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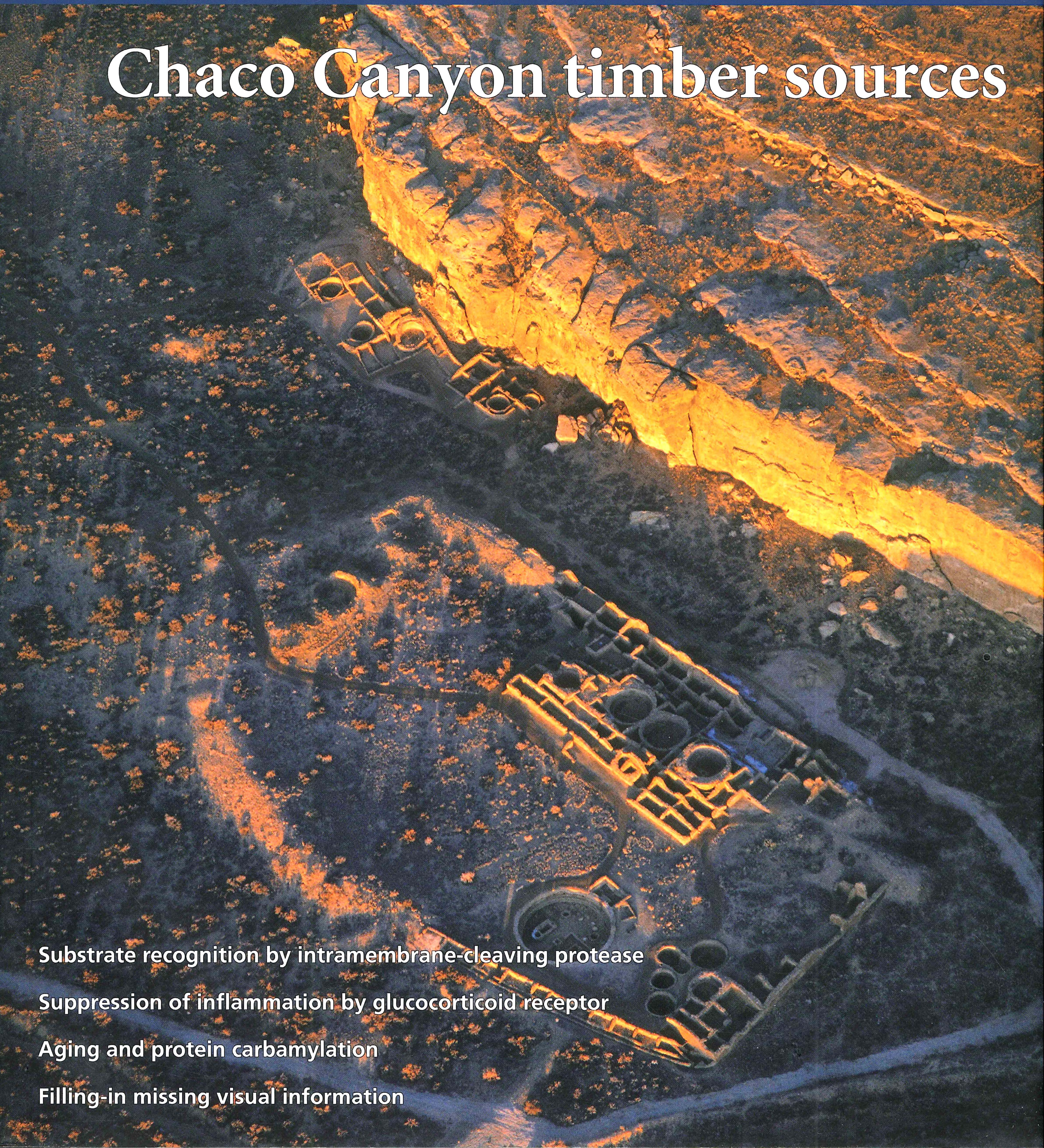
Chaco Canyon timber sources



Substrate recognition by intramembrane-cleaving protease

Suppression of inflammation by glucocorticoid receptor

Aging and protein carbamylation

Filling-in missing visual information

Eleventh-century shift in timber procurement areas for the great houses of Chaco Canyon

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An enduring mystery from the great houses of Chaco Canyon is the origin of more than 240,000 construction timbers. We evaluate probable timber procurement areas for seven great houses by applying tree-ring width-based sourcing to a set of 170 timbers. To our knowledge, this is the first use of tree rings to assess timber origins in the southwestern United States. We found that the Chuska and Zuni Mountains (>75 km distant) were the most likely sources, accounting for 70% of timbers. Most notably, procurement areas changed through time. Before 1020 Common Era (CE) nearly all timbers originated from the Zunis (a previously unrecognized source), but by 1060 CE the Chuskas eclipsed the Zuni area in total wood imports. This shift occurred at the onset of Chaco florescence in the 11th century, a time with substantial expansion of existing great houses and the addition of seven new great houses in the Chaco Core area. It also coincides with the proliferation of Chuskan stone tools and pottery in the archaeological record of Chaco Canyon, further underscoring the link between land use and occupation in the Chuska area and the peak of great house construction. Our findings, based on the most temporally specific and replicated evidence of Chacoan resource procurement obtained to date, corroborate the long-standing but recently challenged interpretation that large numbers of timbers were harvested and transported from distant mountain ranges to build the great houses at Chaco Canyon.

Ancestral Puebloans | archaeology | human–environment interactions | dendrochronology | timber origins

The high desert landscape of Chaco Canyon, New Mexico was the locale of a remarkable cultural development of Ancestral Puebloan peoples, including the construction of some of the largest pre-Columbian buildings in North America (1) (Fig. 1). The monumental "great houses" of Chaco Canyon reflect an elaborate socioecological system that spanned much of the 12,000-km^2 San Juan Basin from 850 to 1140 Common Era (CE) (2). These massive stone masonry structures required a wealth of resources to erect, including an estimated 240,000 trees incorporated as roof beams, door and window lintels, and other building elements (3). The incongruity of the great houses located in a nearly treeless landscape has led archaeologists and paleoecologists to investigate the origins of timbers used in construction (4–9). Beyond the simple curiosity driving this question, the answer has important implications for understanding the complexities of human–environmental interactions, the sociopolitical organization, and the economic structure of Chacoan society (10–12).

The first excavators of the great houses in the early 20th century speculated that construction timbers were harvested locally, perhaps resulting in deforestation of the surrounding landscape (13). Paleoecological studies conducted during the late 1970s and early 1980s, however, showed that ponderosa pine (*Pinus ponderosa*), the primary tree species used in construction, was not abundant enough at the relatively low elevations (1,800–2,000 m above sea level) of Chaco Canyon and nearby mesas to support timber demand (14–16). Spruce (*Picea* spp.) and fir (*Abies* spp.), which account for tens of thousands of construction beams, have been absent from Chaco Canyon for at least 12,000 y and could have only been logged from distant, higher-elevation sites (2,500–3,450 m above sea level) (4). An inadequate supply of timbers in Chaco Canyon and its immediate surroundings during Puebloan occupation strongly suggests long-distance procurement from surrounding mountain ranges, where all three conifers now grow in abundance. This inference was corroborated by strontium isotope ($^{87}Sr/^{86}Sr$)-based sourcing. Through a comparison of $^{87}Sr/^{86}Sr$ values from great-house timbers to $_{87}Sr/_{86}Sr$ values from conifer stands growing today in mountains surrounding the San Juan Basin, two studies concluded that the Chuska Mountains (75 km west) and Mount Taylor (85 km southeast) were the most likely sources for spruce, fir, and ponderosa pine trees (6, 7). Recently, the explanation of long-distance timber transport and the related interpretations of $^{87}Sr/^{86}Sr$ evidence have been challenged and an alternative has been proposed that most great-house timbers (particularly ponderosa pine) were just as likely to have originated from nearby and low-elevation sites within, east, and south of Chaco Canyon (8, 9).

We assessed probable timber origins independently from previous efforts by applying tree-ring width-based sourcing techniques to a set of 170 beams from our archives at the University of Arizona. These beams comprise six tree species from seven great-house structures (Table S1). Tree-ring-based sourcing uses correlation and Student's t tests between beams of unknown origin and site chronologies from likely timber harvesting areas (17) (Fig. S1). Each site chronology, as the average of 40–100 trees, represents tree-ring growth patterns peculiar to an individual landscape. This method of identifying the probable origin of timbers has been applied widely in Europe in the study of archaeological and nautical timbers and

Significance

The iconic great houses of Chaco Canyon occupy a nearly treeless landscape and yet were some of the largest pre-Columbian structures in North America. This incongruity has sparked persistent debate over the origins of more than 240,000 trees used in construction. We used tree-ring methods for determining timber origins for the first time to our knowledge in the southwestern United States and show that 70% of timbers likely originated over 75 km from Chaco. We found that a previously unrecognized timber source, the Zuni Mountains, supplied construction beams as early as the 850s in the Common Era. Further, we elucidate shifting dynamics of procurement that highlight the importance of a single landscape, the Chuska Mountains, in the florescence of the Chacoan system.

Author contributions: C.H.G., T.W.S., and J.S.D. designed research; C.H.G. performed research; C.H.G., T.W.S., and J.S.D. analyzed data; and C.H.G., T.W.S., and J.S.D. wrote the paper.

The authors declare no conflict of interest.

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Data deposition: All tree-ring data used here are available in Dataset S1. Tree-ring chronologies developed as part of this study are available on the International Tree-Ring Data Bank, www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring (accession nos. NM588 and NM589). The database of great house beams is available on the Chaco Research Archive, www.chacoarchive.org/cra/chaco-resources/tree-ring-database.

See Commentary on page 1118.

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Fig. 1. Aerial view of Pueblo Bonito, the largest of the Chaco Canyon great houses. Image courtesy of Adriel Heisey.

artifacts, musical instruments, and paintings on oak panels (17–20). These techniques are underused in North America, but recent efforts in the northeastern United States have revealed distant, inland sources for 18th- and 19th-century nautical timbers (21, 22).

Tree-ring sourcing can only be applied where tree growth patterns are distinguishable between the potential locations of origin. In the southwestern United States tree growth primarily responds to regionally coherent winter precipitation (23, 24), and as a consequence trees across the region tend to share roughly half of their interannual variability (25). Differences between site chronologies are predominantly attributed to variations in topography and subregional-scale climate conditions (26).

We compared great-house beams to the site chronologies of eight potential harvesting areas surrounding the San Juan Basin. Chaco Canyon was not included as one of our sites because it lacked enough remnant wood from the Chaco era to build a local site chronology. To assess the efficacy and accuracy of the tree-ring sourcing method within the San Juan Basin, we tested whether tree-ring growth patterns could be distinguished between the various mountain ranges surrounding Chaco Canyon by applying sourcing methods to living trees of known origin (*SI Text* and Table S2). We found that within the San Juan Basin, despite a broadly coherent climate–tree growth signal, the ring-width growth patterns in individual trees can be used to correctly identify the specific mountain range from which they came (Fig. S2).

Results and Discussion

We defined the source of each of the 170 great-house timbers as the tree growth location with the highest significant Student's *t* value (a combination of correlation and length of overlap, assessed at $\alpha = 0.01$). It is worth noting that many beams had significant *t* values with multiple source areas, and tests of differences among these failed to separate the majority of them. Our use of maximum *t* values to designate probable origins is justified against the results of our evaluation of tree-ring sourcing in the San Juan Basin (*SI Text* and Fig. S2). The accuracy rate of this test is 90% across all four test sites but rises to 100% for the two test sites located within the same mountain range as a source-area chronology. Because the mountain ranges contain far more forest resources than the mesa locations of the other two test sites, it is plausible that much of the great-house construction wood came from areas represented by our eight source-area chronologies. Here, we describe a broad and compelling pattern of origins for great-house timbers that is both independent of and in accord with the sourcing of other Chacoan materials, including timbers.

Maximum *t* values for tree-ring sourcing of beams ranged from 2.86 to 16.01, with 75% greater than 5.58 and only four beams below the often-used yet arbitrary threshold for significance of $t = 3.5$ (27) (Dataset S1). Average *t* values for the Chuska and Zuni Mountains were the highest (Fig. S3*A*). Differences in sourcing strength between species were negligible, although spruce and fir trees had the lowest mean *t* value (Fig. S3*B*). Using more conservative subsets of the sourcing results generated little change in our findings and no differences in interpretation (*SI Text* and Table S3).

We found that 70% of the timbers most likely originated from the Chuska and Zuni Mountains, each >75 km from Chaco Canyon (Fig. 2). No other potential location accounted for more than 9% ($n \leq 16$) of the beams, fewer than would be expected by chance ($\chi^2 = 204$, $P < 0.001$). Sourcing patterns differed somewhat by species (Fig. S4). In the case of ponderosa pine, the Chuskas accounted for 50% and the Zunis for 29%. The Zuni Mountains were also important for piñon (*Pinus edulis*) and juniper (*Juniperus* spp.) trees, accounting for 58%. Results for spruce and fir were similar to those of English et al. (6), with Mount Taylor as the primary source (29%).

Our findings that identify the Chuska and Zuni Mountains as a significant source of great-house beams are consistent with previous interpretations of long-distance timber procurement (4–7, 10, 11). A pair of recent studies, however, challenge this idea based on similarities in the $^{87}Sr/^{86}Sr$ values for trees in the Chuska Mountains and soil in Chaco Canyon (8, 9). They conclude, therefore, that low-elevation sites within and near the Canyon were just as likely sources for ponderosa beams as were the Chuskas, despite a lack of ponderosa pine in the paleoenvironmental record of the Canyon and surrounding areas since ~5,000 y ago (14–16, 28). If large numbers of local ponderosa pines were to exist in the canyon during the Chaco era and were used as construction timbers (8, 9), then we would expect the sourcing of the great-house beams to show a similar pattern to the "sourcing" of modern pines from low-elevation sites within Chaco Canyon (Fig. S2*F*). Modern (post-1300 CE) ponderosa pines growing in north-facing alcoves on the eastern end of the Chaco Core associate most strongly to the Jemez region on the eastern side of the San Juan Basin. The Chuska and Zuni Mountains, where the great-house timbers source, are instead to the west (Fig. 2), suggesting that it is unlikely that trees within or near Chaco Canyon were major sources of construction timbers.

Previously, the Zuni area had been identified as a logical procurement area for timber (11) and other resources (29, 30). Our study is the first to our knowledge to source great-house timbers to the Zuni Mountains. Owing to the general lack of large stands of spruce and fir in the present species composition of the mountain range, the area was not considered in the strontium sourcing studies (6, 7). Our results indicate that wood was imported from the Zunis as early as the 850s CE.

To evaluate changes in procurement areas through time we analyzed only beam specimens that have cutting or near-cutting

SEE COMMENTARY

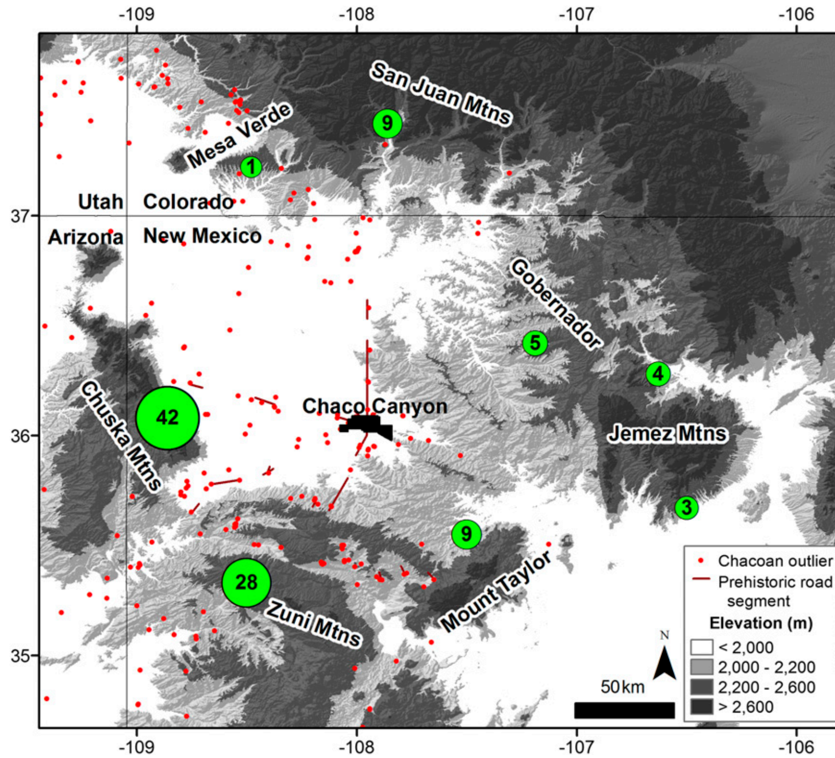

Fig. 2. Source locations for great-house timbers (n = 170). The sizes of the green dots are proportional to the percent of beams sourcing to that location; values provide the percentages. Locations of outlier sites and prehistoric road segments come from Mills et al. (43) and Kantner and Kintigh (44), respectively.

outside dates spanning the temporal range of timber harvesting (Fig. S5). We found that before 1020 CE, nearly all beams sourced to the Zuni Mountains, and thereafter the Chuska Mountains, rose in importance, eclipsing the Zuni region by 1060 CE (Fig. 3 and Fig. S6). This apparent shift in timber procurement coincides with the proliferation of other Chuskan goods in the Chaco Canyon archaeological record (Fig. 4). After *ca*. 1020 CE, Narbona Pass Chert (unique to the Chuska Mountains) accounted for >20% of the chipped stone tool assemblage in Chaco (31). Correspondingly, Chuskan pottery, usually made with temper from Narbona Pass, was extensively imported after *ca*. 1040 CE (32, 33).

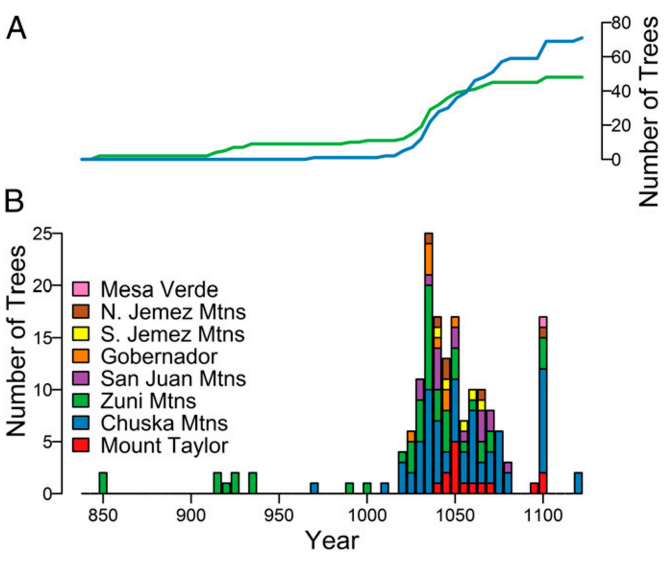

Fig. 3. Time series of great-house timber origins. Both plots are on the same time scale. (*A*) The cumulative sum of beams sourcing to the Zuni (green) and Chuska (blue) Mountains. (*B*) Distribution of cutting dates by 5-y bins for each source location. The bars are plotted on the center year of each bin.

At the same time the Chuska Mountains rose in importance during the middle 11th century CE, there was an onset of major architectural expansion in the Chaco Core area that is additionally defined by a change in masonry style (1). Expansion occurred at existing great houses (Pueblo Bonito, Peñasco Blanco, and Una Vida) and seven new great houses were built, comprising half of the great-house structures in the canyon. Whether this surge in construction and new design drove regional expansion of the Chaco system toward the Chuska Mountains or was in response to expansion in that area remains an open question. An explanation for the shift from mostly Zuni-area timbers in favor of Chuskan wood remains equally elusive but may relate to shorter travel distances between the Chuskas and Chaco that would have facilitated large-scale expansion in the Canyon, or a dwindling resource supply along the Zuni front after centuries of occupation. Improved dating and analyses of the Chaco outlier network, particularly on the eastern front of the Chuska Mountains, may provide answers to both questions (12).

The results of our study independently confirm the hypothesis that distant forested landscapes were the sources for hundreds of thousands of timbers used to build the great houses of Chaco Canyon. Our tree-ring-based results, in accordance with the strontium isotope studies, determine the Chuska Mountains as the primary procurement area. Our discovery of the Zuni Mountains as a source of timber has not only expanded the area from which beams are most likely to have been procured, but it also elucidates a temporal shift in timber procurement. The presence of a network of outlier sites and village clusters at the base of the Chuska and Zuni Mountains (Fig. 2) further supports our conclusions by suggesting a direct connection between these upland forests and the semiarid desert of the Chaco Core area. Given that our findings correspond with isotopic and archeological evidence of increasing use of the

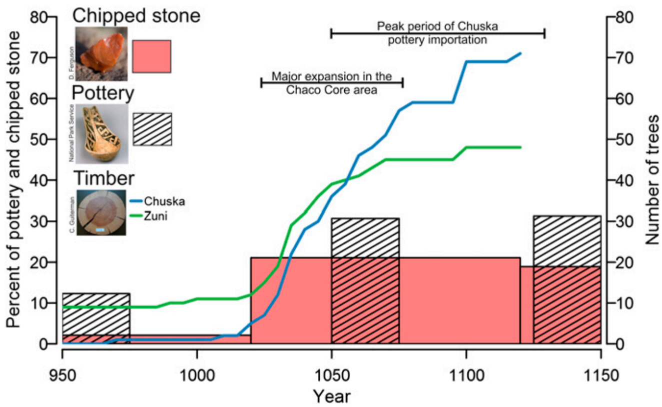

Fig. 4. Time series of the Chaco great-house archaeological record. Percentages for chipped stone and pottery represent the amount of Narbona Pass Chert (31) and Chuskan pottery (1) in those records. Curves for construction timbers are the same as in Fig. 3*A*. Highlighted time periods for construction and importation of pottery come from the Chaco Synthesis Project (1).

Chuskan landscape after 1020 CE (Fig. 4), a preponderance of evidence now indicates the importance of this particular landscape in the development and florescence of the Chacoan system.

The great houses of Chaco Canyon represent an enormous investment in materials, labor, and human ingenuity, requiring favorable environmental conditions and complex socioeconomic structures to construct and maintain. Although Chacoan exchange networks extended as far as Mesoamerica for prestige items (34, 35), the procurement of basic, labor-intensive resources from multiple distant landscapes, with shifting dynamics of use, is a prominent feature of Chacoan society. Testing for similar patterns at other pre-Columbian and historic sites in North America would be a fruitful endeavor and is possible now because of a dense network of long tree-ring chronologies and the rich collection of archaeological wood material housed at the University of Arizona and National Park Service archives.

Materials and Methods

San Juan Basin Tree-Ring Chronologies. We used eight tree-ring chronologies in the San Juan Basin to represent the likely timber harvesting areas for Chaco Canyon great houses (Table 1 and Dataset S1). Each chronology is composed of one to four tree species, with greater numbers of species further back in time. In most cases, the chronologies are built from living tree samples dating back to ~1300 CE, and then extended back in time with archaeological wood from individual sites or site clusters. We assume that beams from these upland archaeological sites represent locally harvested trees because of the abundance of suitable trees near the sites, which is not the case for Chaco Canyon.

One chronology (Mesa Alta) contains no archaeological specimens, with the pre-1600 period consisting of subfossil logs found on the landscape. For this site, we combined two chronologies composed of different species to boost the strength of the local tree-ring growth signal by adding sample depth during the Chaco period. One of these chronologies (MEA) is composed of Douglas-fir (*Pseudotsuga menziesii*) and southwestern white pine (*Pinus strobiformis*) (36), and the other (CDP) is ponderosa pine that we collected for this study. The Chuska Mountains chronology combines ponderosa pine and piñon subfossil wood from Narbona Pass (NPS) that we collected and archaeological wood excavated from 13th-century pueblos at the eastern foot of the mountain range (CHU). This combination was done to boost sample depth and increase the local common signal in the pre-1300s period, and to fill a time gap in our Narbona Pass chronology resulting from a lack of material dating between 1081 and 1140 CE.

Great-House Timbers. We selected Chaco Canyon great-house specimens from the archaeological collections of the Laboratory of Tree-Ring Research at the University of Arizona. To enable systematic selection from thousands of archived specimens, we first digitized the complete record of individual specimen catalog cards for the great houses. These data were assembled into a Microsoft Access database consisting of 6,421 records (the complete database is available from www.chacoarchive.org/cra/chaco-resources/tree-ring-database/). Of these, 2,497 beams have been assigned exact calendar dates. Our selection criteria for specimens to source consisted of conifers that had at least 30 measurable rings, were solid wood (i.e., not charcoal because of its fragility and associated difficulty to measure), came from a distribution of great houses, had cutting or near-cutting outside dates, and represented the temporal distribution of available specimens (Fig. S5). These criteria narrowed our available selection to 1,048 trees. This includes some duplicates where a single beam was sampled more than once by different excavators, resulting in more than one specimen ID or database record. In the process of measuring beams, we took care to avoid duplication by consulting laboratory technician notes, where this is often indicated. In selecting and measuring specimens, we gave preference to older trees, and thus more than 75% of our samples have more than 75 rings.

We measured ring widths to the nearest 0.001 mm on a Velmex system, recorded observations of injuries, ring anomalies, false rings, and frost rings, and photographed each sample. We used the COFECHA computer program (37) to assess the quality of measurements and crossdating (raw measurements are available in Dataset S1). Finally, biological growth trends of the measured beams were removed by division against 50-y cubic smoothing splines (38) in R using the dplR package (39, 40).

In all, we measured 174 specimens, but four were omitted from further analyses because they did not significantly match any of the San Juan Basin chronologies, leaving 170 beams in our final dataset of great-house timbers. These specimens include at least six tree species from seven great-house structures (Table S1). Because spruce and fir are difficult to differentiate (4) they have not historically been differentiated in the archaeological collection, nor has a systematic effort been made to differentiate *Abies lasciocarpa* from *Abies concolor*. Because of these uncertainties, and the relative consistency of spruce and fir as codominants in upper elevation forests, we grouped the two genera into a single category for analyses. We know, however, that our dataset contains both spruce and fir because seven of our beams were identified to their genus by scanning electron microscopy (4).

It is uncertain how well our sample of beams represents the population of great-house construction timbers, of which there were at least 240,000 harvested trees (3). The tree-ring archaeological record is limited to a very small portion of this total estimated population. Fewer than 10,000 beams have been excavated from the great houses, and dendrochronologists could date fewer than 2,500 of those (primarily because many lacked enough rings or adequate growth variability for confirmed dating). This record is all that is available for study, and we have therefore designed our test for origins on a sample of it. We chose a representative sample of the available record with respect to the component of cutting dates rather than other possible parameters or the population of timbers in its entirety. Although there is uncertainty about potential bias in our available sample, we would note that this problem is not unique to this study and exists in paleoecology and

Table 1. Source-area chronologies from the San Juan Basin

Location	Site code	Species*	Date range	Latitude	Longitude	Elevation, m above sea level	Source
Mesa Verde	MVER	1	550–1989	37.22	−108.48	2,263	41
Northern Jemez Mountains	MEA/CDP	1, 2, 3	620–2012	36.28	−106.63	2,525	36, this study
Southern Jemez Mountains	JEM	2, 4	598–1972	35.67	−106.50	2,011	41
Gobernador	GOB	2	623–1989	36.42	−107.19	2,230	41
San Juan Mountains	DUR	1, 4, 5	−319–2009	37.42	−107.86	2,213	41, 42
Zuni Mountains	CIB	1, 2, 4, 5	435–1972	35.33	−108.50	2,072	41
Chuska Mountains	CHU/NAR	1, 2, 4, 6	532–2012	36.09	−108.86	2,650	41, this study
Mount Taylor	CEB	4	680–1986	35.55	−107.50	2,072	41

*Species: 1, *P. menziesii*; 2, *P. ponderosa*; 3, *P. strobiformis*; 4, *P. edulis*; 5, *Pinus flexilis*; 6, *Juniperus* spp.

archaeology in general. Animal or plant specimens and artifacts that survive long times, are discovered, sampled, and effectively dated and analyzed are commonly a very small subset of a much a larger population of unknown statistical distribution. Nevertheless, useful and accurate interpretations and information are often obtained, especially when combined with testing and other, independent lines of evidence, as we have discussed in the present case. It is hoped that further sampling and dating work in the future, and perhaps new methods of analysis, will further test our interpretations.

Analyses. Sourcing archaeological timbers consisted of performing correlation analyses between the measured beams and the eight San Juan Basin chronologies. Before calculating correlations, we removed autocorrelation from each series via autoregression modeling. Statistical significance of the correlations was assessed with one-tailed t tests ($\alpha = 0.01$), whereby the correlation values (Pearson's r) were converted to t values using

$$t = \frac{r\sqrt{n-2}}{(1-r^2)},$$

where n is the length of overlap between the two series (27). Any nonsignificant correlations were excluded from analysis. We assigned the origin of each beam to the location of the regional chronology with the highest significant t value.

To assess whether the number of trees sourcing to each location exceeded what might be expected by chance, we applied the χ^2 goodness-of-fit test (chisq.test) in the R stats package.

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Supporting Information

Guiterman et al. 10.1073/pnas.1514272112

SI Text

Evaluation of Tree-Ring Width-Based Sourcing in the San Juan Basin. Following Daly (45), we tested whether tree-ring growth patterns were distinguishable among landscapes in the San Juan Basin to evaluate the effectiveness of tree-ring sourcing methods in the region. We hypothesized that trees from a given area will correlate most strongly with site chronologies from the same area. For the test, we used the eight chronologies described in the main text to represent each landscape (Table 1) and compared living trees of known origin to them to assess where the trees "source." Data for the trees of known origin came from previously sampled sites in the San Juan Basin and are independent of the chronologies used for sourcing timbers (Table S2). We accessed tree-ring data for five of the six sites from the International Tree-Ring Databank; the sixth site, Chaco Canyon ponderosa pine (Chaco East), consists of wood collected by National Park Service personnel [described by Windes (46)] and archived at the University of Arizona. These trees are from a few scattered ponderosa pine stands found in some cooler/wetter alcoves and north-facing slopes in the eastern portion of Chaco Canyon.

Tree species included in the test sites are ponderosa pine (three sites), piñon (two sites), and Douglas-fir (one site). The two sites closest to Chaco Canyon (Burning Bridge piñon and Chaco East ponderosa) were included to provide a sense of where great-house timbers might source if they were harvested locally. This was done because we lack a Chaco Canyon chronology long enough to compare with great-house timbers. The first four test sites, therefore, represent trees growing in the upland areas most likely to have been used by Chacoans (Table S2).

For each test site, we used a single measurement series from each tree to mirror the methods we use on great-house timbers. All statistical treatments and procedures were identical to the beams, including the standardization, removal of autocorrelation, and calculation of Pearson product-moment correlations and t values. We chose the location of the highest t value as the "source" for the trees of known origin.

Results of these tests support the use of tree-ring based sourcing in the San Juan Basin (Fig. S2). For the four upland sites, 90% of the trees sourced to their known location (Fig. S2 *A*–*D*). For the Chuska Mountains and Jemez Mountains, all 13 trees at each site sourced correctly (Fig. S2 *A* and *B*). The Grand View Ridge piñon site was 75% accurate, with the other trees ($n = 5$) sourcing to the two nearest neighboring ranges (Fig. S2*B*). For the Satan Pass Douglas-fir site just north of the Zuni Mountains, all but two trees sourced to the Zunis, with the other two sourcing to Mesa Alta (Fig. S2*D*). This result could have been driven by differences in growth pattern among species, because both Satan Pass and Mesa Alta include Douglas-fir. These two sites (Grand View Ridge and Satan Pass) were not located in the same mountain range as the nearest source-area chronologies, which may have contributed to their lower rates of accuracy. If we include those trees that sourced to the nearest neighboring range, the overall accuracy rate was 97% (65 out of 67 trees).

The Chaco-area trees (Fig. S2 *E* and *F*) tend to source toward the east, with most trees ($n = 38$) matching best to the Jemez Mountains and Gobernador chronologies. In each test, only two trees sourced to the Zuni and Chuska Mountains. These results contrast those of the great-house timbers, which mostly sourced to the Chuskas and Zunis, supporting the general interpretation that locally grown, Chaco-area trees were unlikely to have been a major source of great-house timbers.

Evaluation of More Conservative Beam Subsets. The length of overlap between an individual beam and a source-area chronology and the strength of correlation are important considerations when evaluating the efficacy of sourcing results. To test whether changing these parameters would affect our results, we created three subsets of the sourcing results based on series length (number of rings) and strength of correlation (t values). Researchers tend to use long series (i.e., more rings) to protect against spurious correlations from low n values, or to group the archaeological tree-ring series into a single, long chronology for sourcing (e.g., refs. 21 and 22). When analyzing the origins of individual specimens, series lengths fewer than 50–75 rings are less common, but beams with 40–50 rings have been successfully sourced (47). Given the high growth variability and strength of cross-dating in our sample of great-house timbers, we use sourcing techniques on specimens with ≥30 rings. To test whether our results were robust against a change in minimum series length, we analyzed a subset of the data that included only those specimens with ≥75 rings, yielding 131 great-house timbers. Although no universal threshold exists for determining matches between beams and source-area chronologies, one of the most conservative minimum t values is 6. Therefore, we created a second subset with beams that sourced with $t \geq 6$, yielding 117 great-house timbers. Finally, we combined these two criteria to include only beams with ≥75 rings and $t \geq 6$, yielding 97 timbers.

Results of these conservative subsets match the full dataset in terms of sourcing locations (Table S3) and the shift from Zuni to Chuska procurement (Fig. S6). The greatest change is for Chuska-origin beams, which are reduced in number with increasingly stringent criteria. The overall pattern, however, is maintained, supporting our use of the full dataset of 170 beams to better represent the tree-ring archaeological record from the great houses of Chaco Canyon.

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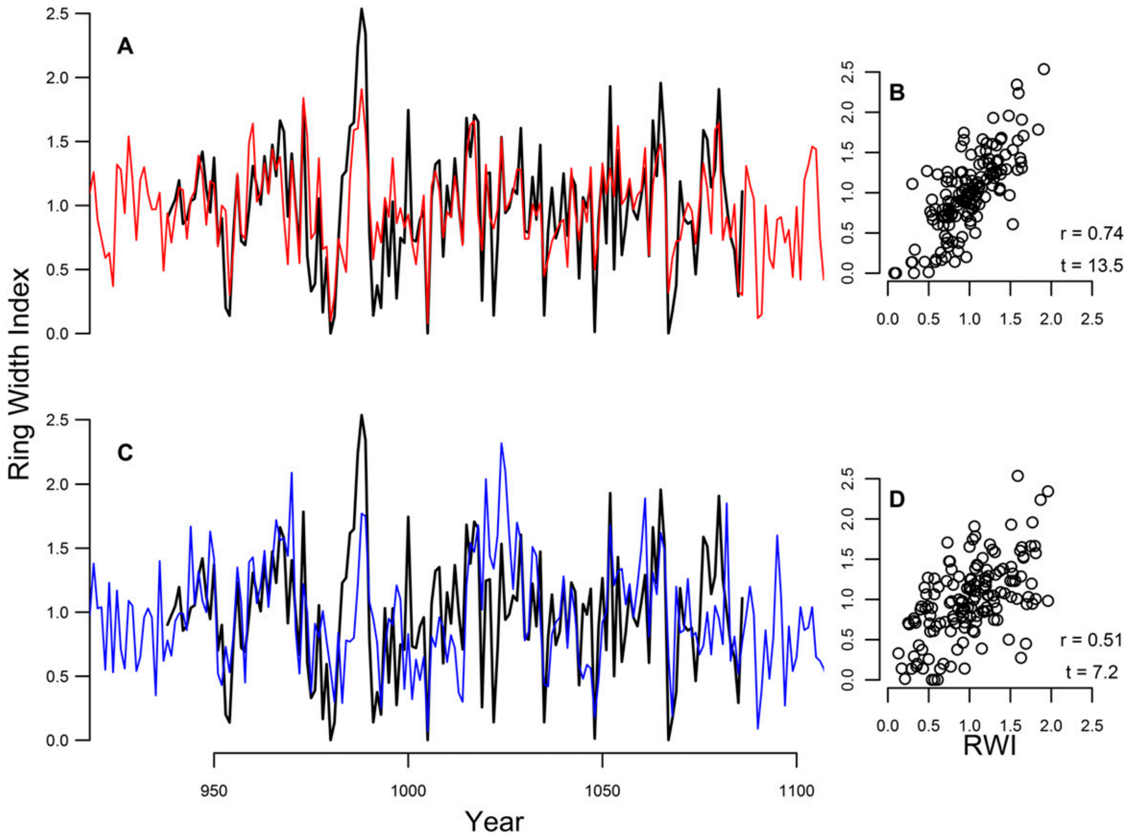

Fig. S1. An example of sourcing a great-house beam via tree-ring-width methods. (*A*) An individual beam (black line), the ponderosa pine JPB-88 from Pueblo del Arroyo, and the Chuskas chronology (red line). (*B*) Bivariate plot comparing the ring-width indices of the beam with the source-area chronology. Correlation (*r*) and *t* values are provided. (*C*) The same beam (JPB-88) with the southern Jemez chronology (blue line). (*D*) As in *B*, but with JPB-88 and the S. Jemez chronology. In this case, the beam clearly matches better to the Chuska area.

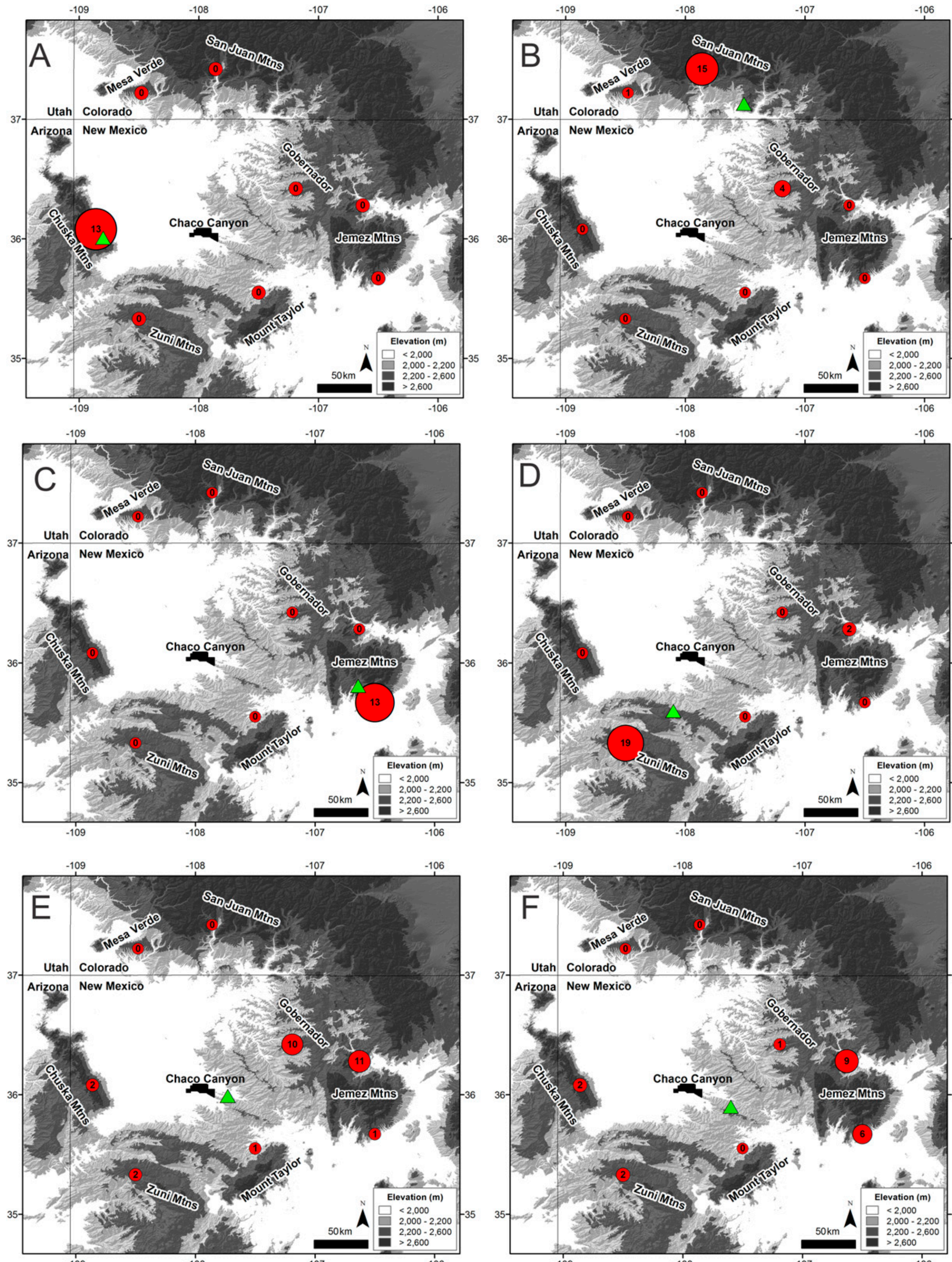

Fig. S2. Evaluation of dendroprovenance in the San Juan Basin. (*A*–*F*) Each tile provides a different test for a set of modern trees (green triangles). Circle sizes are proportional to the number of trees (labeled in the circle) sourcing to a given location. Site information is provided in Table S2; a description of the test is presented in *SI Text*.

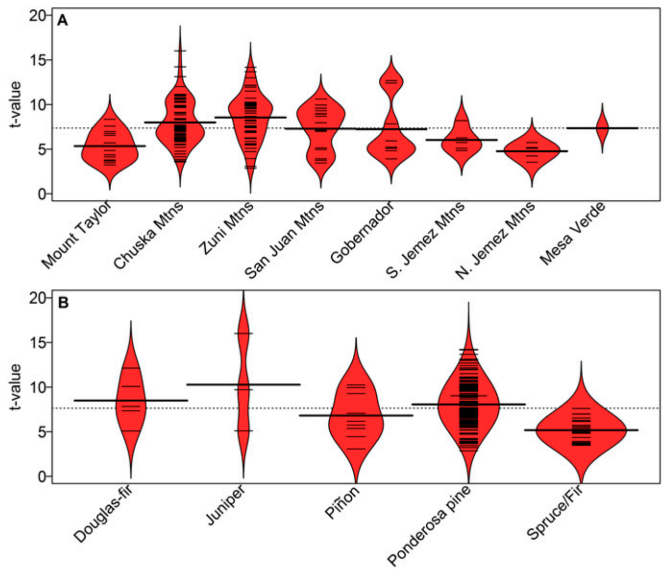

Fig. S3. Strength of sourcing by (*A*) probable location and (*B*) tree species. The *t* values for individual beams are shown as small dashes, and the long black lines give the mean of each category. The dotted lines provide the overall median *t* value in each graph. Polygons indicate the general spread of the *t* values as probability distributions. These are produced by a Gaussian kernel density function with a bandwidth equal to the average SD across all categories in each graph (48).

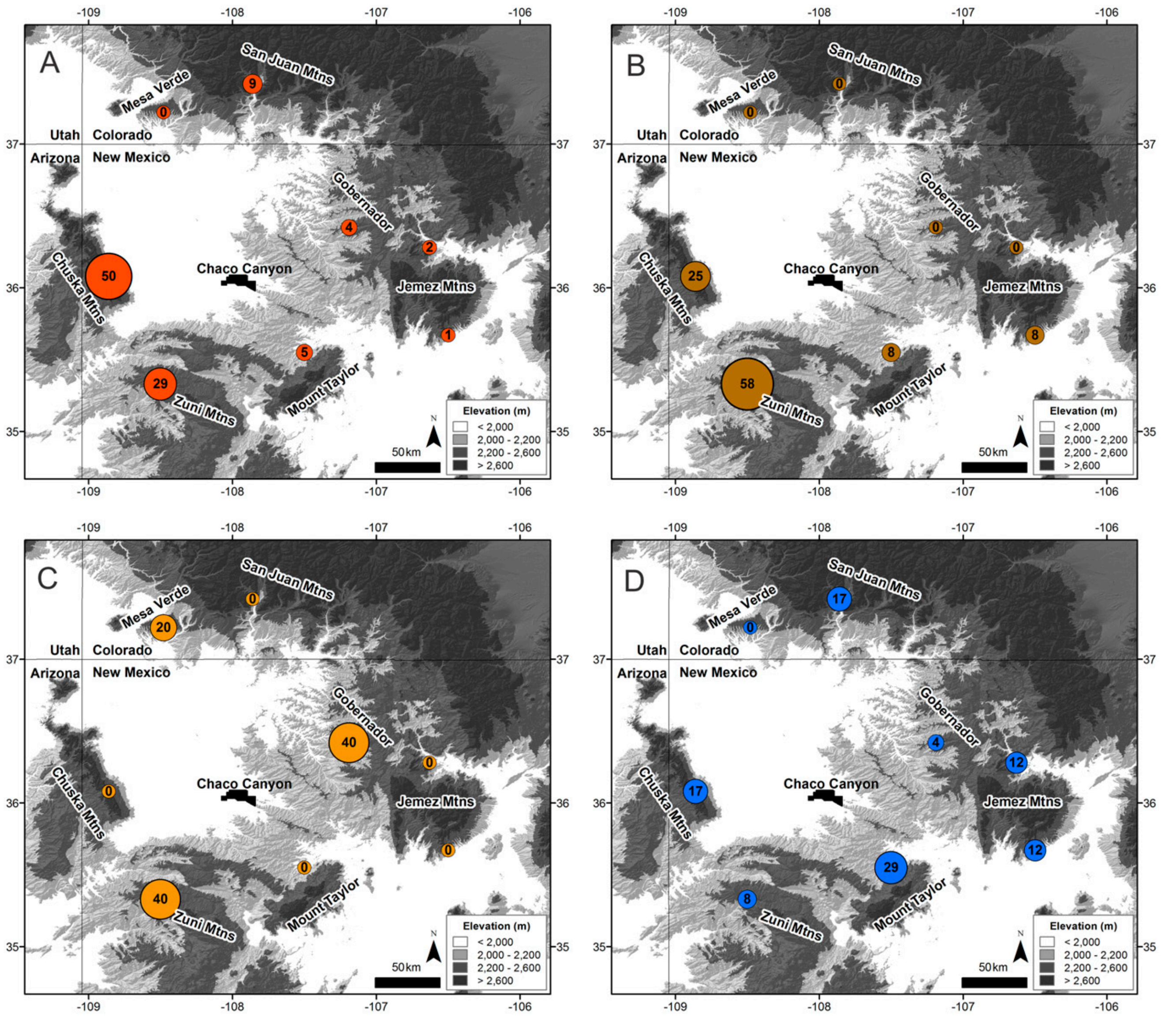

Fig. S4. Sourcing results by tree species. Dot sizes are proportional to the percent of beams sourcing to that location; values provide the percentages. (*A*) Ponderosa pine, (*B*) piñon and juniper, (*C*) Douglas-fir, and (*D*) spruce and fir.

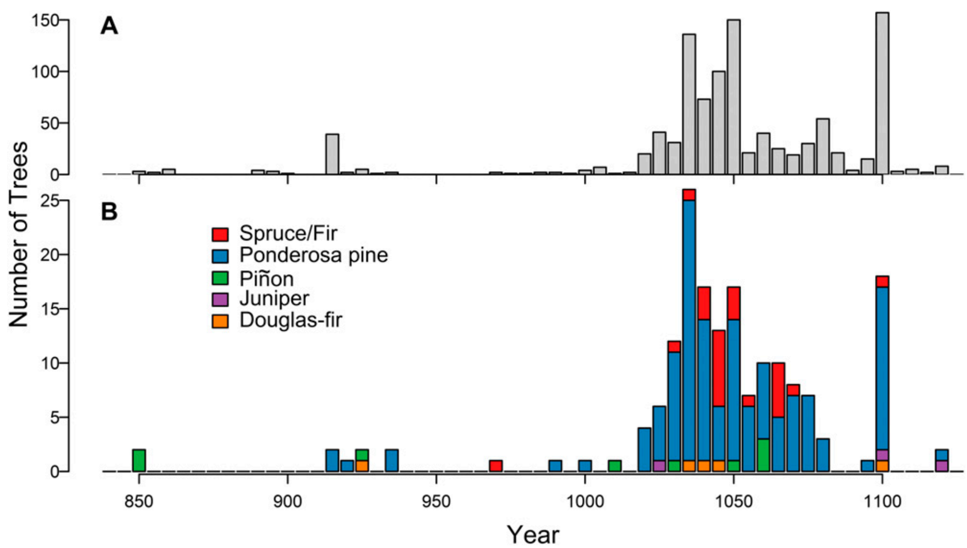

Fig. S5. Temporal distribution of beams with cutting and near cutting outside dates. (*A*) All great-house timbers that met our four criteria described in the text. (*B*) Timbers we analyzed. Spruce and fir are grouped because we did not differentiate these genera.

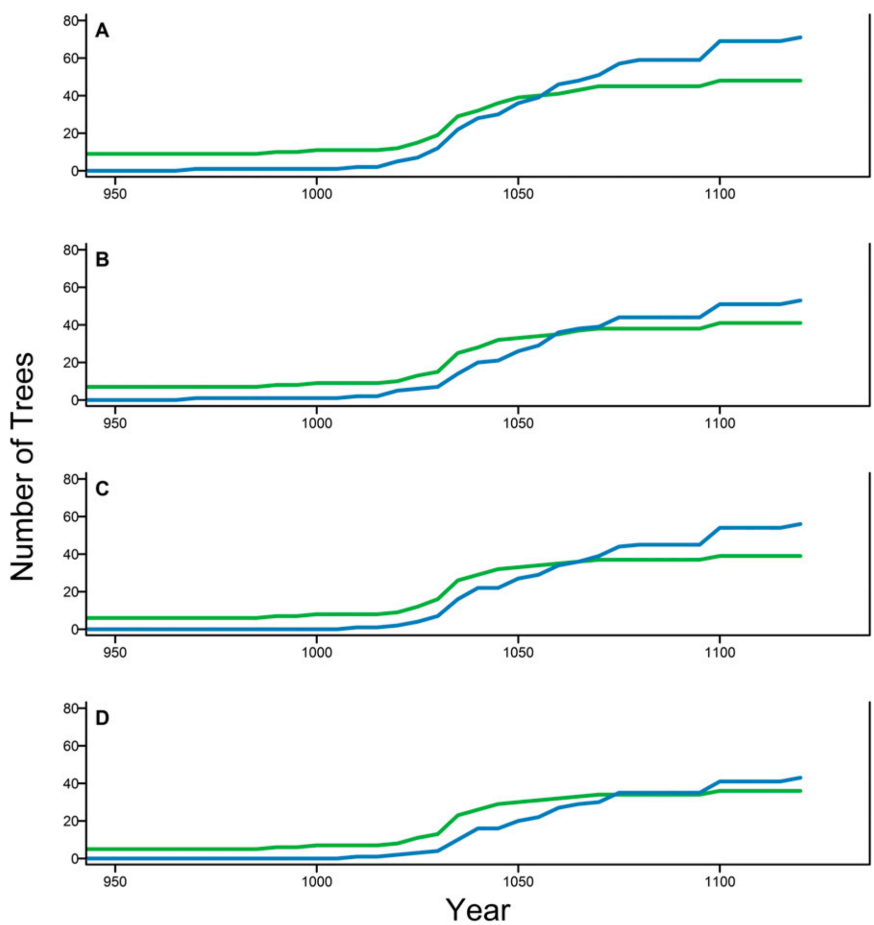

Fig. S6. Comparison of more conservative subsets of great-house timbers. For each plot, the lines show the cumulative sum of source results for the Chuska Mountains (blue) and Zuni Mountains (green), as in Figs. 3 and 4. The above plots show consecutively more conservative subsets of our results. (*A*) the full dataset with series ≥30 rings as in the main text, (*B*) only series ≥75 rings, (*C*) only beams with $t \geq 6$, and (*D*) beams that have ≥75 rings and $t \geq 6$.

Table S1. Number of sourced beams by species and great-house structure

Structure	Douglas-fir	Juniper	Piñon	Ponderosa pine	Spruce/fir	Total
Casa Chiquita				1		1 (100)
Chetro Ketl	1	1	3	73	19	97 (18)
Kin Kletso				2		2 (9)
Peñasco Blanco				5		5 (20)
Pueblo Bonito	3	1	3	27	2	36 (14)
Pueblo del Arroyo	1	1		20	3	25 (13)
Pueblo Pintado			3	1		4 (31)
Total	5 (4)	3 (33)	9 (13)	129 (18)	24 (18)	170 (16)

Values in parentheses provide the percent of the 1,048 available beams meeting our selection criteria.

Table S2. Tree-ring sites used to evaluate tree-ring-based sourcing in the San Juan Basin

Fig. S2 tile	Site name	Species*	No. of trees	Date range	Latitude	Longitude	Elevation, m above sea level	Contributor	ITRDB file†
A	Crystal	PIPO	13	1652–1978	36.01	−108.80	2,755	Cleaveland	NM529
B	Grand View Ridge	PIED	20	1566–2002	37.13	−107.51	2,012	Woodhouse	CO638
C	Cat Mesa	PIPO	13	1572–1986	35.81	−106.64	2,515	Swetnam	NM556
D	Satan Pass	PSME	21	1381–1972	35.60	−108.10	2,286	Dean	NM025
E	Burning Bridge Wash	PIED	20	1629–1976	35.90	−107.60	2,195	Dean	NM053
F	Chaco East	PIPO	27	1372–1994	35.99	−107.73	1,967	Windes (46)	

*Species: PIPO, *P. ponderosa*; PIED, *P. edulis*; PSME, *P. menziesii*.
†Refers to the file name on the International Tree-Ring Data Bank (ITRDB), accessible at www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring.

Table S3. Comparison of sourcing results between conservative subsets of beams

Location	≥30 rings	≥75 rings	$t \geq 6$	≥75 rings and $t \geq 6$
Mesa Verde	1 (1)	0 (0)	1 (1)	0 (0)
Northern Jemez Mountains	6 (4)	4 (3)	0 (0)	0 (0)
Southern Jemez Mountains	5 (3)	4 (3)	2 (2)	2 (2)
Gobernador	8 (5)	6 (5)	3 (3)	3 (3)
San Juan Mountains	16 (9)	12 (9)	11 (9)	9 (9)
Zuni Mountains	48 (28)	41 (31)	39 (33)	36 (37)
Chuska Mountains	71 (42)	53 (40)	56 (48)	43 (44)
Mount Taylor	15 (9)	11 (8)	5 (4)	4 (4)

Shown are the number of beams sourcing to each location given the subset criteria, with the percent of beams meeting that criteria in parentheses.

Other Supporting Information Files

Dataset S1 (XLS)