Dendrochronologia 47 (2018) 38–47

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Source & Sourceability: Towards a probabilistic framework for dendroprovenance based on hypothesis testing and Bayesian inference

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ARTICLE INFO

Keywords:
Frequentist inference
Bayesian inference
Dendroprovenance
Sourcing
p-value
Statistics
US Southwest
Ancestral Pueblo
Anasazi
Tree-rings

ABSTRACT

Long-distance procurement of timber was necessary for the construction of Ancestral Pueblo Great Houses in Chaco Canyon, New Mexico. A number of higher-altitude tree sources were available within 30–70 km, though some isolated trees may have been acquired more locally. Highly regional tree ring variations enable matching some construction timbers to their source. Here, a method is developed which 1) develops a rejection criteria for ruling out sources for a tree ring sequence, 2) quantifies the relative spatial representation of a given source sequence, and 3) applies Bayes theorem to calculate posterior probabilities of source attribution. The application of this method in part supports past sourcing work, but indicates that the majority (59–64%) of timbers cannot be ascribed with even low confidence to the most common high-altitude sources. This analysis supports a model of diverse tree acquisition from a number of different sources, though with high uncertainty for a majority of timbers used in the present study.

1. Introduction

Sourcing of archaeological materials is needed to reconstruct ancient economic systems. In particular, long-distance transportation of artifacts can be a strong indicator of complexity and political authority (Lesure, 1999). Geochemical sourcing has become increasingly common to understand the exchange of ancient goods, using x-ray fluorescence for artifacts made of obsidian (Renfrew et al., 1965) and chert (Nazaroff et al., 2014), neutron activation analysis for ceramics (Crown, 1983), and strontium isotopes for bone and teeth (Copeland et al., 2011). These data provide exact quantitative data (% or ppm), or isotope ratios to an international standard. Their strength is that they allow the rejection of potential sources based on reproducible data (Speakman and Shackley, 2013); in theory the same artifact could be measured using three separate analytical techniques, all of which could agree on a source attribution (Rademaker et al., 2013).

The basis for dendrochronological sourcing was developed by Baillie and Pilcher (1973), was initially used to align sequences to aid in cross-dating beams. However, the principle of using correlations between source sequences and archaeological timbers can allow comparable reliability with geochemical sourcing. A recent study in Chaco Canyon (Guiterman et al., 2016) laid important groundwork in establishing dendroprovenance as a sourcing method. There are a number of challenges that must be addressed to have the same confidence as is held in geochemical methods. This has less to do with the analytical method employed, but rather with the way the data is used in the context of a hypothesis: can a prospective source be rejected based on the data? Can the potential sources be defined spatially, and interpreted probabilistically?

In the present manuscript, a method for dendroprovenancing is outlined which a) provides a hypothesis test for associating tree rings to a particular source, b) defines the spatial extent of a tree source using historical tree ring sequences, and c) uses Bayes theorem to assign a posterior probability of a given tree coming from a spatially defined source. Central to this method is using scaled Z-scores to establish a rejection criterion for sources, which can be used in a determinative (frequentist) or probabilistic (Bayesian) manner.

There are two primary hypotheses tested in the present manuscript. The first hypothesis is that a method can be developed to reject possible tree sources based on historical sequences. The second hypothesis is that such a method can reject potential tree sources for Chaco Canyon despite high correlations between prospective source sequences.

2. Background

Chaco Canyon was the site of a cultural fluorescence in the 10th and 11th centuries CE Large-scale construction of communal masonry “Great Houses” occurred from the 9th to 12th centuries (Windes and McKenna, 2001), with peak construction occurring in the latter half of the 11th century CE (Windes and Ford, 1996). Deforestation of local regions was hypothesized as a potential explanation for the quantity of timbers used (Judd, 1954), though the restriction of *Pinus ponderosa*

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https://doi.org/10.1016/j.dendro.2017.12.004
Received 28 March 2017; Received in revised form 5 October 2017; Accepted 15 December 2017

and *Picea* spp. to elevations above 1980 and 2100 m respectively today (Betancourt and Van Devender, 1981; Brown et al., 2015) suggest longer distance transport may have been necessary (Betancourt et al., 1986). Isolated stands of *P. ponderosa* have been reported in low density groups between Chaco Canyon and Pueblo Pintado 30 km to the southeast (Windes, 2014). *P. ponderosa* grew within the park historically, and was present from its discovery in the 19th century to the 1950′s (Judd, 1954). One *P. ponderosa* specimen with roots was found within Pueblo Bonito during excavations (Wills, 2012).

Understanding the sources of trees in Chaco Canyon provides archaeologists with an opportunity to examine the acquisition of long-distance material during a period of emergent complexity. While it is well established that luxury trade goods were transported from distances as far away as 3000 km (Crown and Hurst, 2009), long distance transport of common construction commodities (English et al., 2001) and food (Benson et al., 2003; Benson, 2010) might indicate the ability of a centralized authority to control labor over a wide area of the Colorado Plateau. The transportation of construction timber from either the Chuska Mountains (60 km to the west) or the Zuni Mountains (70 km to the southwest) would be expensive in time, calories, and water. Understanding the degree to which Chaco Canyon was dependent on such resources provides an important line of evidence for understanding the scope and extent of power in a pre-contact North American society.

Early work with strontium isotopes suggested long-distance procurement from the Chuska Mountains for wood used in Great House construction (English et al., 2001; Reynolds et al., 2005). Similar arguments for long-distance transportation of other commodities such as maize were also proposed based on radiogenic strontium isotope ratios (Benson et al., 2003; Benson, 2010). However these results were argued to be inconclusive due to the indistinguishable strontium isotope signal of the Chuska Mountains and the Cretaceous marine sandstone common across the Colorado Plateau, including Chaco Canyon (Drake et al., 2014; Wills et al., 2014). While long distance transport of goods likely occurred, strontium isotope ratios were not a reliable indicator of that acquisition pattern. However, while maize cultivation was viable in Chaco Canyon (Wills and Dorshow, 2012), tree species, particularly high-altitude species such as *Picea* spp., would have likely required long distance transport.

To directly address the long-distance procurement of wood for Great House construction, Guiterman et al. (2016) applied deondrochronological sourcing using the t-value method developed by Baillie and Pilcher (1973). First, they created tree ring chronologies using a 50-year cubic spline detrending and autoregression corrections. Then they applied a t-value calculated from statistically signifiant correlation coefficient corrected to the number of ring overlaps between a given tree ring sequence and the potential source. The source with the highest t-value with any given tree was concluded by Guiterman et al. (2016) to be the source (Fig. 1). They determined that the Chuska and Zuni Mountains were likely sources of wood despite being 60–70 km away, they based these conclusions on the Chuska and Zuni mountains having the highest quantity of sourced beams in their testing.

The method, while an important improvement over the earlier use of strontium isotopes to source trees, is constrained by the lack of significance testing for the core hypothesis, that the highest t-value was determinative of a source. Secondly, the definition of source was restricted to only those localities for which source tree ring series were procured, excluding areas such as Satan Pass near the Zuni Mountains which has tree cover and is much closer to Chaco Canyon. Guiterman et al. (2016) noted that tree ring sequences from lower altitude sources, such as Satan Pass 30 km to the South and Burning Bridge 17 km to the southeast, were correlated with high altitude locations in the Chuska and Zuni mountains using the t-value metric. However, reliance on the highest t-value result has pitfalls. Mathematically, there will always be a highest t-value regardless of the true source of any tree sequence. The central question posed by Guiterman et al. (2016), which tree rings come from which mountain range, is not properly addressed by which t-value is highest but rather which one is significantly higher than other potential sources. Defining such a significance test, as well as a Bayesian framework to assign the probability of a dendroprovenance attribution, is the central aim of the present study.

The critical value suggested by Baillie and Pilcher (1973) wasn't intended for determining the source of the tree, but rather for aligning chronological matches for dating purposes. An example of why this metric alone is not sufficient for this problem is that all Chaco timbers match at least two different sources if a t-value of 3.5 is used. In fact, the t-values of each source compared to the other possible sources all meet the 3.5 value threshold, the lowest t-value between potential sources (1600–1900CE) is 10.9 (Table 1). To determine dendroprovenance, what is relevant is not that a correlation between two tree ring sequences meets an arbitrary critical value or that one is simply higher than other values, but rather that one potential source is demonstrably significantly better at explaining variation then the plausible alternatives. A broader critique of the Baillie and Pilcher (1973) t-value method is that divorces the t-value from its probabilistic meaning (Fowler and Bridge, 2017). Though, as these authors note, to approach something of 99.9% confidence, a t-value of 3.7 is needed; for sequences shorter than 30 years, a higher t-value is needed. However, in Chaco Canyon, as discussed by Guiterman et al. (2016) and demonstrated in Fig. 1, t-values of greater than 10 exist for multiple sources. While Fowler and Bridge discuss the t-value in the contact of matching chronologies between trees in the British Isles, the results from Chaco unambiguously demonstrate that an arbitrary critical T-value is insufficient evidence to demonstrate a source. For the t-value to be reliable in dendroprovenance, a significance criterion is needed to provide a negative test for the t-value to restore a probabilistic interpretation.

A further difficulty beyond the test statistic used in dendrochronological sourcing in general is in understanding the regional representation of each tree ring sequence. A resource acquisition area, by definition, has a spatial definition that is generalizable. In geochemical provenance studies, the extent of the source must be defined (Rademaker et al., 2013). A distinction must be drawn between the geospatial concept of source that human societies would have used to understand it, and the definition of the source by geochemistry (Hughes, 1998) or, in this case, correlated climatic patterns in tree ring sequences. An unfortunate weakness of using individual tree ring sequences from a small (< 1 km^2 area) is that we cannot know how indicative they are of the larger regional area's pattern. A further difficulty is in sampling of the data − modern tree ring sequences are selected on the basis of their reflectance of climatic patterns; archaeological data will be more or less randomly selected relative to this criteria. Reconciling these challenges requires a robust inference methodology.

3. Frequentist vs. Bayesian Inference

There are two types of inference to consider in quantitative provenance research, geochemical or otherwise. The first is in a hypothesis testing framework as part of frequentist inference; in this case a significance criterion is employed to reject a possible source attribution. This is the most common method in archaeology in particular and scientific research in general. The second is in a probabilistic framework with Bayesian inference; employing a prior probability and revising it in light of new data. This technique is less frequently used in archaeology, but arguably is better at partial-information problems with high uncertainty.

Frequentist inference relies a distribution of expected results given a null hypothesis, and evaluates the probability of the empirical data in this context. Most frequently, a p-value is used to assign the probability of the new data based on the expected outcome of the null hypothesis'