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Reconstruction of seasonal precipitation in Hawai'i using high-resolution carbon isotope measurements across tree rings

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ABSTRACT

Determination of carbon isotope ($\delta^{13}C$) values of tree-ring tissue is a well-established method to reconstruct past climate variability at annual resolution, but such records are limited in tropical latitudes due to the lack of well-defined annual growth bands. Recent work has demonstrated the potential for high-resolution, intra-ring $\delta^{13}C$ records to help define ring boundaries in tropical environments and provide additional climate information at sub-annual resolution. Here we present a high-resolution, intra-ring carbon isotope ($\delta^{13}C$) record of the Hawaiian endemic species *Sophora chrysophylla* (also known as "māmane") in order to assess the ability to extract seasonal climate information from these drought tolerant trees. Tree cores were sampled from high-elevation māmane trees growing on the west side of Mauna Kea, Big Island. Across our entire dataset (1986–2008), we identified a notable decreasing linear trend in the $\delta^{13}C$ record of 0.061‰/year that can be attributed to changes in the $\delta^{13}C$ value of atmospheric CO_2 and pCO_2 concentration associated with fossil fuel burning. Correcting for these affects yields a nearly flat $\delta^{13}C$ record with a slope of −0.0075‰/year, suggesting no long-term trends in climate across the study period. We observe a quasi-periodic change in the $\delta^{13}C$ values [$\Delta(\delta^{13}C)$] measured within each ring that averages 1.09 ± 0.50‰ ($\pm 1\sigma$, $n = 23$) in amplitude. These variations are interpreted as the intra-annual isotopic signal in tree photosynthesis. The $\delta^{13}C$ variability correlates with the visible ring structure of the sample, suggesting the presence of annual growth rings at this tropical high elevation site.

We applied these data to a model that relates the $\Delta(\delta^{13}C)$ value to seasonal changes in precipitation in order to reconstruct annual changes in total summer (May through October) and winter (November through April) precipitation at the site. Across the 23-year record (1986–2008; $n = 579$ $\delta^{13}C$ measurements), reconstructed values for the ratio of summer to winter precipitation, total summer precipitation, and total winter precipitation correlate well with rainfall data collected from a nearby weather station ($r = 0.65$, 0.36, and 0.70, respectively). These results support application of this model to reconstruct inter-annual changes in seasonal precipitation from long-term tree-ring chronologies. They also demonstrate the potential of using māmane $\delta^{13}C$ for future long-term climate reconstructions.

1. Introduction

Stable isotope measurements of tree-ring tissue have shown great potential for reconstructing past climate conditions at annual resolution (Gagen et al., 2007; Kirdyanov et al., 2008; Knorre et al., 2010; Konter et al., 2014; Loader et al., 2010; Loader et al., 2008; Loader et al., 2013; Naulier et al., 2014; Seftigen et al., 2011). New methods for high-resolution sampling across tree rings have allowed for unprecedentedly high-resolution intra-annual stable isotope records (e.g., Dodd et al., 2008; Helle and Schleser, 2004; Schollaen et al., 2014; Schulze et al., 2004) and yielded information not apparent within annually sampled records (e.g., Barbour et al., 2002; Schubert and Jahren, 2011). High-resolution sampling has shown potential for identifying annual growth rings in tropical tree species (Anchukaitis et al., 2008; Fichtler et al., 2010; Pons and Helle, 2011; Schleser et al., 2015) and identifying seasonal events such as tropical cyclones (Li et al., 2011; Miller et al., 2006) and El Niño years (Verheyden et al., 2004). However, high-resolution proxy reconstructions of past precipitation variations from the Pacific Islands are lacking. Understanding the range of naturally induced rainfall variability in this region that is rich in endemic plant (e.g., Price, 2004) and animal (e.g., Case, 1996) species, and is particularly vulnerable to projected human-induced climate change (Benning et al., 2002; Duffy, 2011; Lal et al., 2002), is crucial. Here we present high-resolution, intra-ring $\delta^{13}C$ data across the unique nitrogen fixing and drought-resistant tree, māmane (*Sophora chrysophylla*), which provides the main habitat for endangered palila birds (*Loxioides bailleui*) (Banko et al., 2002; Banko and Farmer, 2014). The wide geographical and environmental extent of māmane, which spans from near sea level to the high-elevation tree line in Hawai'i (Little and Skolmen,

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1989), makes it an excellent species for reconstructing past precipitation variations in the region.

A previous analysis of a global dataset of high-resolution, intra-ring $\delta^{13}C$ data produced a model for quantifying the long-term average seasonal precipitation from a mix of angiosperm and gymnosperm evergreen trees (Schubert and Jahren, 2011). This dataset included limited high-resolution, intra-ring $\delta^{13}C$ data from a māmane tree growing on the upper slopes of Mauna Kea, Hawai'i and were used simply to calibrate the model. Here we expand this dataset to 579 $\delta^{13}C$ measurements across 23 tree rings to produce the first proxy reconstruction of year-to-year changes in total 6-month summer (P_s; May, June, July, August, September, and October) and total 6-month winter (P_w; November, December, January, February, March, and April) precipitation (as defined within Schubert and Jahren, 2011). The high correlation between the actual precipitation data and our reconstructed values demonstrates potential for using māmane to reconstruct long-term records of seasonal precipitation in the Hawaiian Islands.

2. Methods

The main stems of māmane trees growing on the upper slopes of Mauna Kea on the island of Hawai'i (19.83° N, 155.60° W, elevation = 2100 m) (Fig. 1A) were cored at breast height in January 2010. Growth rings representing the years 1986 through 2008 were identified by counting the tree rings within core MKM04A, which showed particularly well-defined ring anatomy (Fig. 1B). Core MKM04A was subsampled by hand using a razor blade in order to precisely follow the ringed anatomy of the wood (Fig. 1B). The slices were cut parallel to the growth bands at a median sampling resolution of 110 μm (measured with a micrometer); a total of 579 subsamples were collected across 23 years of growth (average of ~25 subsamples per growth band). We judiciously sampled at this resolution in order to obtain ~90% of the seasonal intra-ring signal (see Figure 5 within Schubert and Jahren, 2011). Growth rates were not measured for this study; therefore, linear growth within each ring was assumed for all analyses. Bulk wood subsamples were weighed into tin capsules and $\delta^{13}C$ values were determined using a Costech ECS 4010 Elemental Analyzer (Costech Analytical, Valencia, CA, USA) in conjunction with a Thermo Delta V isotope ratio mass spectrometer (Thermo Scientific, Bremen, Germany). Samples were analyzed with two internal lab reference materials (JGLUT, $\delta^{13}C = -13.43‰$; JGLY, $\delta^{13}C = -43.51‰$) and a quality assurance sample (JRICE, $\delta^{13}C = -27.37‰$) that was analyzed as an unknown. All three materials had been previously calibrated and normalized to the VPDB scale using LSVEC and NBS-19 (Schubert and Jahren, 2012). Over the course of all analyses, the JRICE quality assurance sample averaged $-27.35 \pm 0.06‰$ (1σ, $n = 47$), which is in agreement with our calibrated value.

The site is characterized as having a temperate climate with a warm and dry summer ("Csa" Köppen–Geiger climate classification) (Peel et al., 2007). Local monthly climate data are available from nearby weather stations at Pu'u La'au (precipitation) and Bradshaw Army Airfield (AAF) (temperature) (Fig. 1A). Temperature data at Bradshaw AAF were limited to the years 1979–1990, while precipitation records for Pu'u La'au, downloaded from the Online Rainfall Atlas of Hawai'i (Giambelluca et al., 2013), extended from 1920 to 2007. Here we focus only on the precipitation data from 1986 to 2007 in order to match the period of our tree-ring record. Calculated mean annual precipitation (MAP) across this interval is 522 mm (Fig. 2A) and average monthly temperatures span a narrow range from 11.6 °C in February

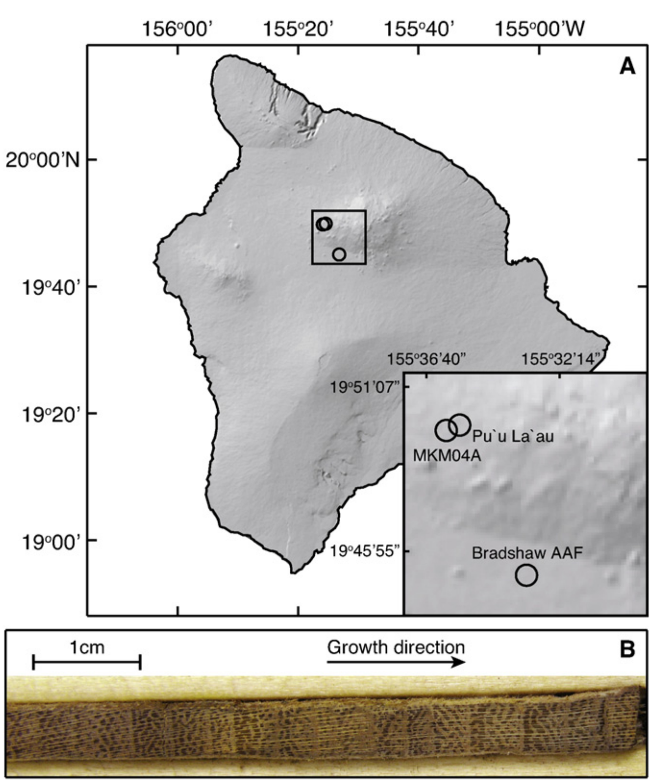

Fig. 1. (A) Digital elevation model of the island of Hawai'i showing the locations of the cored māmane tree (MKM04A) and the Pu'u La'au (precipitation) and Bradshaw Army Airfield (Bradshaw AAF; temperature) weather stations. (B) Photograph of the sampled core showing the growth bands.

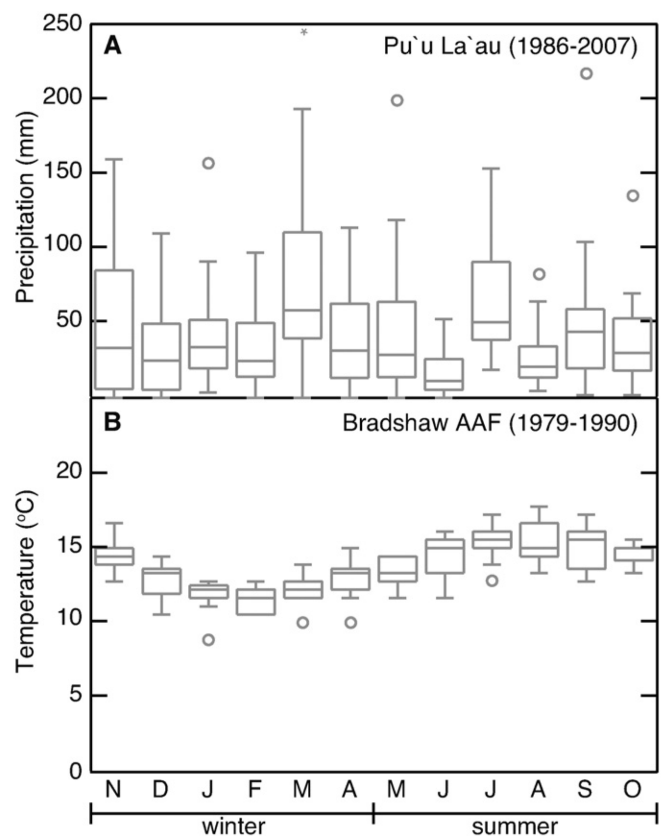

Fig. 2. Box plots showing monthly precipitation and temperature data from Pu'u La'au (1986–2007) (Giambelluca et al., 2013) and Bradshaw Army Airfield (1979–1990) (USAFETAC, 1990), respectively. (A) Monthly precipitation is highly variable from year to year and shows no clear intra-annual trends. Average winter precipitation (P_w) was 288 mm and average summer precipitation (P_s) was 234 mm. A single monthly value of 419 mm (March, 1998) is marked with an asterisk. (B) Due to the tropical latitude of the site, temperature changes throughout the year are small (only a 3.9 °C change in mean monthly temperatures throughout the year), ranging from a mean monthly temperature of 11.6 °C in February to 15.5 °C in August.