is significantly explained by both sample size and juniper, however the oldest pollen assemblage has high leverage upon this relationship. With that point removed, the prediction is lower with both sample size ($r^2 = 0.03$, $p = 0.50$) and juniper ($r^2 = 0.03$, $p = 0.51$). The same point has little leverage on the relationship between piñon and ponderosa, as evidenced when it is removed ($r^2 = 0.83$, $p < 0.001$). Juniper shows no significant relationship with any of the other plants but it is predicted by sample size for each pollen assemblage. When calculated as pollen percentages, the only significant relationship is a negative one between juniper and piñon ($r^2 = 0.45$, $p < 0.001$). Regressions between piñon and ponderosa pines reveal a significant negative relationship when calculated as either species occurrence (Figure 3a) or pollen percentages with juniper removed (Figure 3b). Pollen percentages (with juniper included) show no significant relationship (Figure 3c).

An increase in piñon pine representation in LDD pollen occurs between c. 5440 cal. yr BP and c. 5102 cal. yr BP (Figure 4). Both increases are associated with change-points with high posterior probabilities (Figure 5). A decrease in piñon pine representation occurs at c. 1202 cal. yr BP (Figure 5). The second increase in piñon pine, dated to before c. 5102 cal. yr BP, is rapid and appears to have been associated with a slight increase in aridity and a large increase in ENSO variability (Figure 4).

Discussion

Linear modeling of the relationship between piñon and ponderosa pine, complemented by Bayesian change-point analysis, suggests a process of aridization began before c. 6302 cal. yr BP and accelerated between c. 5440 and c. 5102 cal. yr BP. This is consistent with previous palynological interpretations of the canyon in alluvial sediments (Hall, 1977) and with macrobotanical studies of the canyon (Betancourt and Van Devender, 1981). An more arid climate is also documented in oxygen isotope speleothem records from the Guadalupe Mountains in southern New Mexico (Asmerom et al., 2007) after 6000 BP. Precipitation near the Guadalupe Mountains has varied with precipitation in the San Juan Basin ($r^2 = 0.19$, $p < 0.001$). The relationship between

Table 1. Regressions of LDD pollen in assemblages using taxon totals.

	Piñon pine	Ponderosa pine	Limber pine	Sample size
Juniper	0.15 ($p = 0.10$)	0.11 ($p = 0.16$)	0.25 ($p = 0.03$) ^o	0.87 ($p < 0.001$)***
Piñon pine		0.89 ($p < 0.001$)***	0.70 ($p < 0.001$)***	0.12 ($p = 0.12$)
Ponderosa pine			0.59 ($p < 0.001$)***	0.11 ($p = 0.16$)
Limber pine				0.22 ($p = 0.04$) ^o

Significance codes: ***0.001; **0.01; *0.05; ^o 0.1.

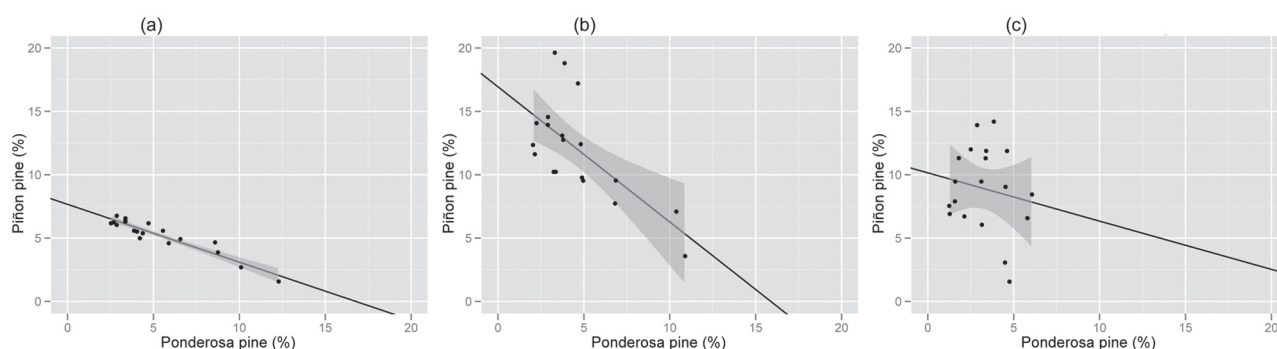


Figure 3. Species occurrence of ponderosa and piñon pine (a), conventional pollen percentage with juniper removed (b), and conventional pollen percentage (c) ($n = 19$). The shaded grey area represents 95% confidence bounds about the regression line. A strong relationship is found between the occurrence (3a) of ponderosa and piñon pine ($r^2 = 0.89$, $p < 0.001$); pollen percentages with juniper removed (3b) had a moderate but still significant relationship ($r^2 = 0.46$, $p = 0.002$); data presented in traditional pollen percentages (3c) have a weaker relationship ($r^2 = 0.03$, $p = 0.49$). A strong linear relationship exists between piñon and ponderosa pine in the Holocene packrat midden records in Chaco Canyon that is not immediately evident when data from long-distance dispersal pollen is normalized to sample size.

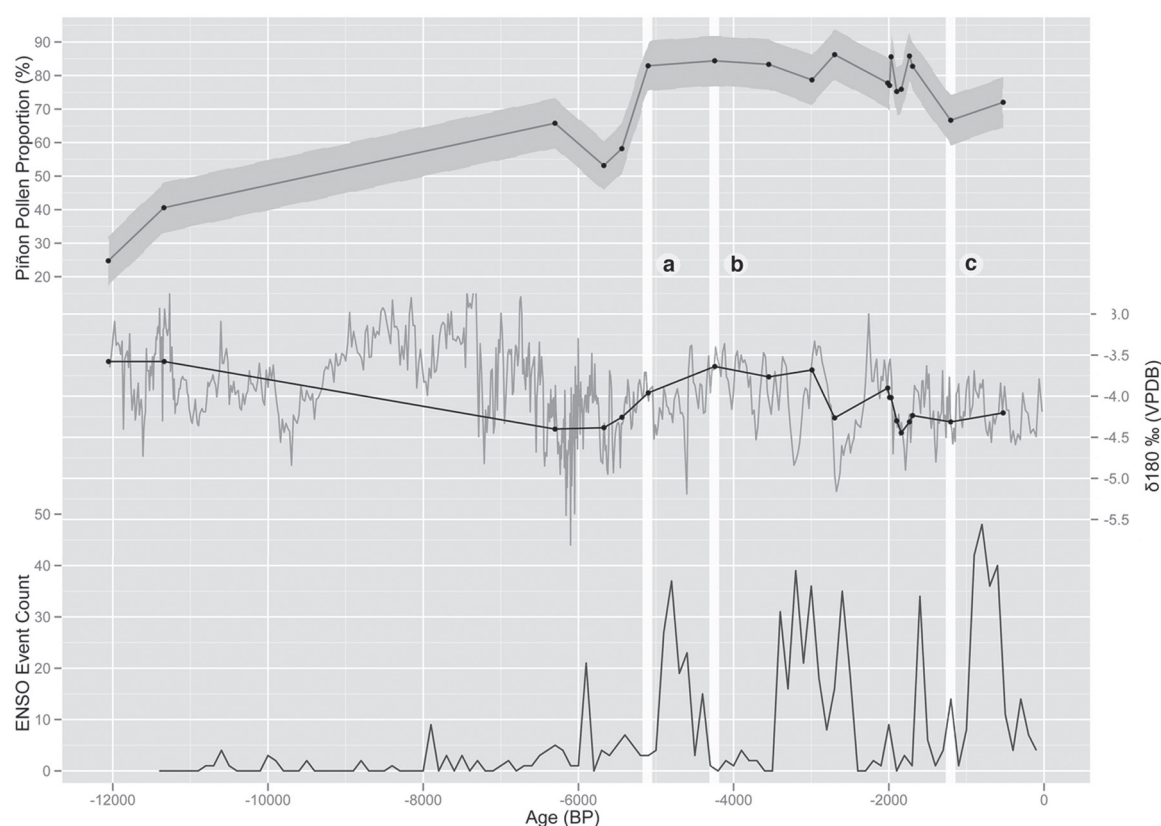


Figure 4. The proportion of piñon pine pollen relative to total long distance dispersal (LDD) pollen during the Holocene in Chaco packrat middens. The shaded area around the line represents 95% confidence levels. The full data set for $\delta^{18}\text{O}$ is shown in the middle of the figure, black dots are values averaged over the 1σ value of each radiocarbon data for pollen assemblages. Ponderosa is more prevalent in the early Holocene (12,000–11,000 cal. yr BP) than other pines, while at some point before c. 6302 cal. yr BP piñon increases in frequency, then rises sharply at c. 5102 cal. yr BP (a), indicating increased aridity and the retreat of the piñon-ponderosa ecotonal boundary to a higher elevation. The earliest directly dated occurrence of *Zea* (b) in Chaco canyon is pollen at c. 3940 ^{14}C yr BP (c. 4364 cal. yr BP) (Hall, 2010), while the oldest maize macrofossil on the Colorado Plateau is dated to c. 4200 cal. yr BP (Huber and Miljour, 2004). A decrease in piñon pollen occurs when macrobotanicals disappear from the midden records at c. 1202 cal. yr BP (c), an event hypothesized to be associated with deforestation (Betancourt and Van Devender, 1981). A gradual increase in aridity beginning at 6000 cal. yr BP and concluding around 4200 cal. yr BP would have favored the spread of piñon pine. Of equal importance, an increase in ENSO events beginning after 5100 cal. yr BP (Moy et al., 2002) would have caused variable precipitation in the Southwest. Increased aridity and precipitation variation would have further restricted the range of ponderosa pine to higher elevations, as it is more susceptible to drought than piñon pine.

precipitation near the Guadalupe Mountains and the San Juan Basin suggest that the stable oxygen isotope speleothem record for Pink Panther Cave has some implications for the climate near Chaco Canyon. The strength of the linear relationships between piñon and ponderosa pollen suggests that low-elevation ponderosa

forests were replaced by piñon-juniper woodlands during the 5.1 ka aridization event. Ecotonal transitions between these two forest types during the past century have been rapid during periods of drought (Adams and Kolb, 2005; Allen and Breshears, 1998; Burkett et al., 2005; Gitlin et al., 2006; Negron et al., 2009) and

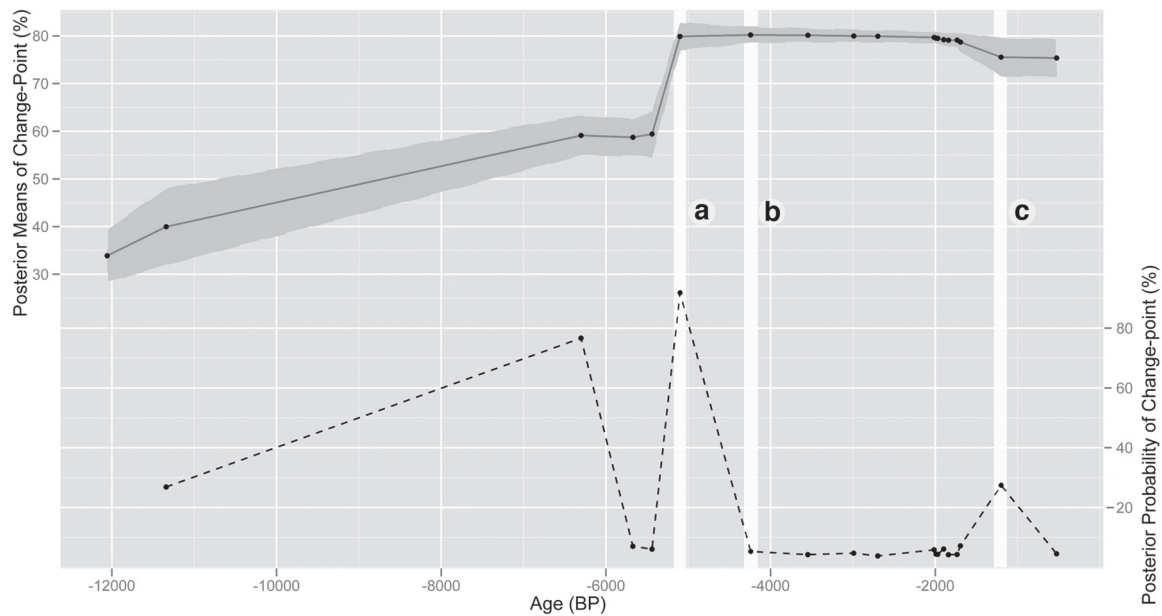


Figure 5. Posterior probabilities of change points generated from pollen data. The shaded area around the line represents the posterior standard deviation resulting from Bayesian change-point analysis. Piñon pine pollen counted as a proportion of all LDD pollen shows a high posterior probability at c. 6302 cal. yr BP (78.70%), c. 5102 cal. yr BP (90.23%) (a), and at c. 1202 cal. yr BP (36.38%) (c). The 5.1 ka aridization event is associated with significant increases in piñon pine pollen in packrat midden records. Almost 3000 years of stability in piñon-ponderosa woodlands follows the domestication of maize (b). The decrease in piñon pine pollen at c. 1202 cal. yr BP (c) (with a posterior probability of 30.96%) is associated with the hypothesized deforestation of piñon pine in Chaco Canyon (Betancourt and Van Devender, 1981).

therefore the aridization period between c. 5440 and c. 5102 cal. yr BP may have been the result of a similar episode of punctuated droughts.

The initial appearance of piñon macrobotanicals in Chaco packrat middens at c. 6302 cal. yr BP corresponds to the last occurrence of ponderosa remains (Betancourt and Van Devender, 1981). This is also the point at which piñon pollen frequencies first exceed those of ponderosa (Hall, 1988) (Figure 4). During the late Wisconsin period, piñon was restricted to southern New Mexico but it is last identified in packrat middens in this region around c. 11,100 BP (Lanner and Van Devender, 1981; Van Devender et al., 1984). The sharp increase in piñon pine between c. 5440 and 5102 cal. yr BP suggests a settling in to the modern range of piñon in the mountain ranges framing the San Juan Basin. Oxygen-isotope records from Pink Panther cave to the South suggest a decrease in precipitation at that time that would have made the Southwest more vulnerable to droughts (Figure 4), conditions that would have limited ponderosa pine trees to higher elevations with more predictable rainfall and encouraged the range expansion of the more drought-tolerant piñon.

An aridization event at 5100 BP is reflected in multiple climate records worldwide. A sharp drop in precipitation at 5100 cal. yr BP was observed in oxygen-isotope speleothem records in Soreq cave in Israel (Bar-Matthews et al., 1997, 2003). Dolomite and CaCO_3 concentrations in the Gulf of Oman increase during this time period (Cullen et al., 2000). A similar increase of dolomite and CaCO_3 at c. 4200 cal. yr BP was associated with increased aridity and civilization collapse in the Middle East and North Africa (Cullen et al., 2000). Similar shifts in aridity are evident in lower lake levels in Spain, Portugal, and Greece at the same time (Harrison and Digerfeldt, 1993), suggesting that a widespread series of droughts took place globally c. 5100 BP. A sharp increase in ENSO events occurred around c. 5000 cal. yr BP and lasted until c. 4200 cal. yr BP, bracketed by the 5.1 and 4.2 kiloyear events (Moy et al., 2002). El Niño events are associated with increased precipitation in the US Southwest, while La Niña events are associated with below-average precipitation (Arriaga-Ramírez and Cavazos, 2010). This would have resulted in rapid

growth of vegetation in El Niño years and die-offs during La Niña years. Charcoal records from the Sonoran desert in Arizona indicate an increase in fire frequency between c. 5330 and 4400 cal. yr BP, possibly because of the increase in ENSO activity (Brunnelle et al., 2010). The mid-Holocene increase in piñon pine from Chaco Canyon is thus firmly situated within a global period of aridization and increased climatic variability.

The 5.1 ka aridization period occurred before the introduction of maize cultivation to the northern Southwest. The oldest directly dated maize cob from the Colorado plateau is c. 4200 cal. yr BP in west-central New Mexico (Huber and Miljour, 2004), with a number of sites in the region producing maize at c. 4000 BP (Hard et al., 2010; Wills, 2005). The earliest evidence for maize agriculture comes from *Zea mays* pollen in Chaco packrat middens at c. 3940 ^{14}C yr BP (c. 4364 cal. yr BP) (Hall, 2010). The earliest introduction of maize therefore occurs near another major mid-Holocene global aridization event near c. 4200 cal. yr BP (Cullen et al., 2000). The relationship between maize introduction to the Chaco region and mid-Holocene aridity was probably indirect, with the expansion of piñon-juniper woodlands creating a vastly greater set of economic opportunities for pre-agricultural foragers. Piñon seeds (or nuts) are an especially high return wild resource, rich in nutrients and calories, occurring in large patches with predictable mast periodicity and amenable to storage and thus prolonged availability (Madsen and Rhode, 1990). The dietary importance of piñon seeds is reflected in occurrence of property rights in piñon woodlands by Native American groups throughout the American West during the historic period. Therefore we argue that the introduction of maize to the northern Southwest (Colorado Plateau), including Chaco Canyon, took place within an overall expansion of diet breadth and greater availability of plant foods associated with increasing aridity. It is intriguing that chenopodium, a major economic plant in prehistoric North America that was domesticated in the Eastern Woodlands (Smith and Cowan, 1987), also shows a spike at c. 4243 cal. yr BP in the Chaco data.

It is possible that the 5.1 ka period of aridization, together with a subsequent spike in aridity around 4200 cal. yr BP (Cullen et al.,

2000) produced ecological changes in resource structure that set the stage for the introduction of maize agriculture to human foragers. Maize was domesticated in central America by 6500 BP, and entered the Southwest around 2000 years later (Merrill et al., 2009). The oldest dated maize (*Zea mays*) macrofossil on the Colorado Plateau is c. 4200 cal. yr BP (Huber and Miljour, 2004) and a number of sites in the region have produced maize specimens dating to 4000 BP, while *Zea mays* pollen from Chaco Canyon packrat middens is directly dated to c. 3940 ¹⁴C yr BP (c. 4364 cal. yr BP) (Hall, 2010). Archaeologists are unsure what sociocultural processes were responsible for the transmission of maize from south to north, whether diffusion between hunter-gatherer groups or the migration of farmers, or some combination of both (Merrill et al., 2009; Wills, 1995), but there is a consensus among researchers that maize must have been valuable and must have fit into local economies without disruption. However, although maize seems to have dispersed through the Southwest, this cultivated plant does not appear to have provided the foundation for sedentary lifeways until much later, perhaps around 3000 BP in southern Arizona and 2000 BP on the Colorado Plateau. In other words, the historical record suggests that initially maize was useful but not immediately transformative (Wills, 2005). On the Colorado Plateau, the widespread development of piñon-juniper woodlands may be critical to understanding why the earliest involvement with maize did not result in a dramatic shift to sedentary adaptations.

The mid-Holocene expansion of piñon-juniper woodlands in response to aridization produced an expansion in diet breadth for human foragers, especially high return (in calories and nutrients) foods such as piñon nuts, which occurred in large patches with predictable periodicities and were amenable to storage (Barlow and Metcalfe, 1996; Janetski, 1999; Madsen and Rhode, 1990). Piñon nuts were so important to historic hunter-gatherer groups in the western USA that individual bands or families claimed property rights over collecting areas and were able to sustain sedentary winter camps in those areas (Simms, 1985). Consequently the replacement of ponderosa pine forests by piñon woodlands likely created conditions favoring territorial control over productive collecting localities by hunter-gatherers. Such geographic stability is essential to the successful cultivation of maize, which requires annual storage, seed selection, planting and harvesting.

The frequency of radiocarbon-dated archaeological sites on the Colorado Plateau increased dramatically between c. 4400 and 4000 ¹⁴C yr BP (c. 4950 and 4450 cal. yr BP) (Chapin, 2005: 168), a trend that likely tracked an increasingly intensive occupation of the emergent piñon-juniper woodlands by foragers, as well as repetitive use of particular site locations (see Rhode and Madsen, 1998; Simms, 1985). In addition to piñon, hunter-gatherer groups were also utilizing low-return small seed resources, including grasses, chenopodium and amaranth that are common in piñon-juniper woodlands. Small seed use was facilitated through technological innovations in basketry (for winnowing, parching, storage and transport) and grinding stones (or producing flour) (Geib and Jolie, 2008). In short, following the expansion of piñon-juniper woodlands at c. 5102 cal. yr BP, the archaeological record reveals intensive land-use systems by foragers who invested in the collection, processing and storage of seeds.

There are clear consistencies between the requirements for maize cultivation and the nature of hunter-gatherer economies on the Colorado Plateau between c. 5000 and 4000 BP. The basic organization of small kin-based groups included behaviors such as food storage and localized extractive strategies that were a good fit for introduced cultigens. These behaviors co-evolved with the expanding piñon-juniper habitat and the attendant economic opportunities provided by greater resource diversity (Wills, 1988a, 1988b). The fact that hunter-gatherers were already using

low-return plants helps explain the rapid introduction of maize, which offered relatively high caloric yields without significantly greater costs (see Barlow, 2002). We do not argue that maize was adopted because the Colorado Plateau environment was transformed in the mid Holocene, but rather that this transformation promoted foraging behaviors that made the acquisition of maize and other cultigens beneficial once they became available. The prolonged period between the adoption of maize and the emergence of sedentary agricultural societies in the piñon-juniper woodlands suggests that the resulting mix of wild and domesticated food resources was a stable or resilient adaptation. Archaeologists argue that this apparent stability reflects a wide range of local subsistence patterns, some incorporating very little maize cultivation, others much more (Wills, 2005). In general, greater emphasis on maize cultivation probably indicates fewer opportunities for obtaining higher ranked resources (Barlow, 2002). The mid-Holocene expansion of piñon-juniper woodlands created opportunities for incipient farmers but also created opportunities for foragers to maintain essentially hunting and gathering production systems.

The temporal relationship between piñon and ponderosa pine offers a clear picture of environmental change over the past 6000 years in Chaco Canyon with a substantial species replacement taking place in the mid Holocene. Simple linear regression indicates significant relationships between the two species (Table 1). The sharp decline in ponderosa and limber pine between c. 5440 and 5102 cal. yr BP (Figure 4) suggests that an increase in droughts was a feature of the aridization that occurred at that time. This hypothesis is supported by a decrease in rainfall reflected in higher $\delta^{18}\text{O}$ values. Following this period, the present ecotonal boundary in the Chaco region between these species was established as a result of continued droughts associated with a large increase in ENSO events. The expansion of piñon-juniper woodlands and their multimillennial stability raised local resource values for human hunter-gatherer populations and promoted foraging behaviors that paved the way for the adoption of maize agriculture during the following millennium.

Seppä and Bennett (2003) characterized Quaternary pollen analysis as 'approaching a state that could be called a minor crisis' (2003: 549). This was due to a lack of hypothesis testing and frequent uncritical and speculative interpretations on changes in pollen diagrams. In part this is a structural issue; the normalization of pollen counts to sample size tends to preclude inter-site comparisons of taxa. Species such as piñon and ponderosa pine, which have been observed to vary with regard to climate (Allen and Breshears, 1998), are an example of this phenomenon. When normalized to sample size, the relationship between piñon and ponderosa pine is either lost or weakened (Table 1; Figure 3). Fluctuations in other taxa, which can be unrelated to climate, can add error to a clear climatic signal. This can be demonstrated by contrasting the Mockingbird Canyon 2 (c. 2990 cal. yr BP) assemblage with Gallo Wash 1 (c. 1839 cal. yr BP) assemblage. The Mockingbird Canyon 2 assemblage contains 82 grains of piñon pine pollen while Gallo Wash 1 contains 85 grains. When calculated as pollen percentage, piñon pollen in Mockingbird Canyon 2 represents 6.71% of the assemblage, while piñon pollen in Gallo Wash 1 represents 14.91% of the assemblage; this dramatic difference in representation is not the consequence of a change in piñon pine pollen, but rather the surrounding vegetation. Even when juniper pollen is removed from the sample, there is still a large difference between the Mockingbird Canyon 2 and Gallo Wash 1 pollen percentages (10.22% and 17.21%, respectively). When calculated as species occurrence, the difference between the two assemblages is far less pronounced (5.38% and 5.58%, respectively).

The species occurrence has the potential to help clarify climate signals in multiple pollen assemblages. By normalizing to

the taxon totals, rather than to the assemblage totals, it is possible to express pollen taxa relative to its own history. Critically, this metric incorporates hypothesis testing into its structure. By expressing assemblage size as a percent of all pollen, a null hypothesis can be formulated. This null hypothesis would stipulate that for every 1% increase in each pollen assemblage's size, a corresponding 1% increase should be observed in each taxon. In this study, taxon that reproduce through long distance wind dispersal were tested against this null hypothesis. Juniper was found to have a highly significant relationship with sample size, suggesting that its variation followed the prediction of the null hypothesis ($r^2 = 0.87$, $p < 0.001$). Both piñon and ponderosa pine had non-significant relationships with sample size (Table 1), suggesting that other factors contributed to their variation over time. Both species had a significant negative relationship with each other ($r^2 = 0.89$, $p < 0.001$), suggesting that the Holocene time series of the two taxa were governed by similar competitive dynamics observed in the 20th century (Allen and Breshears, 1998).

The metric of species occurrence is not intended to be a replacement for, or superior to, the pollen percentage metric used in pollen diagrams. The pollen diagram has been immensely useful for almost a century following its development (Manten, 1966). Pollen data can be recovered globally, and records often span thousands of years. While the pollen diagram is a highly useful way to express large quantities of pollen data, it should not be the only method employed to analyze pollen assemblages. The pollen percentage metric does not test for significance of changes in taxa frequency and it cannot address interspecific competition reflected in long-distance dispersal pollen, such as that between piñon and ponderosa pine. Linear modeling of the relationship between taxa that compete at ecotonal boundaries can complement existing palynological methods by assessing the significance of changes in multiple pollen assemblages. Bayesian change-point analysis can help assess the significance of changes in long-term records. When the relationship between taxa at ecotonal boundaries is explicated, then modern ecological studies can help researchers better understand prehistoric changes in vegetation. Tests against sample size can identify species that may vary independently of their environmental context, such as plants under human cultivation. Robust linear modeling and hypothesis testing can contribute to significantly more detailed paleoclimate interpretations.

Supplementary computer code in the R computing language (2.15.0) is available online.

Acknowledgements

We thank Glen MacDonald for comments on potential factors regarding the interpretation of packrat midden pollen assemblages and information about Southwestern fires associated with increases in ENSO events at 5,000 BP. Suzanne Fish and Susan Smith analyzed pollen samples from the Pueblo Alto trash mound as part of the ongoing Chaco Stratigraphy Project at the University of New Mexico. Special thanks go to Stephen Hall and Bruce Smith for comments on an early draft of the manuscript. David Hanson suggested linear modeling using pollen percentage data with Juniper pollen removed.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Adams HA and Kolb TA (2005) Tree growth response to drought and temperature in a mountain landscape in Northern Arizona, USA. *Journal of Biogeography* 32: 1629–1640.

- Allen CD and Breshears DD (1998) Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences USA* 95(25): 14,839–14,842.
- Arriaga-Ramírez S and Cavazos T (2010) Regional trends of daily precipitation indices in northwest Mexico and southwest US. *Journal of Geophysical Research* 115: d14.
- Asmerom Y, Polyak V, Burns S et al. (2007) Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology* 35(1): 1–4.
- Bar-Matthews M, Ayalon A, Gilmour M et al. (2003) Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. *Geochimica Cosmochimica Acta* 67(17): 3181–3199.
- Bar-Matthews M, Ayalon A and Kauffman A (1997) Late Quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research* 47: 155–168.
- Barlow RK (2002) Predicting maize agriculture among the Fremont: An economic comparison of farming and foraging in the American Southwest. *American Antiquity* 67: 65–88.
- Barlow K and Metcalfe D (1996) Plant utility indices: Two Great Basin examples. *Journal of Archaeological Science* 23: 351–371.
- Barry D and Hartigan JA (1993) A Bayesian analysis for change point problems. *Journal of the American Statistical Association* 35(3): 309–319.
- Betancourt JL and Van Devender TR (1981) Holocene vegetation in Chaco Canyon, New Mexico. *Science* 214(4521): 656–658.
- Birks HJB (1993) Quaternary palaeoecology and vegetation science – Current contributions and possible future developments. *Reviews of Palaeobotany and Palynology* 79: 153–177.
- Brunnelle A, Minckley TA, Blissett S et al. (2010) A ~8000 year fire history from an Arizona/Sonoran borderland ciénaga. *Journal of Arid Environments* 74: 475–481.
- Burkett VR, Wilcox DA, Stottlemeyer R et al. (2005) Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. *Ecological Complexity* 2: 357–394.
- Calcote R (1995) Pollen source area and pollen productivity: Evidence from forest hollows. *Journal of Ecology* 83(4): 591–602.
- Chapin NM (2005) *Hunter-gatherer technological organization: The Archaic period in northern New Mexico*. Dissertation, The University of New Mexico.
- Crown PL and Hurst WJ (2009) Evidence of cacao use in the Prehispanic American Southeast. *Proceedings of the National Academy of Science USA* 106(7): 2110–2113.
- Cullen HM, deMenocal PB, Hemming S et al. (2000) Climate change and the collapse of the Akkadian Empire: Evidence from the deep sea. *Geology* 28: 379–382.
- Davis MB, Brubaker LB and Webb T III (1973) Calibration of absolute pollen influx. In: Birks HJB and West RG (eds) *Quaternary Plant Ecology*. Oxford: Blackwell Scientific Publications, pp. 9–25.
- Davis OK and Anderson RS (1987) Pollen in packrat (Neotoma) middens: Pollen transport and the relationship of pollen to vegetation. *Palynology* 11: 185–198.
- Davis OK and Anderson RS (1988) Pollen in packrat (Neotoma) middens: Pollen transport and the relationship of pollen to vegetation: Reply. *Palynology* 12: 226–229.
- Erdman C and Emerson JW (2007) bcp: An R package for performing a bayesian analysis of change point problems. *Journal of Statistical Software* 23(3): 1–13.
- Geib PR and Jolie EA (2008) The role of basketry in early Holocene small seed exploitation: Implications of a ca. 9,000 year-old basket from Cowboy Cave, Utah. *American Antiquity* 73: 83–102.
- Gitlin AR, Stultz CM, Bowker MA et al. (2006) Mortality gradients within and among dominant plant populations as barometers of ecosystem change during extreme drought. *Conservation Biology* 20(5): 1477–1486.
- Gray ST, Betancourt JL, Jackson ST et al. (2006) Role of multidecadal climate variability in the range extension of Pinyon pine. *Ecology* 87(5): 1124–1130.
- Hall SA (1977) Late Quaternary sedimentation and paleoecological history of Chaco Canyon, New Mexico. *Geological Society of America Bulletin* 88: 1593–1618.
- Hall SA (1988) Prehistoric vegetation and environment at Chaco Canyon. *American Antiquity* 53(3): 582–292.
- Hall SA (2010) Early maize pollen from Chaco Canyon, New Mexico, USA. *Palynology* 34(1): 125–137.
- Hard RJ, MacWilliams AC, Roney JR et al. (2010) Early agriculture in Chihuahua, Mexico. In: Staller J, Tykot R and Benz B (eds) *Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography,*

- Domestication, and Evolution of Maize*. Burlington: Academic Press, pp. 471–485.
- Harrison SP and Digerfeldt G (1993) European lakes as paleohydrological and paleoclimatic indicators. *Quaternary Science Reviews* 12: 233–248.
- Huber EK and Miljour HJ (2004) Early maize on the Colorado Plateau: New dates from West-Central New Mexico. *Ninth Southwest Symposium*. Ciudad de Chihuahua, Mexico, 9–10 January.
- Janetski J (1999) Role of pinyon-juniper woodlands in Aboriginal societies of the Desert West. *USDA Forest Service Proceedings*, Rocky Mountain Research Station, Ogden UT.
- Lanner RM and Van Devender TR (1981) Late Pleistocene piñon pines in the Chihuahuan Desert. *Quaternary Research* 15: 278–290.
- MacDonald GM (1993) Methodological falsification and the interpretation of palaeoecological records: The cause of the early Holocene birch decline in western Canada. *Reviews of Palaeobotany and Palynology* 79: 83–97.
- Madsen DB and Rhode D (1990) Early Holocene Pinyon (*Pinus monophylla*) in the Northern Great Basin. *Quaternary Research* 33: 94–101.
- Manten AA (1966) Half a century of modern palynology. *Earth Science Reviews* 2: 277–316.
- Merrill WL, Hard RJ, Mabry JB et al. (2009) The diffusion of maize to the Southwestern United States and its impact. *Proceedings of the National Academy of Sciences, USA* 106(50): 21,019–21,026.
- Moy CM, Seltzer GO, Rodbell DT et al. (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420: 162–165.
- Negron JF, McMillin JD, Anhold JA et al. (2009) Bark beetle-caused mortality in a drought-affected ponderosa pine landscape in Arizona, USA. *Forest Ecology and Management* 257: 1353–1362.
- Pearson GA (1920) Factors controlling the distribution of forest types, part 1. *Ecology* 1(3): 139–159.
- Reimer PJ, Baillie MGL, Bard E et al. (2009) Intcal 09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 51(4): 1111–1150.
- Rhode D and Madsen DB (1998) Pine nut use in the early Holocene and beyond: The Danger Cave archaeobotanical record. *Journal of Archaeological Science* 25: 1199–1210.
- Ritchie JC (1995) Current trends in studies of long-term plant community dynamics. *New Phytologist* 130: 469–494.
- Seppä H and Bennett KD (2003) Quaternary pollen analysis: Recent progress in paleoecology and paleoclimatology. *Progress in Physical Geography* 27(4): 548–579.
- Simms SR (1985) Pine nut use in three Great Basin cases: Data, theory and a fragmentary record. *Journal of California and Great Basin Anthropology* 7: 166–175.
- Smith BD and Cowan CW (1987) Domesticated *Chenopodium* in prehistoric Eastern North America: New accelerator dates from Eastern Kentucky. *American Antiquity* 52: 355–357.
- Stuart G, Gries C and Hope D (2006) The relationship between pollen and extant vegetation across an arid urban ecosystem and surrounding desert in Southwest US. *Journal of Biogeography* 33: 573–591.
- Stuiver M and Reimer PJ (1993) Extended 14C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35: 215–230.
- Toll MS (1983) Changing patterns in plant utilization for food and fuel: Evidence from flotation and macrobotanical remains. In: Hogan P and Winter JC (eds) *Economy and Interaction Along the Lower Chaco River*. Albuquerque: Maxwell Museum of Anthropology, pp. 331–350.
- United States Geological Survey National Gap Analysis Program (2004) *Provisional Digital Land Cover Map for the Southwestern United States*. Version 1.0. RS/GIS Laboratory, College of Natural Resources, Utah State University.
- Van Devender TR (1988) Pollen in packrat (Neotoma) middens: Pollen transport and the relationship of pollen to vegetation: Discussion. *Palynology* 12: 221–226.
- Van Devender TR, Betancourt JL and Wimberly M (1984) Biogeographic implications of a packrat midden sequence from the Sacramento Mountains, South Central New Mexico. *Quaternary Research* 22: 344–360.
- Webb RH (1986) Spatial and temporal distributions of radiocarbon ages on rodent middens from the Southwestern United States. *Radiocarbon* 28(1): 1–8.
- Wills WH (1995) Archaic foraging and the beginning of food production in the American Southwest. In: Price TD and Gebauer AB (eds) *Last Hunters – First Farmers*. Santa Fe: School of American Research Press, pp. 215–242.
- Wills WH (1988a) *Early Prehistoric Agriculture in the American Southwest*. Santa Fe: School of American Research Press.
- Wills WH (1988b) Agriculture and sedentism in the American Southwest: Evidence and interpretations. *Journal of World Prehistory* 2: 445–488.
- Wills WH (2001) Ritual and mound formation during the Bonito phase in Chaco Canyon. *American Antiquity* 66(3): 433–451.
- Wills WH (2005) Economic competition and agricultural involution in the Pre-contact North American Southwest. In: Scarborough VL (ed.) *A Catalyst for Ideas: Anthropological Archaeology and the Legacy of Douglas W. Schwartz*. Santa Fe: School of American Research Press, pp. 41–68.
- Wills WH and Windes TC (1989) Evidence for population aggregation and dispersal during the Basketmaker III period in Chaco Canyon, New Mexico. *American Antiquity* 54(2): 347–369.