Correction

ANTHROPOLOGY

The authors note that, due to a printer’s error, two data deposition links published incorrectly. For the tree-ring chronologies on the International Tree-Ring Data Bank, the link for accession no. NM588 should be https://www.ncdc.noaa.gov/cdo/f?p=519:1:0:::P1_STUDY_ID:19279 and the link for accession no. NM589 should be https://www.ncdc.noaa.gov/cdo/f?p=519:1:::P1_STUDY_ID:19280.

The authors also note that, due to a printer’s error, the following text appeared incorrectly: on page 1, right column, first paragraph, lines 6 and 7, “$^{87}\text{Sr}/^{86}\text{Sr}$” should instead appear as “$^{87}\text{Sr}/^{86}\text{Sr}$.”

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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.

**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.

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). Paleocological 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 correlates the 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...
values for tree-ring sourcing of beams ranged from $t$ values for the Chuska and Zuni Mountains to designate probable origins. 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. S3A). Differences in sourcing strength between species were negligible, although spruce and fir trees had the lowest mean $t$ value (Fig. S3B). 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% ($n < 16$) 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 and Zuni Mountains and soil in Chaco Canyon (8, 9). These studies 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. S2F). 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 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.

![Aerial view of Pueblo Bonito, the largest of the Chaco Canyon great houses. Image courtesy of Adriel Heisey.](image-url)
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).

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 archaeological evidence of increasing use of the

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**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.

**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.
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 the 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 strobusliformis) (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 archived 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 confers 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. 5). 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 (39) they have not historically been differentiated in the archaeological collection, nor has a systematic effort been made to differentiate Abies lasiocarpa 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 (40).

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 narrow that list even further by rejection of radiocarbon dates that are not well constrained in the archaeological context (41). 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 paleoanthropology.

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

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

*Species: 1, P. menziesii; 2, P. ponderosa; 3, P. strobusliformis; 4, P. edulis; 5, Pinus flexulis; 6, Juniperus spp.
Sourcing archaeological timbers consisted of performing correlation analyses between the measured beams and the eight San Juan Basin construction beams, Chaco Canyon, New Mexico. Am Antiq 82:265–283.

We thank the Navajo Nation and the Navajo Society. 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 larger population of unknown origin. Archaeological tree-ring records were digitized and their associated specimens retrieved by P. P. Creasman and G. D. Flax. Edward Cook provided invaluable assistance with the archaeological data. We thank A. Helsley for useful comments on an earlier draft of this manuscript. D. Meko for statistical advice, and D. Ford and B. Mills for their many insights and support. This study was supported by Western National Parks Association Grant 13-02 and National Park Service Desert Southwest Cooperative Ecosystem Studies Units Grant UAZDS-381. Additional support was provided by National Science Foundation Dynamics of Coupled Natural and Human Systems Award 1114898 (to T.W.S.) and by the Laboratory of Tree-Ring Research.

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 (α = 0.01), whereby the correlation values (Pearson’s r) were converted to t values using

\[ t = \frac{r \sqrt{n - 2}}{\sqrt{1 - r^2}} \]

where \( n \) is the length of overlap between the two series (27). Any non-significant 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 \( \chi^2 \) goodness-of-fit test (chisq.test) in the R stats package.

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