Native American depopulation, reforestation, and fire regimes in the Southwest United States, 1492–1900 CE

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Native American populations declined between 1492 and 1900 CE, instigated by the European colonization of the Americas. However, the magnitude, tempo, and ecological effects of this depopulation remain the source of enduring debates. Recently, scholars have linked indigenous demographic decline, Neotropical reforestation, and shifting fire regimes to global changes in climate, atmosphere, and the Early Anthropocene hypothesis. In light of these studies, we assess these processes in conifer-dominated forests of the Southwest United States. We compare light detection and ranging data, archaeology, dendrochronology, and historical records from the Jemez Province of New Mexico to quantify population losses, establish dates of depopulation events, and determine the extent and timing of forest regrowth and fire regimes between 1492 and 1900. We present a new formula for the estimation of Pueblo population based on architectural remains and apply this formula to 18 archaeological sites in the Jemez Province. A dendrochronological study of remnant wood establishes dates of terminal occupation at these sites. By combining our results with historical records, we report a model of pre- and post-Columbian population dynamics in the Jemez Province. Our results indicate that the indigenous population of the Jemez Province declined by 87% following European colonization but that this reduction occurred nearly a century after initial contact. Depopulation also triggered an increase in the frequency of extensive surface fires between 1640 and 1900. Ultimately, this study illustrates the quality of integrated archaeological and paleoecological data needed to assess the links between Native American population decline and ecological change after European contact.

archaeology | dendrochronology | Ancestral Pueblo | anthropogenic landscapes | Anthropocene

How many people lived in the Americas in 1492? How many Native Americans died as a result of warfare, famine, and diseases introduced from the Old World? What was the pace of depopulation? How did this demographic decline affect the environment? These questions comprise some of the most contested and vexing disputes in the study of American Indian history. For more than a century scholars have deliberated the magnitude and tempo of indigenous population decline between 1492 and 1900 CE. Advocates of early and catastrophic depopulation models (dubbed "high counters") spar with more conservative critics of this approach, the latter reckoning population reductions smaller by several orders of magnitude (1–8). In recent years, these debates have grown to consider not only the timing and degree of indigenous demographic decline in the Americas, but also its ecological effects. Over the past decade, researchers have posited that plummeting post-Columbian American Indian populations prompted changes in fire regimes (9, 10), reforestation (11), and carbon sequestration (12–17), ultimately amplifying the global cooling of the Little Ice Age (18). Recent studies suggest that depopulation in the Americas triggered effects momentous enough to usher in an entirely new geological epoch, signaling the transition from the Holocene to the Anthropocene (19) and providing new fodder for debates regarding the "Early Anthropocene" hypothesis (20).

A plurality of these studies share the assumption that Native American population losses initiated a decline in biomass burning after 1500, particularly in the humid Neotropics. According to this theory, demographic collapse spurred the regeneration of forests and sequestration of atmospheric carbon, contributing to global cooling. These studies are ambiguous, however, in that the observed ecological changes and global temperature changes are roughly coeval, resulting in countervailing interpretations of anthropogenic vs. climatic causality (21–25). Arguments for the anthropogenic origins of 16th century global temperature changes rely on hypothetical (and highly contentious) population estimates, many of which neglect to incorporate first-order data related directly to Native American demography. Without precise, independent reconstructions of human population dynamics, these studies are vulnerable to circular reasoning in which poorly resolved evidence for population decline is used to support the inference of anthropogenic changes in climate and atmosphere, which in turn corroborate the timing and magnitude of depopulation.

Here we use a strong case approach to these issues using independent demographic and paleoecological datasets to build a chronology of population decline, forest growth, and fire regime changes after European contact in the dry forests of the Southwest United States. Our data derive from the archaeology, dendrochronology, and historical records of the Jemez Province of northern New Mexico between 1492 and 1900. We devise absolute population estimates for the archaeology of the Jemez Province using airborne light detection and ranging (LiDAR)

Significance

Debates about the magnitude, tempo, and ecological effects of Native American depopulation after 1492 CE constitute some of the most contentious issues in American Indian history. Was population decline rapid and catastrophic, with effects extensive enough to change even the earth's atmosphere? Or was depopulation more moderate, with indigenous numbers declining slowly after European colonization? Through a study of archaeology and dendrochronology, we conclude that neither of these scenarios accurately characterizes Pueblo peoples in the Southwest United States. Among the Jemez pueblos of New Mexico, depopulation struck swiftly and irrevocably, but occurred nearly a century after first contact with Europeans. This population crash subsequently altered the local environment, spurring the growth of trees and facilitating the spread of frequent forest fires.

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data, enabling us to quantify population losses at a regional scale. Importantly, we collected the archaeological and tree-ring datasets from spatially contiguous locations, allowing us to simultaneously address both regional population dynamics and forest ecology across the pre- and post-European contact periods. Although this case study differs from the bulk of post-1492 Anthropocene research in terms of forest composition and fire regime contexts, it illustrates the quality of integrated archaeological and paleoecological data needed to assess the Early Anthropocene burning hypothesis at the local level.

Study Area

The Jemez Province is a physiographic and cultural region of northern New Mexico located in the southwest quadrant of the Jemez Mountains, 55 km north of Albuquerque and 65 km west of Santa Fe (Fig. 1*A*) (26). Physiographically it is defined by the Rio Guadalupe, Jemez River, and Vallecitos Creek drainages. These streams run through deep canyons surrounded by towering, flat-topped mesas. Today these mesas are covered with continuous stands of conifer-dominated middle elevation forests comprised of ponderosa pine, gambel oak, piñon, and juniper trees (*Pinus ponderosa, Quercus gambelli, Pinus edulis,* and *Juniperus* spp., respectively). Culturally, the Jemez Province is defined by the distribution of archaeological sites exhibiting high frequencies (>30%) of Jemez black-on-white ceramics. These sites are culturally affiliated with Towa-speaking Pueblo peoples living west of the Rio Grande (26). Their descendants constitute the modern Pueblo of Jemez, a federally recognized Indian tribe and sovereign nation. Today nearly 2,000 Jemez tribal members live at the village of Walatowa (also known as Jemez Pueblo), located at the southern end of the Jemez Province.

Between 1300 and 1600, the Jemez Province emerged as a center of ancestral Puebloan settlement in the northern Rio Grande region (27, 28). During that period, Jemez people constructed more than 30 villages of multistoried stone masonry architecture surrounding enclosed plazas, ranging in size from 50 to more than 1,500 rooms (26). They also built more than 3,000 one- and two-room secondary settlements known as "field houses," which were located outside the large villages among agricultural fields and occupied seasonally (29). For this study, we focused exclusively on large village sites to quantify ancestral Jemez populations because ethnohistorical and archaeological studies suggest that field house occupants maintained permanent residences at the large villages (30). Today these large village sites consist of rubble mounds formed from collapsed architecture (Fig. 1 *B* and *C*).

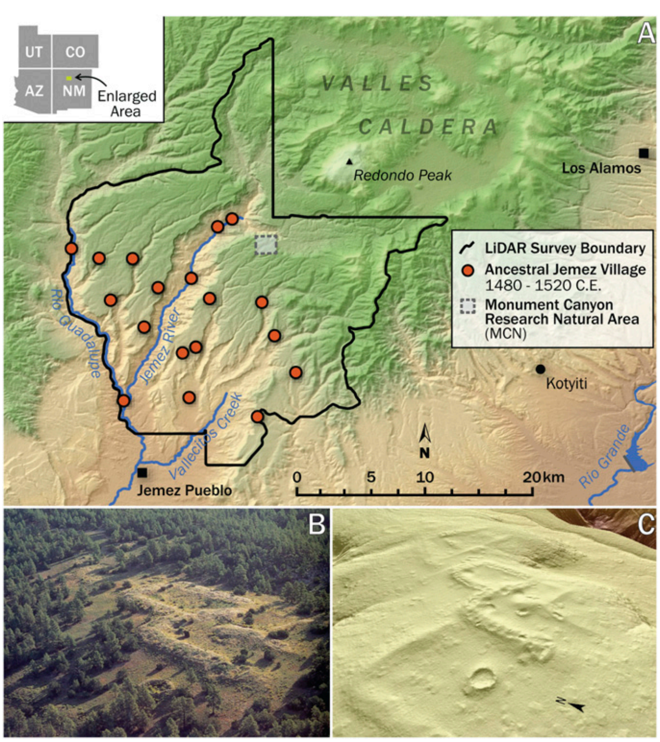

Fig. 1. Ancestral Pueblo villages of the Jemez Province, New Mexico. (*A*) Locations of sites occupied between 1480 and 1520 CE. (*B*) Aerial photograph of Kwastiyukwa, LA 482 (85). (*C*) LiDAR model of Kwastiyukwa.

Table 1. Sixteenth and 17th century records of population and settlement in the Jemez Province (29)

Date (CE)	Source	Population estimate	Number of villages
1541	Castañeda (31)	—	10*
1581	Gallegos (91)	—	15
1583	Espejo (91)	"As many as 30,000"	7
1598	Oñate (92)	—	11
1621–1622	Zárate (49)	6,566	—
1622	Vetancurt (93)	5,000†	1
1630	Benavides (50)	3,000	2
1641–1644	anonymous (51)	1,860	1

*Includes sites listed as "Hemes, seven villages" and "Aguas Calientes, three villages" (see discussions in refs. 26 and 94).

†Vetancurt penned this estimate in the late 1690s, but wrote about the 1622 founding of San Diego de la Congregación.

The first direct encounter between the indigenous inhabitants of the Jemez Province and Europeans occurred in 1541 (31). Interactions remained sporadic for the next eight decades, even after the 1598 establishment of Spanish colonial settlements in New Mexico. In the 1620s, Franciscan friars constructed two Catholic missions among the Jemez with the explicit intent of gathering the residents of the Province into centralized facilities (a policy known as congregación).

Debates about the size of 16th and 17th century populations of the Jemez Province mirror those for North America as a whole. High counters estimate 30,000 residents or more on the eve of European contact, whereas skeptics reckon populations 1/10th that size (29, 32, 33). A dearth of census data hampers the construction of accurate estimates, with no vital records of births or deaths in the Jemez Province surviving the 17th century. A smattering of historical references present a wide range of population estimates and reported number of villages occupied between 1541 and 1650 (Table 1). The general trend of these estimates indicates demographic decline throughout the 17th century, both in terms of total population and number of occupied villages. However, archaeological studies challenge the reliability of these historical chronicles. Kulisheck's analysis of 30 field house sites in the Jemez Province documents intensified use during the period 1525–1650. He concludes that the region did not suffer a significant population decline between these years and that "disease may not have been a major factor in demographic change" during the 17th century (29, 34). Similarly, although Spanish colonial accounts assert that the Jemez vacated the vast majority of their villages by the mid-17th century under congregación, ceramic assemblages at many of these sites contain pottery produced by Pueblo women up to 1700. The presence of these late 17th century ceramics (specifically Rio Grande Glaze F pottery) has led archaeologists to suggest that the large villages of the Jemez Province harbored sizeable populations even after 1650, calling into question accounts of demographic collapse contained in historical documents (26, 32, 35, 36).

Based on previous studies of post-Columbian Native American demography, we set out to evaluate four competing hypotheses regarding Jemez population dynamics in the 16th and 17th centuries: (*i*) large-scale depopulation occurred before direct Pueblo–European contact, as a result of pandemic disease events that swept north from central Mexico in the 1520s–1530s (the Dobyns hypothesis) (3); (*ii*) the largest losses occurred from 1541 to 1598, between the first direct contacts and the establishment of permanent colonial settlements (the contact hypothesis) (37, 38); (*iii*) population decline occurred during the early colonial period (1598–1680), after the establishment of missions and sustained daily interactions between Puebloans and Spaniards (the mission hypothesis) (39); or (*iv*) no large scale population changes occurred before 1680 (the null hypothesis) (29). To evaluate these hypotheses in light of Early Anthropocene research, we quantified the magnitude of population losses, refined the timing of depopulation events, and studied the effects of demographic decline on forest composition and fire regimes in the Jemez Province.

To quantify the population of the Jemez Province immediately before European contact, we identified 18 ancestral Jemez villages that were occupied during the period between 1480 and 1520 (Table 2). We then estimated the population of these villages through a measurement of their architecture using LiDAR data (*Methods*). Dating of these occupations is based on tree-ring sequences from architectural wood unearthed in previous archaeological excavations and the presence of Rio Grande Glaze D ceramics (production dates of 1480–1550). This group comprises all villages larger than 10 rooms in the Jemez Province known to date to the latter 15th and early 16th centuries (26). Note, however, that occupations of these sites were not limited solely to this era. Most were founded during the 14th or 15th centuries and hosted populations into the 17th century.

To determine the timing of terminal occupations at Jemez villages, we conducted a tree establishment study of remnant wood and old growth trees growing within 120 m of the plaza architecture at these sites (*Methods*). Our analysis suggests that the terrain surrounding Jemez villages was denuded of trees during periods of human occupation due to demands for wood used in construction, heating, and cooking. Accordingly, we can use the date that trees began to regrow on these sites as a proxy for their final inhabitation. We measured tree establishment dates to provide evidence for the timing of depopulation at these villages. Furthermore, we analyzed tree-ring fire scar data from within the Jemez Province and from locations throughout the larger Jemez Mountains region to examine the effects of depopulation on fire regimes in both local and regional contexts.

Results

The results of our population study reveal that the large villages of the Jemez Province could have housed a maximum of 9,903 persons in the late 1400s to early 1500s. However, this figure overestimates momentary population as it neglects to account for what Schact (40) terms "the contemporaneity problem." That is, this maximum estimate assumes occupation of every square meter of every room at every site across the Jemez Province for the entire period in question. To account for unoccupied architecture, rooms built after this period, and fluctuations in occupation at each of the sites, we follow previous studies of Pueblo population in applying ratios of the average amount of occupied to total architecture at these sites (41–46). To allow for the widest range of possibilities, we report pre-Hispanic population figures as a range representing occupation between 50% and 80% of the rooms in the Jemez Province (Table 2). Based on these figures, we calculate that the 18 Jemez villages occupied at the turn of the 16th century housed between 4,951 and 7,922 inhabitants, or ~5,000–8,000 persons.

Our tree establishment studies suggest that wide-scale depopulation occurred at Jemez villages between 1620 and 1640. We measured dates of ponderosa pine establishment at the pueblos of Kiatsukwa, Kwastiyukwa, and Tovakwa and found that tree growth began in the 1630s and 1640s, with additional pulses of tree recruitment occurring in the subsequent three decades (Fig. 2). Based on these tree establishment records, we estimate *termini ante quem* for the occupation of these villages in the 1640s. Estimates of terminal inhabitations in the 1640s represent a significant revision of previous assessments. Based solely

Table 2. Population estimates for large villages of the Jemez Province, 1480–1520

LA no.	Site name	Rubble volume (m^3)	Floor area (m^2)	Maximum population	50–80% population
96	Patokwa*	1,248.40	1,585.47	285	142–228
123	Unshagi[†]	NA	1,391.80	250	125–200
132/133	Kiatsukwa	4,403.11	5,591.95	1,004	502–803
303	Seshukwa	5,802.33	7,368.96	1,323	661–1058
398	—	1,213.34	1,540.94	277	138–221
479	Wahadaykwa	1,409.34	1,789.86	321	161–257
481	Amoxiumqua	3,143.81	3,992.64	717	358–573
482	Kwastiyukwa	6,334.12	8,044.33	1,444	722–1155
483	Towakwa	1,807.68	2,295.75	412	206–330
484	Tovakwa	5,440.46	6,909.38	1,240	620–992
541	Nonishagi	2,350.78	2,985.49	536	268–429
679	Giusewa[‡]	1,101.70	1,399.16	251	126–201
5918	—	1,832.73	2,327.57	418	209–334
24788	Wahajhamkwa	3,817.60	4,848.35	870	435–696
24789	—	585.70	743.84	134	67–107
44000	Hanakwa	1,207.80	1,533.91	275	138–220
44001	—	417.39	530.09	95	48–76
46340	Kiashita	218.84	277.93	50	25–40
Totals				9,903	4,951–7,922

NA, not applicable.

*Includes south mound (pre-1680 component) only (72).

[†]Because large portions of LA 123 were excavated and not backfilled, volumetric calculations underrepresent total floor area. Floor area calculation is based on Reiter's excavation data (94). See Liebmann 2006, appendix F (72).

[‡]Includes Pueblo architecture west of mission church only. However, because much of the site is obscured by modern construction, these estimates likely under-represent the 16th century architecture and population.

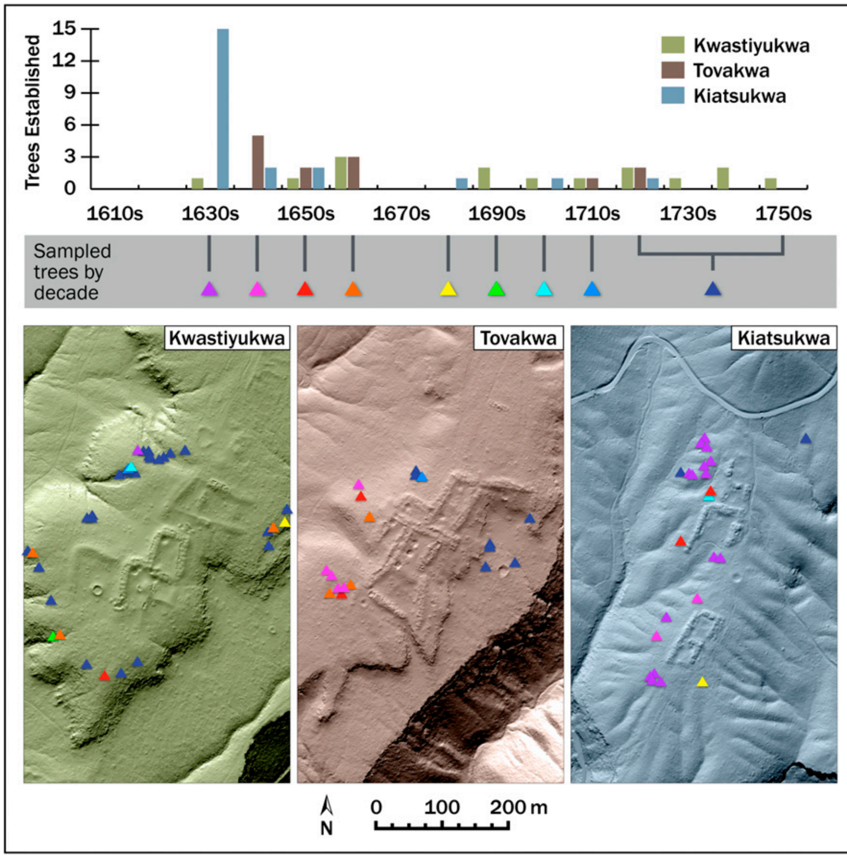

Fig. 2. Tree establishment at large villages of the Jemez Province. (*Upper*) Number of trees and dates of establishment at Kwastiyukwa (LA 482), Tovakwa (LA 484), and Kiatsukwa (LA 132/133). (*Lower*) locations of sampled trees at Kwastiyukwa (*Left*), Tovakwa (*Center*), and Kiatsukwa (*Right*).

on ceramic cross-dating, prior estimates had posited dates of final occupation up to 60 y later (26, 33, 36). Note that our study investigated population dynamics at large village sites only, however. Whereas we are confident that the terminal inhabitation of these villages dates to between 1620 and 1640, it is likely that smaller agricultural sites such as field houses remained in use for decades thereafter throughout the Jemez Province (29, 34, 35).

The depopulation of large Jemez villages prompted a shift in fire regimes throughout the Province. The fire history of 198 trees sampled in the Monument Canyon Research Natural Area (MCN), an unlogged 259-ha stand of old-growth ponderosa pines located within the Jemez Province (Fig. 1*A*), shows that spreading surface fires increased in frequency after 1620. This increase coincides with the expansion of Franciscan evangelical efforts and the construction of two Catholic missions in the Jemez Province, as well as the early stages of depopulation at the large villages (Fig. 3 and Fig. S1). Fire scars from MCN indicate that before 1620, extensive surface fires burned through the Province once every 17 y ($n = 7$ extensive fires between 1500 and 1619). After 1620, fine fuels increased on a scale sufficient to convey extensive surface fires once every 10.9 y ($n = 11$ extensive fires between 1620 and 1739). This rise in the number of spreading surface fires indicates that reforestation occurred during the mid- to late 17th century, a result of changing land use patterns brought on by the depopulation of large villages throughout the Jemez Province. This fire regime continued into the late 1800s, when intensive livestock grazing and policies of fire suppression disrupted incidents of widespread fire once again (47).

The MCN dataset has the advantage of being contained entirely within the Jemez Province, in close proximity to the sites we used to generate our population estimates. However, to evaluate the broader effects of depopulation throughout the northern Rio Grande region, we used a larger sample of 1,377 fire-scarred trees from across the Jemez Mountains region

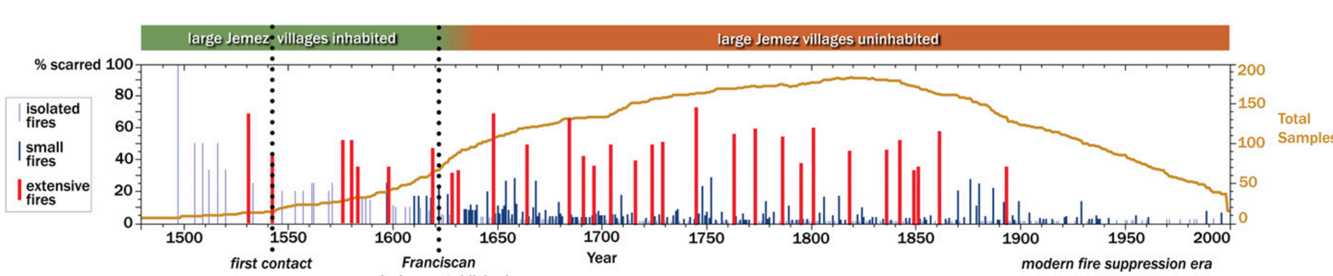

Fig. 3. Jemez Province fire chronology 1480–2010 CE, based on 198 tree-ring samples from the Monument Canyon Research Natural Area (86).

(which includes data from MCN and other locations within the Jemez Province, as well as the Valles Caldera to the north and the Pajarito Plateau to the east; Fig. S2). This larger regional dataset reveals an increase in landscape-scale fires after 1620 as well (Fig. 4 *B* and *C*). Between 1500 and 1619, landscape-scale fires (defined as evidence for burning in greater than 25% of sampled trees) burned across the Jemez Mountains only once every 60 y ($n = 2$). Between 1621 and 1900, landscape-scale fires occurred once every 16.5 y ($n = 17$). At the same time, landscape-scale fire synchrony increased, suggesting the importance of top-down climatic controls on fire activity (48).

Discussion

Comparing our LiDAR-based population estimates and tree-ring data to the 17th century documentary records produced by colonial Spaniards reveals the tempo of depopulation in the Jemez Province (Fig. 4*A*). Our archaeological estimate of 5,000–8,000 residents accords with the record of fray Geronimo Zárate Salmerón, a Franciscan friar stationed among the Jemez between 1621 and 1626. During his stint in the Province, fray Geronimo chronicled the baptism of 6,566 "souls" (49). This figure sits remarkably close to the mean of our 5,000- to 8,000-person archaeological calculation, at 63% of the maximum regional population estimate. Combined with Kulisheck's evidence for sustained relative populations from field house data (29, 32–35), the archaeological evidence and Zárate Salmerón's record suggest a modicum of demographic continuity from pre-Hispanic times into the early colonial period in the Jemez Province. In other words, the preponderance of historical and archaeological evidence indicates that no large-scale demographic collapse occurred before the first direct contacts between the Jemez and Europeans (pre-1541) or during the period of early Spanish

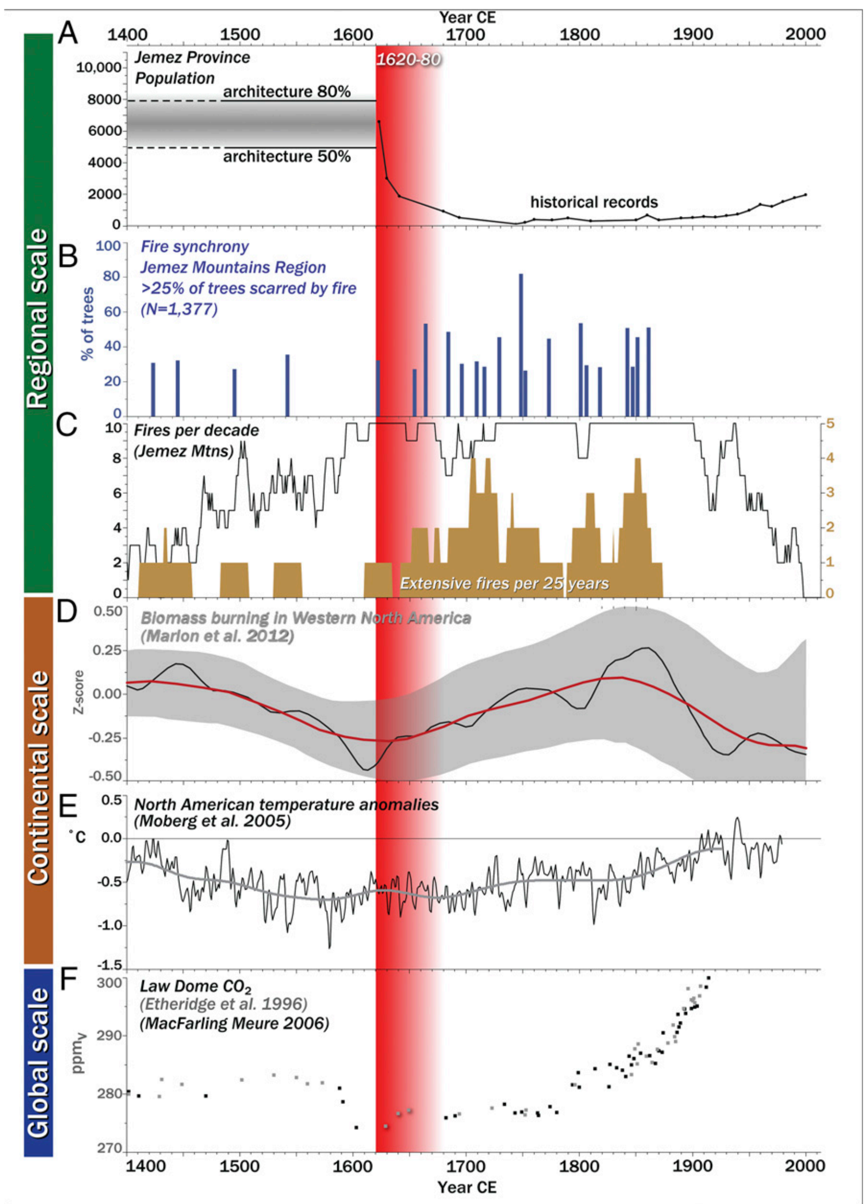

Fig. 4. Comparison of regional, continental, and global data on climate and fire regimes, 1400–2000 CE. Red column indicates period of major Jemez demographic decline. (*A*) Native American population in the Jemez Province. (*B*) Chronology of regional fire synchrony based on 1,377 samples from across the Jemez Mountains region. (*C*) Fires per decade and extensive fires per 25 y in the Jemez Mountains. (*D*) Biomass burning in western North America (87). (*E*) North American temperature anomalies (88). (*F*) Global atmospheric CO_2 recorded in Law Dome, Antarctica (89, 90).

exploration, before the establishment of permanent colonial settlements (1541–1598).

Following the expansion of missionary efforts in the 1620s, Spanish colonial records register a large-scale diminution of the Jemez population over the subsequent 20 y (Table 1). Half the populace reportedly succumbed to two waves of epidemic diseases, violence, and famine by 1630, leaving just 3,000 remaining in the Province (50). The number of Jemez residents further dropped to just 1,860 persons by 1644, according to colonial records (51). At the same time, tree rings record the recruitment of ponderosa pines at large Jemez villages during this period. Dendrochronology provides a source of data independent of Spanish colonial records to objectively assess the timing of depopulation. Tree establishment dates indicate *termini ante quem* in the 1630s–1640s for these sites. We are confident that these dates represent the cessation of occupation and not the limits of dendrochronology in the region because trees sampled from other locales in the Jemez Province regularly show evidence of establishment dates in the early 1500s, with occasional dates as early as 1300. If terminal occupations of these sites occurred earlier or later than 1640, we would expect corresponding evidence for tree recruitment (*Methods*).

The recruitment of ponderosa pine stands after the depopulation of large Jemez villages coincided with a shift in fire regimes and an increase in the number and synchrony of spreading surface fires between 1640 and 1900. Despite the increase in frequency of extensive fires following the 17th century demographic collapse, the recovering forest would have sequestered more carbon than the more open anthropogenic landscape (52). Furthermore, the establishment of more regular extensive fires would have promoted the recruitment and maintenance of large diameter trees in higher densities than under the previous, anthropogenically formed regime.

By 1681, the resident population of the Jemez Province had gathered en masse at the village of Patokwa (LA 96) (53). According to our LiDAR-based architectural estimates, Patokwa housed a maximum population of 833 persons in the early 1680s. Again, this archaeologically derived estimate accords well with historical documentation. Spanish military journals record that, in 1694, after more than a decade of drought, migration, and violent conflict, the resident population of the Jemez Province stood at less than 600 persons (53). Thus, in the six decades between 1620 and 1680, the population of the Jemez Province declined from ∼6,500 to less than 850, a loss of 87%.

Implications

Archaeological, historical, and dendrochronological data from the Jemez Province combine to paint a picture of demographic stability at large Pueblo villages between 1492 and 1620, with drastic declines in the subsequent six decades. This finding supports the third of our working hypotheses, the mission hypothesis, and refutes the Dobyns, contact, and null hypotheses. Archaeological and historical records attest to demographic stability across the pre-Hispanic/early contact period (1480–1620). Widespread depopulation at large village sites began between 1620 and 1640, following the establishment of Franciscan missions in the region (Fig. 4*A*). Historical records suggest that a deadly combination of pestilence, warfare, and famine initiated the depopulation of large Jemez villages (50, 54). Archaeological studies indicate that dispersion to field house sites and migration to other regions could account for some of this population reduction as well (29, 32–35, 55).

Our population reconstruction contrasts with recent studies of Pueblo demography that hypothesize little to no depopulation before 1680 (29, 32–36), as well as radical high counter models proposing catastrophic depopulation beginning in the 16th century (37, 56, 57). Evidence for large-scale depopulation concomitant with the establishment of missions can also be found in other regions of the Southwest United States. Specifically, Eckert's paleodemographic study of burial data from the village of Hawikku found "that the Zuni did not suffer a massive population decline due to epidemic diseases until after the Spanish mission was built at Hawikku in 1629" (39). The mission hypothesis is also supported by Ubelaker's calculations of Southwestern demography culled from data in the *Handbook of North American Indians* (56). Ubelaker estimates that the steepest population declines occurred in the 17th century, only after the establishment of permanent colonial and missionary settlements among the Pueblos.

To evaluate the Early Anthropocene burning hypothesis, scholars need accurate assessments of the timing, magnitude, and effects of post-Columbian indigenous depopulation at regional scales throughout North and South America. Archaeological evidence from the Jemez Province supports the notion that the European colonization of the Americas unleashed forces that ultimately destroyed a staggering number of human lives. However, unlike in the Neotropics and the Eastern United States, where fires decreased after 1492, landscape-scale fire events in the Southwest United States increased substantially following European colonization. These changes in population and fire regimes in the Southwest United States occurred nearly a century later than the Amazonian cases frequently posited in support of the Early Anthropocene burning hypothesis. Nevertheless, the net effect of population decline and ponderosa pine reforestation in the Jemez Province was one of carbon sequestration. Similar processes may have occurred in other pine-dominant landscapes across the Western United States. In combination, their reforestation could have amplified the drop in global CO_2 recorded in Antarctic ice core records (16, 18, 19) (Fig. 4 *D* and *F*). However, reliably extrapolating data from the Western United States to global scales requires further investigation of the extent of human occupation and forest modification in those other locales.

This study demonstrates that the timing of initial post-Columbian depopulation events in the Southwest United States were not coterminous with initial episodes in the Andes, central and southern Amazonia, Central Mexico, or the Caribbean. Within North America, the data from the Jemez Province add to a growing body of archaeological evidence attesting to the variegated nature of post-Columbian indigenous population decline. The timing and severity of depopulation events varied across the continent. Archaeological evidence fails to support the notion that sweeping pandemics uniformly depopulated North America (58–65). As a result, we caution against expanding data from any single region to continental, hemispheric, or global scales in support of the Early Anthropocene burning hypothesis.

Our study presents further evidence that simplistic assumptions about human–fire relationships should be discarded (66). Although sample depth is limited for the pre-mission period occupation of the Jemez Province (ca. 1300–1620 CE), the available tree-ring records indicate that surface fires were suppressed in the vicinity of large villages but that small fires were common in agricultural, hunting, and more remote settings (Figs. 3 and 4 *B* and *C*). Such a complex mosaic of fire regimes is consistent with existing models of anthropogenic pyrodiversity, with likely consequences for biodiversity and carbon budgets (67). The assumption that more (indigenous) people equates to more fire activity (68) fails to accurately characterize these complex conditions. Rather, Early Anthropocene research requires nuanced considerations of fire use and fuel impacts within specific cultural contexts (66, 69–71). Pan-regional, continental, and hemispheric syntheses of human–fire relationships that rest on simplistic assumptions will continue to be of limited use in evaluating the Early Anthropocene burning hypothesis until they consider the spatial heterogeneity of population histories, fire histories, and land-use behavior.

Methods

Population Estimates. We used ESRI's ArcGIS 10.3 software to calculate the volume of remnant architecture at each of the 18 villages listed in Table 1. Using data derived from an airborne LiDAR survey conducted by the US Forest Service in 2012, we created triangulated irregular networks (TINs) for each site using the LiDAR point cloud's last return (i.e., the ground surface). We then used the 3D Analyst extension's "Surface Difference" function to calculate the volumetric difference between the architectural TIN and the surrounding natural topography, providing a measurement of the volume of extant masonry rubble at each site.

To determine a constant of proportionality for the amount of floor area represented by each cubic meter of architectural rubble, we relied on Liebmann's survey of the ancestral Jemez village of Boletsakwa (LA 136). This survey used standing walls, in situ wall remnants, exposed wall alignments, and intrasite topography to determine the spatial extents of 168 ground-floor rooms and the locations of 47 additional second-floor rooms (72). By dividing the total floor area of all 215 rooms at Boletsakwa (2,301.88 m^2) by the volume of architectural rubble revealed in the LiDAR survey (1,812.51 m^3), we calculated a constant of 1.27 m^2 of floor area per cubic meter of architectural rubble. Applying this constant of proportionality to the 18 ancestral Jemez villages occupied between 1480 and 1520 allowed us to derive measurements of floor area from the architectural remains of each site (Table 2).

Although this model only measures architectural rubble above the modern ground surface, the floor area constant accounts for subsurface remains through its calculation of proportionality between visible rubble and the original architectural footprint. Furthermore, geoarchaeological research at similar mesa-top archaeological sites on the nearby Pajarito Plateau indicates that the bases of Classic Period (1300–1600 CE) tuff-masonry walls are typically buried by less than 20 cm of post-1450 eolian and colluvial sediments, suggesting that the modern surface is an adequate, if conservative, baseline for estimating rubble volume (73).

To translate our floor area calculations into estimates of population, we chose not to rely on cross-cultural constants (74–78) or calculations based on ethnographic data (42, 79). Instead, we developed a new estimate of the average floor area occupied per Pueblo person in the Northern Rio Grande region. This constant is based on archaeological and historical data from the nearby site of Kotyiti (LA 295), another plaza-oriented, mesa-top pueblo constructed of multistoried tuff masonry architecture (Fig. 1*A*). Kotyiti harbors a unique suite of attributes that allow for precise measurements of both floor area and momentary population: single occupation of a short duration with an absence of earlier or later construction; an historically documented population; complete exposure of all ground floor living surfaces through excavation; and precise documentation of room sizes using modern cartographic techniques.

Kotyiti was constructed, occupied, and vacated in a period of just 14 y between 1680 and 1694 (80). Based on this short duration, we assume that 100% of the floor area was in use during its brief inhabitation. Spanish military journals record the size of its population as 342 noncombatants in 1694 (81). Adding to this number 72 resident warriors representing 21% of the noncombatant population [a figure independently derived by both Upham (56) and Liebmann (72) based on two different datasets] results in a population estimate of 414 persons in residence. Finally, the site was excavated in its entirety by Nelson (82) and mapped using modern cartographic techniques by Preucel (80). Preucel's study provides a precise measurement of floor area for 137 ground-floor rooms, as well as evidence for an additional 21 second-story rooms. The total floor area of all residential rooms at Kotyiti sums to 2,304.6 m^2. Based on these figures, each of the 414 residents of Kotyiti occupied 5.57 m^2 of floor area per person, on average.

We applied the floor area constant to the LiDAR-derived measurements of the 18 Jemez villages occupied between 1480 and 1520 according to the following equation: $1.27(v)/5.57$ = number of occupants (where v stands for the volume of architectural remains at a given site, 1.27 is the constant of proportionality between volume and floor area, and 5.57 represents the average number of square meters occupied per person).

Dendrochronology. To establish the earliest dates for tree recruitment at archaeological sites in the Jemez Province, we sampled cross sections from remnant wood and old growth trees within 120 m of architectural remains at five ancestral Jemez large villages: Kiatsukwa (LA 132/133), Boletsakwa (LA 136), Kwastiyukwa (LA 482), Tovakwa (LA 484), and Wabakwa (LA 478). To obtain the most accurate establishment dates possible, sections were taken at or near the root crown. We used both visual and statistical dating methods to assign a calendar year to each tree ring. Tree establishment dates were placed in 10-y bins to account for the imprecision of these estimates. By "tree establishment" we mean dates within 3–5 y of a seed's germination. In cases where we sampled above the root crown, we used an adjustment to account for number of years for the shoot to grow to the sample height. These adjustments were produced with growth rates derived from ponderosa pine in similar environments (5.9 cm/y for the first 1.37 m of growth) (83, 84). In cases where the pith was not present, we estimated the number of rings to center using concentric ring circles matching the width and curvature of the sample's interior rings.

To assess the validity of tree establishment as a signifier of *termini ante quem* occupation at ancestral Jemez villages, we performed tests at two sites with established dates of terminal occupation outside the chronological range of our population study: Boletsakwa and Wabakwa. At Boletsakwa, tree-ring dates collected from architectural roof beams (unearthed during archaeological excavations in the mid-20th century) confirm that the site was constructed in 1683 (53). Spanish documents attest that the occupation of Boletsakwa lasted just 12 y, with the last full-time residents vacating the village in 1695 (81). We compared the inner ring/establishment dates on ponderosa pines growing in the immediate vicinity of the site with the final inhabitation date of 1695 to determine the relationship between forest recruitment and terminal occupation (Fig. S3). The results verify a strong correlation between tree recruitment dates and the date of terminal occupation. Although two trees located on the site periphery predated the 1683 establishment of the village, both had trunk circumferences of less than 5 cm in that year, indicating that they were mere saplings during the site's inhabitation and impractical for use in building or heating. Tree establishment commenced on a wide scale in 1705, 10 y after the terminal occupation of Boletsakwa. Strong pulses of tree recruitment occurred over the course of the following two decades, with 19 trees exhibiting establishment dates between 1705 and 1725.

To test the limits of tree establishment on the early end of the temporal spectrum, we sampled remnant wood and old growth trees in the vicinity of Wabakwa (LA 478), a large ancestral Jemez village dated to 1200–1500 based on associated ceramics (26). There we documented a tree with an establishment date of 1559. Furthermore, multiple samples in the MCN data set exhibit establishment dates in the 1300s–1400s (Fig. S1), proving that it is possible to ascertain ponderosa pine establishment dates before the 17th century in the Jemez Province. In other words, this method is not limited to use at sites depopulated in the 17th century or later. Tree establishment studies can theoretically be used to ascertain dates of terminal occupation in the 14th, 15th, and 16th centuries at other ancestral Puebloan sites as well.

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