FURTHER INVESTIGATION OF THE DENDROCHRONOLOGICAL POTENTIAL OF MĀMANE (*SOPHORA CHRYSOPHYLLA*) ON MAUNA KEA, HAWAI‘I

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ABSTRACT

In order to better understand and predict the future effects of global climate change, researchers must utilize methods that allow accurate interpretation of pre-instrumental environmental conditions. Dendrochronology is especially useful because of its ability to utilize climate proxies spanning tremendous spatial and temporal scales in the form of tree rings. The construction of a global network of tree-ring chronologies is already well underway, but temperate bias has resulted in an underrepresentation of the tropics. The Hawaiian Archipelago provides a unique opportunity to gather tree ring data from an undersampled region of the eastern tropics. I used classical dendrochronological methods to expand on previous research on Hawai‘i Island, adding trees from an additional site at a subalpine forest at Pu‘u La‘au, and extending the tree-ring chronology for māmane (Sophora chrysophylla) from 86 years to 173 years. I also investigated the growth-climate relationship of māmane at Pu‘u La‘au and found that rainfall is a poor predictor for tree growth.
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INTRODUCTION

In the face of global climate change, dendrochronological methods have gained popularity for their ability to provide robust proxies for pre-instrumental climate data with annual resolution. Dendrochronology is the discipline of assigning calendar years to tree rings and using these dated rings to detect environmental signals common to a population of trees. Through the study of the effects of climate variables such as precipitation and temperature on tree ring widths and patterns, it is possible to reconstruct pre-instrumental climate conditions as well as model future trends. Tree rings allow researchers to obtain annually resolved climate data from some of the oldest paleo proxy archives on the planet (Hughes 2002, Martinelli 2004, Coulthard and Smith 2013). In an extreme example, Yang et al. (2013) used a dated tree-ring series of the Qilian juniper (Juniperus przewalskii) to construct a 3,500 year-long record of annual precipitation for the northeastern Tibetan Plateau. However, such studies are only possible if the trees used form one ring per year. Such rings are considered “annual” and are the result of intra-annual variability in limiting factors for growth, such as monthly temperature or precipitation (Fritts 1976, Stokes and Smiley 1968).

There is an abundance of tree ring data and climate reconstructions from temperate and semi-arid forests with strong seasonality in temperature, but the tropics are greatly underrepresented by comparison (Worbes 2002). This is largely due to the once-prevailing notion that the tropics lack seasonality in temperature and/or precipitation that precludes annual periodicity in ring formation (Worbes 2002). In the early 20th century, however, Geiger (1915) and Coster (1923) demonstrated a strong correlation between precipitation from seasonal monsoons and wood growth on the island of Java in Indonesia, and Berlage (1931) followed up on this research and constructed the first tree-ring chronology in the tropics. Researchers
continue to find new species that produce annual rings in response to seasonal precipitation in
the tropics, such as *Callitris intratropica* in Northern Australia (Baker et al. 2008) and *Afzelia
xylocarpa* in Western Thailand (Vlam et al. 2013). In Northern Vietnam, a 535-year tree ring
chronology from the conifer *Fokienia hodginsii* was used to reconstruct pre-instrumental local
hydroclimate (Sano et al. 2009).

Networks of tree-ring chronologies have proven to be instrumental in studying and
understanding large-scale climate fluctuations such as El-Niño Southern Oscillation (ENSO)
(Stahle et al. 1998, Enquist and Leffler 2001). Annually resolved tree-ring chronologies serve as
proxies for climatic conditions over a much longer period than is available from instrumental
meteorological and oceanographic records (Stahle et al. 1998). Valuable insights into ENSO
variability have already been gained from tree-ring records in the western tropical Pacific
(D’Arrigo et al. 2008). However, terrestrially-derived climate proxies from the eastern tropical
Pacific are lacking. Current climate models from this area rely on sea surface temperatures (SST)
and coral growth rings as proxies for pre-instrumental climate records (Cobb et al. 2003).

Situated in the tropical Pacific, the Hawaiian Archipelago offers an opportunity to collect
information from the data-sparse eastern dipole of ENSO variability. Terrestrially derived
climate proxies from this region could help climatologists better understand spatial and temporal
patterns of El Niño (Rodriguez et al. 2005). With its high volcanoes that create a steep rainfall
and temperature gradient, Hawai‘i Island hosts great climatic and ecological diversity and holds
promise for dendrochronological exploration. The dormant volcano Mauna Kea reaches 4,207 m
above sea level and is the highest point in the state of Hawai‘i. Annual rainfall exceeds 6,500
mm in the lowland wet forests on Mauna Kea’s eastern flank, and yet the subalpine woodlands
on the mountain’s northwestern aspect less than 45 km away receive under 500 mm
(Giambelluca et al. 2013).

Māmane (*Sophora chrysophylla*) is a canopy dominant tree species in the montane
woodlands on Hawai‘i Island. The high climatic seasonality seen at higher elevations in Hawai‘i,
combined with the abundance of well-preserved māmane specimens as coarse woody debris,
makes the species an ideal candidate for dendrochronological studies. Francisco et al. (2015)
explored the dendrochronological potential of māmane trees on Hawai‘i Island and demonstrated
that māmane sampled from the southwestern slopes of Mauna Kea volcano display annual
periodicity in their ring formation. Additionally, Francisco et al. (2015) found that tree-ring
patterns of this tropical species were strongly correlated with local rainfall data. The tree-ring
chronology produced was 86 years long, spanning from 1927-2012 (Francisco et al. 2015) and is
currently the longest māmane chronology in Hawai‘i. However, the trees used in the Francisco et
al. (2015) study were small (<15 cm diameter at breast height). Māmane trees commonly reach
40 cm dbh or greater on Mauna Kea, indicating that there is potential to extend the māmane
chronology much further back in time and to provide better information for pre-instrumental
climate variability models. Therefore, the primary objectives of this study were to: i) determine if
larger and older māmane samples may be used to create an independent, extended māmane tree-
ring chronology and ii) investigate the growth-climate relationship of these māmane trees.

**METHODS**

**Study species**

Māmane is an endemic Hawaiian tree species in the genus Fabaceae that occurs from
near sea level to at least 3,000 m on the main Hawaiian islands (Rock 1920, Lamb 1981). On the
island of Hawai‘i, māmane dominates the subalpine woodlands on Mauna Kea volcano between
approximately 2,200-2,900m elevation. It typically averages less than 8m in height, but some individuals greater than 15m have been recorded (Wagner et al. 1990, Scowcroft and Conrad 1992). These trees are also important as the primary food source for the critically endangered Pālila (*Loxioides bailleui*), a highly specialized endemic bird species of Hawaiian honeycreeper that feeds primarily on young māmane seedpods (Lindsey et al. 1995).

**Study sites**

I collected māmane samples from the subalpine woodland at Pu‘u La‘au on the southwestern slope of Mauna Kea on the Island of Hawai‘i (19°50'4" N, 155°34'4" W), Pu‘u Mali on the northern slope (19°53'57" N, 155°26'16" W), and Pōhakuloa Training Area (PTA) on the southern slope (19°44'55" N, 155°31'32" W). The subalpine woodlands within the study site are dominated by māmane and naio (*Myoporum sandwicense*) and extend up to 2,900 m elevation: the highest forest line on any oceanic peak in the tropics (Leuschner 1996). This boundary is largely driven by the year-round stable temperature inversion occurs around 1,800 m elevation (Leuschner 1996, Juvik and Perreira 1973). Temperatures range from overnight lows below freezing to highs above 20°C (Scowcroft and Conrad 1992). Annual rainfall in the area ranges from 490-705 mm (Giambelluca et al. 2013), with a pronounced wet season occurring from November to April and a dry season from May to October (van Riper 1980, Scott et al. 1984). Soils in the study area are composed of poorly developed volcanic ash, sand, and cinders with low water-retention capacity (Scowcroft 1983, Scowcroft and Conrad 1992). Site characteristics are presented in Table 1.

**Sample collection and processing**

I located and sampled dead māmane trees from Pu‘u La‘au (*n* = 30) in Spring 2015. I also examined 21 undated māmane series that Francisco et al. (2015) collected from Pu‘u Mali.
Sample collection was limited to dead fallen trees because māmane are ecologically important and declining on Mauna Kea, largely as a result of landscape disturbance and alteration by invasive ungulates (Juvik and Juvik 1984). Larger diameter and signs of advanced decay such as worn or absent bark and sapwood were used as selection criteria in an attempt to select for older samples. I also selected for trees with concentric growth, and discarded cross sections that were rotten throughout. Following standard dendrochronology protocol, a 3-6 cm thick cross-sectional disc was cut with a chainsaw from the area above the buttress but below the first branches of each tree (Speer 2010, Stokes & Smiley 1968). Diameters of these discs ranged from 19.7 cm to 55.3 cm. Discs were planed and sanded in the lab with handheld power tools. To ensure clear ring boundary definition, I polished one side with coarse grit sandpaper of sizes 50, 80, and 120, then fine grit sizes 320, 400, and 600, as outlined in Francisco et al. (2015).

Additionally, I utilized a dated chronology consisting of *Pinus radiata*, *Pinus jeffreyi*, and *Cedrus deodara* cores (n=8) collected from Puʻu Laʻau and spanning the years 1927-2012 to assign calendar years to our younger māmane samples. This was done with a method called “crossdating” and is explained in detail below. I also crossdated undated māmane samples that Francisco et al. (2015) collected from Puʻu Laʻau (n = 20) and Pu'u Mali (n = 36) to bolster our chronology and test for a common climate signal between sites, respectively.

**Ring width analysis and crossdating**

Crossdating is a fundamental technique in dendrochronology in which unique patterns of wide and narrow tree rings are first matched among sub-samples from the same tree, then between trees from different stand and site locations (Braker 2002). This technique helps ensure that the correct calendar years are associated with individual tree rings. The high diversity of tree species in the tropics is accompanied by similarly diverse wood structure (Worbes 1989). As
such, the first step in creating a chronology from māmane was understanding how to identify growth ring boundaries. In the previous study on Mauna Kea, the latewood boundary that defines the end of annual radial growth each year was identified by terminal parenchyma bands. These were identified as light colored bands up to 0.5 mm thick that formed a continuous ring around the entire māmane cross section. In this study, tree ring boundaries were identified under a dissecting microscope and ring widths were measured at a precision of 0.001mm using a VELMEX system (Velmex, Inc.) and MeasureJ2X software (Speer 2010). When possible, up to three radii were drawn through the least distorted sections from the innermost identifiable ring to the outside of each cross-sectional māmane disc. Sample mortality dates were unknown, so the innermost ring of each sample was assigned an arbitrary date of 0. These radii were then crossdated within samples and the error checking software Cofecha (Grissino-Mayer 2001) was used to ensure missing and false rings were correctly identified. These “floating” ring series were compiled into an undated māmane chronology for Puʻu Laʻau. Next, calendar dates were assigned by cross-dating with the 86-year long conifer chronology produced by Francisco et al. (2015). We then attempted to crossdate undated Pu'u Mali samples collected by K. Francisco in 2012 with our resulting Puʻu Laʻau site chronology. Crossdating was done in Cofecha by using our dated Puʻu Laʻau series as a “dated master” and the floating Pu'u Mali samples as “undated.” In the dated master, every tree ring has been assigned a calendar year, and Cofecha used these unique patterns of wide and narrow rings to suggest dates for undated, “floating” samples that maximize the Pearson coefficient for the entire series. The resulting crossdated māmane tree-ring chronology adds one more site to Hawaiʻi Island and spans 173-years.
Tree-ring series detrending and chronology production

Tree-ring data were detrended and the chronology produced using ARSTAN (Cook 1985), a program that removes age-dependent and non-climatic trends through a process known as ‘standardization’ (Fritts 1976). In order to preserve tree-ring variability at inter-annual to inter-decadal time scales, we used a Friedman variable span smoother with a variable-span sensitivity set to a moderately flexible value of 4 (Francisco et al. 2015). This data-adaptive approach is particularly useful for modeling tree-ring growth in disturbed forests such as Pu‘u La‘au. The mean chronology was then calculated using a robust (biweight) mean with bootstrap confidence limits. The average correlation between series was calculated using a 20-year running window with a 19 year overlap (Wigley et al. 1984, Francisco et al. 2015) and all other options were set to the default ARSTAN settings.

Climate analyses

A mean ring width chronology was produced with the DPLR package (Bunn 2008) in the statistical software R (R Core Team 2013) and correlated with extrapolated monthly rainfall data from the Rainfall Atlas of Hawai‘i (Giambelluca et al. 2011) using the bootRes package (Zang and Biondi 2013). The Anderson-Darling test for normality showed that both mean-ring width indices (A = 1.519, p < 0.001) and rainfall data (A = 2.347, p < 0.0001) were not normally distributed, so the non-parametric Spearman’s rank correlation was used. I also used the R package “climwin” (Bailey and van de Pol 2017) to use a linear model with a sliding window function to quantitatively determine lagged effects of rainfall on māmane growth. All eight Pine/Cedar series were removed from the chronology for these analyses because their larger ring widths could skew the results.
Because so little is known about the nature and timing of māmane growth response to climate, we ran a suite of tests using all relevant climate variables incorporating time lags of up to six-months (see appendix). This was done by inputting the māmane chronology into Climate Explorer (www.climexp.knmi.nl), a web-based application for paleoclimatic research managed by the Royal Netherlands Meteorological Institute (KNMI) that makes a comprehensive collection of climate data and analysis tools readily available. Originally intended for analysis of the ENSO teleconnection, Climate Explorer has gained popularity among the paleoclimate research community (Trouet and Oldenborgh 2013). Māmane ring width data for each calendar year in our chronology were compiled to replicate the monthly format of instrumental datasets. Our chronology was then correlated with modeled climate data from NCAR/NCEP reanalysis (Trouet and Oldenborgh 2013). This “gridpoint” data was deemed the best option due to the paucity of available station data in the area.

**Radiocarbon dating**

During the process of photosynthesis, trees fix atmospheric carbon and incorporate the radioisotope $^{14}$C, which decays at a fixed exponential rate once the tree dies (Hua et al. 1999). Natural radiocarbon dating can be used to determine the age of dead trees through an equation that factors in the remaining amount of $^{14}$C in a sample and the fixed exponential rate of decay. Ideally, samples should be older than 350 years in order to ensure accurate results, as fluctuations in atmospheric $^{14}$C can otherwise cause problems (Stuiver et al. 1998).

A 25 mm drill bit was used to extract 5 mg of wood shavings from the approximate center of the 10 largest undated māmane samples from Pu‘u La‘au. We inferred that larger samples would have the highest chance of being the oldest, and would therefore be the most likely to meet the 350 year age criterion for accurate dating (Stuiver et al. 1998) and have the
potential to extend the māmane chronology even farther back in time with additional samples. Wood shavings were packaged in plastic vials, labeled, and shipped to the NSF-Arizona Accelerator Mass Spectrometry Laboratory at the University of Arizona for radiocarbon dating (Francisco et al. 2015). The program OXCAL 4.0 was used to identify all possible points where the resulting radiocarbon values intersected the Northern Hemisphere calibration curve, INTCAL04, then calculate relative probabilities, summing to 95.4%, for each date range (Bronk Ramsey 1995, Bronk Ramsey 2001, Reimer et al. 2004).

RESULTS

Crossdating summary statistics and quality assessment

The resulting Pu‘u La‘au site chronology is composed of 52 dated series (44 māmane and 8 pine/cedar) with 2,848 rings and spans the years 1830-2012 with an interseries correlation of 0.528 and an average mean sensitivity of 0.389 (Table 2). In general, interseries correlation values above 0.5 and mean sensitivity values above 0.3 are desirable (Grissino-Mayer 2001). Attempts to crossdate Pu‘u Mali samples were unsuccessful and yielded low interseries correlation values (below 0.5), so these trees were excluded.

Māmane ring boundary definition was not always sufficient for internal crossdating. Of the 64 māmane samples collected from Pu‘u La‘au, 31 were successfully crossdated internally. Of these, 10 were crossdated to the Pu‘u La‘au conifer chronology, and 10 samples were then crossdated to the resulting māmane-conifer composite. The remaining 11 samples could not be dated.

Individual raw ring-width series (n = 44) and their mean values are presented in Figure 1. The mean of the detrended ring-width series, or our standardized site chronology, is displayed in Figure 2. The RBar is a metric quantifying the strength of the growth signal common to trees
within a standardized site chronology (Wigley et al. 1984, Francisco et al. 2015). The RBar for our Puʻu Laʻau site chronology (Figure 3) shows the strongest common signal, expressed by smaller error bars, in the years 1944-1972. This indicates a stronger climatic response in māmane during that time period. The Expressed Population Signal (EPS) indicates the strength of the common signal in a chronology in relation to sample depth (Wigley et al. 1984). Chronologies with EPS values higher than 0.85 tend to be viable for climate analyses (Wigley et al. 1984). The EPS values for our Puʻu Laʻau māmane chronology are generally above the 0.85 threshold, with a significant drop around 1880 and minor dips in the 1890s, 1920s, late 1930s, and the late 1970s (Figure 3).

**Climate correlations**

The Spearman’s rank correlation between our māmane mean ring width chronology and local rainfall indicated a negative relationship between tree growth and rainfall in December of the previous year ($r = -0.22$, $p = 0.055$). Results from climwin sliding window function suggested that the effects of rainfall on māmane growth are lagged by seven months ($\Delta AIC = 0.318$), five months ($\Delta AIC = 0.439$), and six months ($\Delta AIC = 0.503$), but the linear model used indicated no significant relationship ($p = 0.83$).

Correlation field output from KNMI Climate Explorer ([www.climexp.knmi.nl](http://www.climexp.knmi.nl)) indicate possible significant interactions between our māmane ring-width chronology and net shortwave solar radiation and wind speed lagged by six months (see appendix).

**Radiocarbon dating**

Eight of ten samples submitted for radiocarbon dating had median calibrated $^{14}$C ages ranging from 106-180 years (Table 5). Two samples were found to be too young to be accurately dated. Sample $^{14}$C age estimates intersected the calibration curve between two and four times,
and probabilities for age interval 1 (the interval with the highest probability value) spanned 46.6-69.2%, with ages ranging from 89-142 years (Francisco et al. 2015). Five of eight samples (M5, M11, M13, M15, and M16) had ring counts that fell within the age interval 1 (Francisco et al. 2015).

**DISCUSSION**

The māmane chronology produced here spans the years 1830-2003 (173 years) and extends māmane tree-ring records for Hawai‘i by 96 years. The increase in sample depth from 9 dated trees in the previous study (Francisco et al. 2015) to 20 dated trees in our study, combined with the use of larger, older trees, allowed us to create a much longer chronology. This longer chronology would be expected to allow an increased ability to detect climate signals that span multiple decades and a better understanding of the stand dynamics of these trees. The former is especially useful for studying weather anomalies such as El Niño, while the latter can help forest managers make decisions that are more informed. Unfortunately, long-term time-series climate data for the study site other than rainfall are nonexistent, and these rainfall records only date back to 1920.

The subalpine woodlands on Mauna Kea have been subject to disturbance and degradation (Juvik and Juvik 1984) that may have drastically affected māmane growth-climate relationships. The pulses of higher error and weaker signal strength seen in RBAR and EPS values for the māmane chronology from 1830-1940 and 1974-2003 may reflect the higher feral ungulate population densities on Mauna Kea during these periods. The subalpine woodlands on Mauna Kea have been impacted by browsing by feral sheep (*Ovis aries*), feral cattle (*Bos taurus*), and other ungulates since the early 1800s (Kramer 1971). Browsing by feral ungulates, as well as invasion by non-native herbaceous and woody vegetation severely disrupted māmane
growth and regeneration at Puʻu Laʻau (Scowcroft 1983). However, by the late 1930s, government-sponsored eradication efforts yielded results, with the complete extirpation of feral cattle and a reduction in feral sheep populations from ~40,000 to ~200 individuals (Juvik and Juvik 1984). These conservation efforts were reversed in the 1950s, when the then Territorial Government decided to shift its emphasis from eradication to sustainable sport hunting (Juvik and Juvik 1984). A surge in feral sheep populations to over 4,000 by 1955, as well as the introduction of mouflon sheep (*Ovis musimon*), resulted in further degradation of māmane-naio woodlands on Mauna Kea until eradication efforts once again reduced their populations in the early 1980s (Juvik and Juvik 1984). Feral and mouflon sheep populations persist to this day on Mauna Kea. Incidentally, the weakest climate signal in the māmane chronology, expressed as larger error bars in the RBAR and EPS values below 0.85, occur in years predating active ungulate management (Figure 3).

Under the principle of limiting factors (Fritts 1971, 1976), plant growth is constrained by the most limiting primary environmental variable. In addition, the principle of ecological amplitude states that tree species may grow and reproduce across a range of habitats (Fritts 1981, 1976). When combined, these two fundamental principles of dendrochronology describe how tree growth is most sensitive to environmental variables at the margins of a species’ range (George and Ault 2014). For example, Palmer and Ogden (1983) found that temperature, not precipitation, limited kauri (*Agathis australis*) growth at higher elevations in New Zealand. In addition, Young et al (2010) found that growth in Scots pine (*Pinus sylvestris*) in Norway was limited by cloud cover rather than temperature. The lack of positive correlations between tree-ring growth patterns and rainfall indicate that other variables should be investigated. In an 11-month study on neighboring Mauna Loa, Juvik and Perreira (1973) demonstrated that intercepted
fog water comprised a substantial fraction of total precipitation, especially during drier summer months at elevations between 1,500-2,500 m. This “fog drip” phenomenon is not measured in traditional rain gauges and could explain why māmane growth did not respond to rainfall alone. Māmane trees growing near the forest line at Puʻu Laʻau could be limited by a combination of temperature and the timing of moisture availability. Unlike temperate regions, where water is readily available in spring/summer, Puʻu Laʻau gets most its annual rainfall in the winter (Scowcroft 1983), when temperatures are too low for optimal growth. To test this, I recommend running a generalized linear model (GLM) using rainfall as well as the additional variables that determine fog precipitation: temperature, cloud cover, and wind speed. These data are typically available as daily and monthly averages based on models on a coarse spatial scale, so there will be some challenge in acquiring multi-decadal time series on a fine enough spatial scale.

Dendrochronology at a new site, especially one in the tropics, often involves a great deal of troubleshooting. One of the main challenges to dating our larger māmane samples was non-concentric stem shape and “wedging,” or inconsistency of ring widths in the same year’s growth (Worbes 2002). In many cases, I could bypass sections of the tree rings that displayed wedging and create a tree ring series from non-disturbed portions of the wood. This is known as the “broken radius” approach, and has led to success in studies in the neotropics (Worbes 2002). Rings that did not span the entire circumference of the sample were also apparent in many samples regardless of size and shape. These “false rings” do not represent a year’s growth and can therefore lead to errors in assigning calendar years. To minimize the inclusion of false rings in our chronology, we traced every ring around the entire circumference of each sample before marking it as a true ring. This became increasingly difficult and time consuming in samples exceeding 40 cm diameter, and there was an added difficulty of severe distortion of the
innermost rings. Palmer and Cook (2017 personal communication) suggested troublesome resins and tannins as the culprit for this distortion and recommended the use of paint thinner. However, the use of turpentine as a solvent did little to increase ring boundary resolution, and only the outermost sections of these larger samples tended to produce reliable ring series.

In addition, while our sample size was relatively small, our results provided no evidence that māmane trees reach ages greater than approximately 200 years. In the previous study, median $^{14}$C calibrated age of māmane samples from Pu‘u La‘au for 8 trees ranged from 114-180 years (Francisco et al. 2015). Although there was high variability associated with these age estimates, this corroborates with our results and suggests that datable dead māmane samples in the study area are relatively young (<200 y).

**CONCLUSION**

Previous research on Hawai‘i Island has shown that younger māmane (<100 y) from Pōhakuloa Training Area demonstrate annual ring formation that reflects rainfall from August of the previous year (Francisco et al. 2015). However, our findings suggest that while older māmane (>100 y) at Pu‘u La‘au form annual rings (as evidenced by high r-values in the chronology), we did not observe the expected rainfall-limited growth-climate relationship. The māmane chronology common signal strength, as indicated by the dendroclimatic indicators RBAR and EPS, was strongest from 1940-1960. This reflects a possible “ungulate signal” remaining in the chronology despite detrending in ARSTAN. The localized weather patterns at the study site pose a challenge when acquiring reliable time-series climate data. The only local time series we had at our disposal was for rainfall. However, the results and existing literature suggest that māmane growth at Pu‘u La‘au is not limited by rainfall, and it is worthwhile to examine if these trees may instead be limited by temperature and fog drip. To test this, I strongly
recommend that future efforts focus on finding and using data for temperature, cloud cover, solar radiation, and wind speed in a Generalized Linear Model. The results from my study indicate that while the growth-climate relationship of māmane at Pu‘u La‘au is unclear, the tree rings from this species do seem to tell a story of complex climate and land-use interactions in the subalpine woodlands of Mauna Kea.
**Table 1.** Characteristics of the three sites used in this study. Rainfall data taken from rain gauge data provided in the Rainfall Atlas of Hawai‘i (Giambelluca et al. 2013). Substrate age is based on the Geologic Map of the State of Hawai‘i (Sherrod et al. 2007).

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Annual Rainfall (mm)</th>
<th>Elevation (m)</th>
<th>Aspect</th>
<th>Substrate Age (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu‘u La‘au</td>
<td>490.4</td>
<td>2,200-2,785</td>
<td>West</td>
<td>~11 ka</td>
</tr>
<tr>
<td>Pu‘u Mali</td>
<td>705.5</td>
<td>2,170-2,370</td>
<td>North</td>
<td>~11 ka</td>
</tr>
<tr>
<td>Pōhakuloa Training Area</td>
<td>430.6</td>
<td>1,984</td>
<td>South</td>
<td>~200</td>
</tr>
</tbody>
</table>

**Table 2.** General summary statistics of the conifer (*Pinus radiata*, *Pinus jeffreyi*, *Cedrus deodara*) and *Sophora chrysophylla* tree-ring chronologies from Pu‘u La‘au on Mauna Kea, Hawai‘i.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Pu‘u La‘au Pine/Cedar</th>
<th>Pu‘u La‘au māmane</th>
</tr>
</thead>
<tbody>
<tr>
<td>time span</td>
<td>1927-2012 (86 y)</td>
<td>1830-2003 (173 y)</td>
</tr>
<tr>
<td>number cores (trees)</td>
<td>12(6)</td>
<td>44(20)</td>
</tr>
<tr>
<td>number of rings in series</td>
<td>483</td>
<td>2,365</td>
</tr>
<tr>
<td>median series length (y)</td>
<td>60.5</td>
<td>51.5</td>
</tr>
<tr>
<td>mean series intercorrelation</td>
<td>0.746</td>
<td>0.495</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.384</td>
<td>0.376</td>
</tr>
<tr>
<td>autocorrelation</td>
<td>-0.18</td>
<td>-0.16</td>
</tr>
<tr>
<td>mean sensitivity</td>
<td>0.404</td>
<td>0.386</td>
</tr>
</tbody>
</table>
Table 3. Spearman’s rank correlation coefficients relating māmane mean ring-width chronology and Pu’u La’au rainfall data from previous year’s July through current December.

<table>
<thead>
<tr>
<th>Site</th>
<th>Month</th>
<th>r-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu’u La’au</td>
<td>prev_August</td>
<td>-0.21</td>
<td>0.055</td>
</tr>
<tr>
<td>Pu’u Mali</td>
<td>July</td>
<td>0.25</td>
<td>0.021</td>
</tr>
<tr>
<td>Pōhakuloa</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4. Rain gauge metadata from the Rainfall Atlas of Hawai‘i (Giambelluca et al. 2013).

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat_DD</th>
<th>Long_DD</th>
<th>Elevation (m)</th>
<th>Observer</th>
<th>Min Year</th>
<th>Max Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu’u La’au</td>
<td>19.83195</td>
<td>-155.592</td>
<td>2,268</td>
<td>State Division of Forestry</td>
<td>1932</td>
<td>1977</td>
</tr>
<tr>
<td>Pu’u Mali</td>
<td>19.90722</td>
<td>-155.437</td>
<td>2,121</td>
<td>Kukaiau Ranch</td>
<td>1932</td>
<td>1976</td>
</tr>
<tr>
<td>PTA</td>
<td>19.74862</td>
<td>-155.526</td>
<td>1,984</td>
<td>State Division of Forestry</td>
<td>1938</td>
<td>1978</td>
</tr>
</tbody>
</table>
Table 5. Estimates of ring numbers and median calibrated $^{14}$C age (BP represents before 1950), calibrated age interval, and 95.4% confidence interval probability from OXCAL 4.0 for eight māmane (*Sophora chrysophylla*) cross-sections from Pu‘u La‘au, Hawai‘i.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Ring Number Estimate (yrs)</th>
<th>$^{14}$C Calibrated Age (median yrs BP)</th>
<th>Age Interval 1 (yrs BP), Probability (%)</th>
<th>Age Interval 2 (yrs BP), Probability (%)</th>
<th>Age Interval 3 (yrs BP), Probability (%)</th>
<th>Age Interval 4 (yrs BP), Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>118</td>
<td>180</td>
<td>133-225, 48.0</td>
<td>253-310, 26.7</td>
<td>(-4)-34, 17.2</td>
<td>73-115, 3.6</td>
</tr>
<tr>
<td>M5</td>
<td>112</td>
<td>126</td>
<td>9-151, 59.1</td>
<td>173-275, 36.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M10</td>
<td>95</td>
<td>173</td>
<td>124-231, 47.0</td>
<td>243-296, 18.6</td>
<td>(-3)-37, 17.6</td>
<td>65-119, 12.2</td>
</tr>
<tr>
<td>M11</td>
<td>89</td>
<td>114</td>
<td>11-150, 65.2</td>
<td>186-270, 30.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M13</td>
<td>105</td>
<td>114</td>
<td>11-150, 65.6</td>
<td>186-270, 29.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M15</td>
<td>122</td>
<td>106</td>
<td>20-145, 69.2</td>
<td>215-268, 26.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M16</td>
<td>102</td>
<td>114</td>
<td>11-150, 65.3</td>
<td>187-270, 30.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M17</td>
<td>110</td>
<td>152</td>
<td>166-285, 46.6</td>
<td>58-155, 31.8</td>
<td>(-2)-43, 16.9</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Raw tree-ring series ($n = 52$) and the series mean (red curve) from 20 cross sections of *Sophora chrysophylla* from Pu‘u La‘au, Hawai‘i.

Figure 2. Raw tree-ring series mean and detrended curve of a 173-y chronology (1830-2003) of *Sophora chrysophylla* from Pu‘u La‘au, Hawai‘i based on 20 cross sections (a). Number of samples used in chronology production (b).
Figure 3. Detrended RBar with a 20-y window and 19-y overlap. Expressed Population Signal (EPS) values of a 173-y chronology (1830-2003) of Sophora chrysophylla from Pu‘u La‘au, Hawai‘i based on 20 cross-sections.
Figure 4. Mean monthly rainfall taken from rain gauge data at Pu’u La’au, Pu’u Mali, and Pōhakuloa Training Area (PTA) on Hawai‘i Island. Values are extrapolated from the Rainfall Atlas of Hawai‘i (Giambelluca et al. 2013).
Figure S1. Correlation field comparing māmane ring width chronology to the wind speed in September of the previous year. Twentieth Century Reanalysis V2c 1851-2011.
Figure S2. Correlation field comparing māmane ring width chronology to wind speed in November of the previous year. Twentieth Century Reanalysis V2c 1851-2011
Figure S3. Correlation field comparing māmane ring width chronology to net surface shortwave radiation in September of the previous year. NCEP/NCAR R1 1948-now.
Figure S4. Correlation field comparing māmane ring width chronology to net surface shortwave radiation in October of the previous year. NCEP/NCAR R1 1948-now.
LITERATURE CITED


