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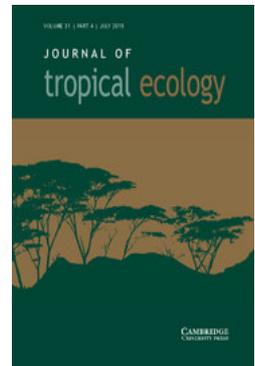
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SHORT COMMUNICATION

Annual rings in a native Hawaiian tree, *Sophora chrysophylla*, on Maunakea, Hawai‘i

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Abstract: Annual rings are not commonly produced in tropical trees because they grow in a relatively aseasonal environment. However, in the subalpine zones of Hawai‘i’s highest volcanoes, there is often strong seasonal variability in temperature and rainfall. Using classical dendrochronological methods, annual growth rings were shown to occur in *Sophora chrysophylla*, a native tree species on Maunakea, Hawai‘i. Chronologies were established from nearby non-native, live conifer trees and these were used to verify the dates from a total of 52 series from 22 *S. chrysophylla* trees, establishing an 86-y chronology (1926–2011). Ring-width patterns were significantly correlated with monthly rainfall from August of the previous year. This study is the first in the eastern tropical Pacific region to demonstrate annual growth rings in trees.

Key Words: chronology, cross-dating, dendrochronology, tree age, tree-rings, tropics

When trees form annual growth rings, the ring patterns can be used to gain information on growth rates, stand history, and to better understand past climate variability (Fritts 1976, Speer 2010). Annual rings develop as a consequence of intra-annual variability in suitable growing conditions, such as those related to monthly temperature or precipitation (Fritts 1976, Stokes & Smiley 1968).

The existence of annual tree-rings is well-established in temperate and semi-arid forests with strong temperature seasonality. Recent studies have demonstrated that some tree species growing in tropical areas with a predictable dry season or seasonal flooding also produce annual growth rings (Baker *et al.* 2005, Fichtler *et al.* 2003, 2004, Schöngart *et al.* 2004, Worbes 1999, Worbes *et al.* 2003). Tree-ring records do not yet exist for islands within the eastern tropical Pacific region, however they are of considerable potential significance for two reasons. First, forests in this region support a globally unique and

highly threatened endemic flora and fauna. Second, the eastern tropical Pacific region is important to regional and global climate dynamics because it is where much of the variability in the El Niño–Southern Oscillation (ENSO) phenomenon originates. Long tree-ring records from the western Pacific have provided important insights into ENSO and ENSO-induced drought variability at decadal and centennial time-scales, but no such records exist for the eastern dipole of ENSO (D’Arrigo *et al.* 2008, Fowler 2008).

In January 2010, we began exploring the slopes of Maunaloa and Maunakea on the island of Hawai‘i searching for possible candidate tree species that could be studied using tree-ring dating methods. The most promising of the tree species examined was *Sophora chrysophylla*, commonly called māmane, a native tree that is dominant in these subalpine ecosystems and has long been known to produce rings. The primary goal of this study was to determine if these rings are produced annually, and if so, to develop a tree-ring chronology for *S. chrysophylla* on the slopes of Maunakea. A second goal was

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to use the tree-ring chronology to explore the relationship between ring-width patterns and rainfall variability of this ecologically important species.

The climate of the subalpine woodlands on the slopes of Maunakea is seasonally variable, with frost occurring regularly from January to April (Juvik *et al.* 1993, Scowcroft 1983). Temperatures range from night-time lows a few degrees below 0°C to daytime highs above 20°C with mean annual rainfall of 350–750 mm (Scott *et al.* 1984, Scowcroft & Conrad 1992, van Riper 1980). The wet season generally occurs from November to April and the dry season from May to October (Scowcroft 1983, van Riper 1980). The soils in the area are very fine, sandy loams formed from volcanic ash, sand and cinders, resulting in low water-retention capacity (Scowcroft 1983, Scowcroft & Conrad 1992).

Increment cores from live trees are best used for tree-ring analysis when trees have distinct annual rings and concentric radial growth (Worbes 1995). Hawaiian trees at high elevations often grow asymmetrically, and the oldest portion of the trunk (first ring) is rarely located at the centre (Hart 2010). During the preliminary phase of this study, several increment cores of *S. chrysophylla* were inspected, and the rings were not clearly defined under the microscope. Given this and the asymmetric growth habit of *S. chrysophylla*, it was necessary to inspect entire cross-sections to visually identify complete rings around the circuit of the stem.

We located and sampled 22 *S. chrysophylla* trees from an area known as Pōhakuloa, which is located on the southern slope of Maunakea (19°44'4"N, 155°30'1"W) with an altitudinal range of 2045–2100 m asl. Seven samples were collected live in 2002, and 15 samples were collected in 2011 from dead trees in an area that was burned in a forest fire in August 2009. A 3–6-cm-thick cross-sectional disc was collected with a chainsaw from between 1–3 m above the base of each tree. Samples were transported to the laboratory where the surfaces of the cross-sections were prepared for cross-dating.

With no known mortality dates of most of our trees (it is possible that some of those that burned at the Pōhakuloa study area were already dead) we explored the possibility of assigning calendar years to *S. chrysophylla* rings by cross-dating the ring-width series to those of nearby populations of exotic conifers, which included *Pinus radiata*, *Pinus jeffreyi* and *Cedrus deodara*. An increment borer was used to extract a continuous core of wood from the bark to the pith of these living conifer trees (Speer 2010, Stokes & Smiley 1968). One *P. jeffreyi*, three *C. deodara* and two *P. radiata* were sampled at approximately 2275 m asl on the western slope and 2470 m asl on the north-eastern slope of Maunakea in 2012. Two cores were collected from each tree. Samples were transported to the laboratory where the surfaces of the cores were prepared for cross-dating.

The ring boundaries of the *S. chrysophylla* cross-sections were visually identified, checked, and marked across three different radii that were drawn through the least disturbed sectors of the wood starting from the same innermost growth ring to the outermost distinguishable and visually cross-dated ring. The ring boundaries of the conifer cores were also visually identified, checked and marked across the two subsamples from each sampled tree. Ring-widths were then digitally measured at a precision of 0.001 mm using a Velmex Measuring System (Velmex, Inc.) and the MeasureJ2X computer software program (Speer 2010). Since the death dates of the 2011 collection of the *S. chrysophylla* samples were unknown, ring-widths were measured with no connection to calendar dates, and the resulting tree-ring series were considered undated. Ring-widths from the 2002 *S. chrysophylla* collection, and the 2012 conifer cores were measured as dated rings since they were collected from live trees, and the growth ring closest to the bark was used as a reference date for the most recent growing season.

The raw data were then imported into Cofecha, a statistical software program that numerically verifies the accuracy of the cross-dating (Grissino-Mayer 2001). Cross-dating was first conducted within individual conifer cores and *S. chrysophylla* cross-sections. After cross-dating within individual trees was verified, Cofecha was then used to check the cross-dating between the combined *S. chrysophylla* collections with the conifer samples. Based on results from the Cofecha output on within-site cross-dating, the necessary adjustments were made in assigning calendar dates to the undated *S. chrysophylla* samples using the editing software program Edrm (Grissino-Mayer 2001). Updated raw ring-width data were then compiled for each site and re-checked in Cofecha for dating accuracy.

Raw ring-width data were analysed and a site chronology was developed for the Pōhakuloa site using ARSTAN, a software program that removes age-dependent and non-climatic trends in the data through standardization (Cook 1985). A Friedman variable span smoother with a variable-span sensitivity level set to nine (least flexible) was used to detrend the tree-ring series; this data-adaptive option is useful in modelling the growth curves of disturbed tree-ring series that do not evolve through time in a homogeneous way, and leaves intact tree-ring variability at inter-annual to decadal time scales (Friedman 1984). A robust (biweight) mean with bootstrap confidence limits was then used to calculate the mean chronology. The running RBar, the average correlation between series (a measure of chronology signal strength), was set with a 20-y window and a 19-y overlap (Wigley *et al.* 1984). All other options were set to default.

The resulting tree-ring index chronology was used to investigate the relationship between local climate

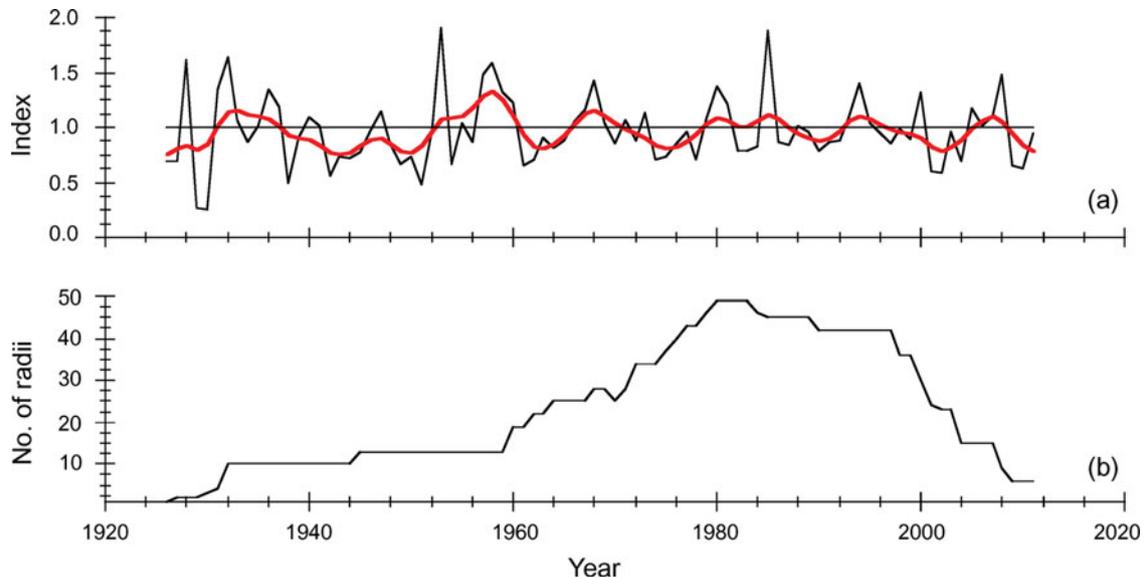


Figure 1. Raw tree-ring series mean and detrended curve (red curve) of an 86-y chronology (1926–2011) of *Sophora chrysophylla* from Pōhakuloa, Hawai'i based on 52 radii from 22 trees (a). Number of radii used to produce the chronology (b).

and annual growth patterns of the *S. chrysophylla* from the Pōhakuloa site using the software program PCReg (<http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>). Local precipitation data were gathered from a nearby rain gauge station at 1986 m asl operated by the Hawai'i State Division of Forestry and Wildlife (SKN #107, 19°44'55" N, 155°31'32" W), and spans from 1938–1976 (<http://rainfall.geography.hawaii.edu>). To help determine the month most critical for tree growth a Pearson correlation analysis was conducted to examine the relationship between the current year's tree-ring index and the monthly precipitation within the present year, as well as the previous year (1-y lag) (Fritts 1976).

An 86-y chronology spanning 1927–2012 was established using 12 radii from six conifer trees. This chronology included 591 rings with a median series length of 45 y, 0.631 mean series intercorrelation, 0.308 chronology standard deviation, 0.203 chronology lag-1 autocorrelation and 0.331 mean sensitivity. This provides the first evidence that conifers with temperate origins may produce annual growth rings when introduced to tropical areas, such as Hawai'i.

An 86-y chronology spanning from 1926–2011 was established using 52 radii from 22 *S. chrysophylla* trees from the Pōhakuloa site. This chronology included 2003 rings with a median series length of 32 y, 0.255 mean series intercorrelation, 0.314 chronology standard deviation, 0.096 chronology lag-1 autocorrelation and 0.303 mean sensitivity. The mean of the detrended ring-width series (standardized site chronology) is presented in Figure 1.

The *S. chrysophylla* chronology was characterized by a high RBar value and Expressed Population Signal (EPS) values (a measure of the common variability within a chronology in relation to sample depth) greater than 0.85, indicating high inter-annual variability and a strong common signal (Figure 2). The correlations between local monthly rainfall and the standardized chronology index for *S. chrysophylla* indicate that precipitation in August of the previous year is the best predictor of growth, with stem radial growth greatest in years following an August with heavier rainfall ($r = 0.377$, $P = 0.019$). These measures provide evidence for the chronology's reliability as a proxy for climate-change studies, as well as its usefulness in studying the ecology of *S. chrysophylla*.

Cross-dating is based on the presence of a common interannual variation in the periodic growth patterns of trees from a similar area due to a common set of growth-limiting factors most often related to climate. Trees that do not show any synchronization in the variation of growth patterns will not cross-date (Stahle 1999). The ability to cross-date multiple time-series within and among individual samples of *S. chrysophylla* and among the non-native conifers provides strong evidence that the growth rings in *S. chrysophylla* are indeed annual.

Since the successfully cross-dated trees at Pōhakuloa were smaller relative to those from other sites on Maunakea, the growth rings in the cross-sections were fairly clear. To strengthen the Pōhakuloa chronology it is imperative to find larger, older or longer dead *S. chrysophylla* samples that would provide longer time-series for cross-dating and would also extend the chronology further back in time. However, our results revealed that samples from even our largest trees (up to

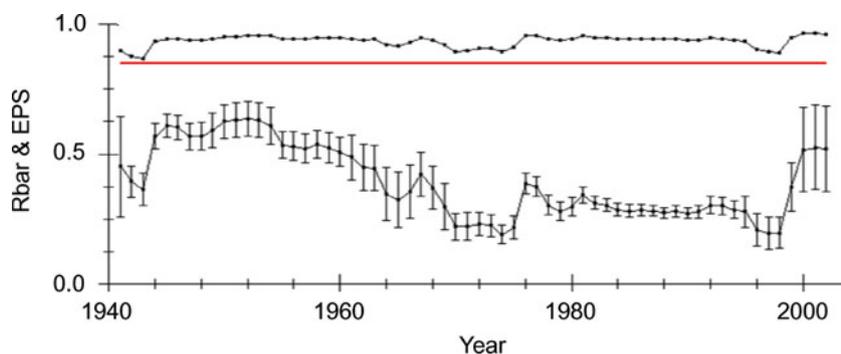


Figure 2. High detrended RBar values (a measure of the strength of the common growth signal within a standardized site chronology), based on a 20-y window and a 19-y overlap, and Expressed Population Signal (EPS) values (a measure of the common variability within a chronology in relation to sample depth) greater than 0.85 (red line) from an 86-y chronology (1926–2011) of 22 *Sophora chrysophylla* trees from Pōhakuloa, Hawai'i indicate high inter-annual variability, a strong common signal, and reliability of this chronology as a proxy for climate change and ecological studies.

55.7 cm diameter) may be relatively young (<150 y). While this may diminish their usefulness as records for how climate has varied over the past centuries in this region of the Pacific, it does provide hope for the success of ongoing restoration efforts of these forests.

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