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Cellulose oxygen isotopic composition of teak (*Tectona grandis*) collected from Java Island: a tool for dendrochronological and dendroclimatological analysis

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A R T I C L E I N F O

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A B S T R A C T

The oxygen isotopic composition ($\delta^{18}O$) of tree-ring cellulose has been recognized as a powerful tool for dendroclimatological and dendrochronological investigations in Asia. Only a few studies of cellulose $\delta^{18}O$ so far published, however, have been conducted in Indonesia, and the spatial coherence of cellulose $\delta^{18}O$ has yet to be clarified. In this study we measured cellulose $\delta^{18}O$ of teak (*Tectona grandis*) collected from four sites on Java Island to evaluate the similarity between the different teak $\delta^{18}O$ values and the potential for using teak $\delta^{18}O$ both as a climate proxy and as a tool for cross-dating. Cellulose $\delta^{18}O$ time series of Javanese teaks were found to be significantly correlated in all of the comparisons between sites, even between sites separated by a distance as great as 400 km. While significant correlations did not appear in the ring width data between our samples (expressed population signal (EPS) = 0.64; Rbar = 0.23; sample depth = 10), they were found between the cellulose $\delta^{18}O$ values (EPS = 0.89; Rbar = 0.58; sample depth = 10). These results suggest that teak $\delta^{18}O$ variations have higher spatial coherence and might be a useful tool for cross-dating. A significant negative correlation was observed between cellulose $\delta^{18}O$ and the relative humidity/precipitation during the rainy season, indicating that the cellulose $\delta^{18}O$ of Javanese teak is an effective proxy for relative humidity/precipitation during the rainy season. Cellulose $\delta^{18}O$ was found to be positively correlated with precipitation during the dry season preceding the growing season, whereas it showed no correlations with the temperature and Palmer Drought Severity Index (PDSI), the key constraints of $\delta^{18}O$ on the Indochina Peninsula.

1. Introduction

Java Island is a densely populated region that suffers droughts and floods brought by monsoons related with El Niño-Southern Oscillation (ENSO) or the Indian Ocean dipole mode almost every year (D'Arrigo and Smerdon, 2008). Elucidating and predicting annual monsoon variability requires reliable information related to past monsoon activity. Acquiring such information can be difficult, however, as instrumental climate data in this region are spatially and temporally limited. Any elucidation of ancient monsoon activity requires proxy climate records of high resolution spanning long periods of time. Several groups have sought to collect such records by conducting dendroclimatic studies using teak (*Tectona grandis*) on Java Island (DeBoer, 1951; D'Arrigo et al., 1994; Poussart et al., 2004; D'Arrigo et al., 2006; Schollaen et al., 2013).

A master ring width chronology for teak in central Java was first

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published in the 1930s (Berlage, 1931) and has since been updated in more recent studies (D'Arrigo et al., 1994, 2006; Bijaksana et al., 2007; Cook et al., 2010; Schollaen et al., 2013). The ring width of teak is closely related to precipitation during the dry season preceding the growing season (DeBoer, 1951; D'Arrigo et al., 1994; Schollaen et al., 2013) and highly correlated with the Palmer Drought Severity Index (PDSI; Palmer, 1965) of the previous dry season (D'Arrigo et al., 2006). Upon finding this latter relation between the ring width of teak and PDSI, D'Arrigo et al. (2006) used it to reconstruct the monsoon drought over Java.

The oxygen isotopic composition ($\delta^{18}O$) of tree-ring cellulose has been investigated as a water environment proxy similar to precipitation or relative humidity during the growing (rainy) season. Trees take up soil water at their roots with no isotopic fractionation and transport it to leaves through xylem. The $\delta^{18}O$ of leaf water is influenced by transpiration, as expressed by the Craig-Gordon equation with a number of assumptions (Craig and Gordon, 1965; Dongmann et al., 1974; Nakatsuka, 2007; Sano et al., 2012):

$$\delta^{18}O_{leaf\ water} = \delta^{18}O_{xylem\ water} + (\varepsilon^* + \varepsilon_k)(1 - RH)$$

where RH is relative humidity, ε^* is the equilibrium fractionation factor associated with the liquid-to-vapor phase change, and ε_k is the kinetic isotope fractionation factor related to vapor diffusion. Tree-ring cellulose is synthesized from photosynthetic sugar, and its $\delta^{18}O$ is affected by two factors. The first is biochemical fractionation associated with the synthesis of photosynthetic sugar (sucrose) using leaf water. The second is the exchange of oxygen isotope between sugar and xylem water before cellulose synthesis. The following equation expresses the two processes together (Roden et al., 2000):

$$\delta^{18}O_{cellulose} = f(\delta^{18}O_{xylem\ water} + \varepsilon_o) + (1 - f)(\delta^{18}O_{leaf\ water} + \varepsilon_o)$$

where f refers to the fraction of oxygen exchanged between sugar and xylem water, and ε_o is the biochemical fractionation factor. Overall, the $\delta^{18}O$ of tree-ring cellulose is mainly controlled by the $\delta^{18}O$ of soil water and relative humidity. The $\delta^{18}O$ of soil water has been found to be related to precipitation, as the $\delta^{18}O$ of rainfall exhibits a negative correlation with precipitation, or what is known as the "amount effect" (Dansgaard, 1964; Kurita et al., 2009). Thus, cellulose $\delta^{18}O$ is also affected by precipitation.

Previous studies using teak $\delta^{18}O$ in the Asia monsoon area presented correlations with precipitation, PDSI, relative humidity, and temperature (Poussart et al., 2004; Managave et al., 2011; Schollaen et al., 2013; Buajan et al., 2016). Managave et al. (2011) reported a correlation between teak $\delta^{18}O$ in India with precipitation. Five years later, Buajan et al. (2016) found that teak $\delta^{18}O$ in Thailand was related to PDSI, precipitation, relative humidity, and temperature. A number of reports have described tree-ring $\delta^{18}O$ records of Java Island in Indonesia. Poussart et al. (2004) built a tree-ring $\delta^{18}O$ record spanning the period 1950–1990 from two teak cores collected from Saradan in eastern Java. Their inter-annual $\delta^{18}O$ time series was highly reproducible and suggested common climate factor controls over cellulose $\delta^{18}O$ variation in Javanese teak. Schollaen et al. (2013) established a $\delta^{18}O$ chronology using seven teak tree cores collected from the eastern part of central Java spanning the period from 1900 to 2007. Their findings demonstrated that teak $\delta^{18}O$ was positively correlated with precipitation during the dry season before the growing season and negatively correlated with precipitation during the rainy season. Schollaen and her colleagues presented teak $\delta^{18}O$ variations at only one location on Java Island. Although these previous studies highlighted that $\delta^{18}O$ could serve as a proxy for precipitation using teak samples collected from a limited area of Java Island (central Java), the spatial coherence among teak $\delta^{18}O$ values over Java Island has not been clarified. In this study we analyzed teak $\delta^{18}O$ from four new sites on Java Island in order to explore the spatial features of $\delta^{18}O$ over the whole of the island. We also sought to identify the key drivers controlling $\delta^{18}O$ variability at each station by conducting a correlation analysis with meteorological data (temperature, relative humidity, precipitation, and PDSI).

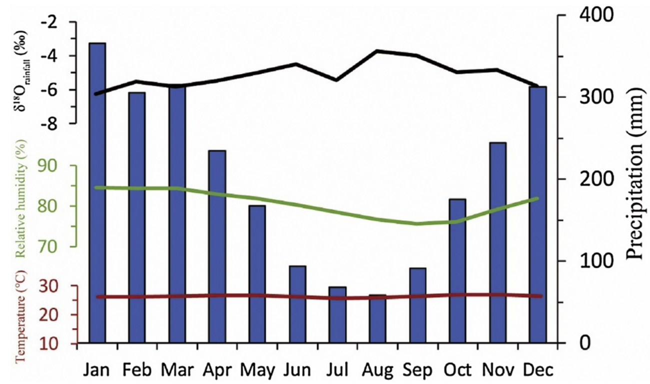

Fig. 1. Mean monthly (1961–1995) temperature, precipitation, and relative humidity from Java (CRU TS 3.23 area average (10°S–5°S, 105°E– 15°E)). Mean monthly oxygen isotopic composition in rainfall at Jakarta (obtained from the Global Network of Isotopes in Precipitation).

2. Materials and methods

2.1. Study sites and teak samples

The tropical monsoon climate of Java is characterized by a seasonal cycle of precipitation (a rainy season) from November to April and a dry season from May to October (Fig. 1). The temperature of the island remains almost constant throughout the year, while the relative humidity cycles between high during the rainy season and low during the dry season (Fig. 1). The $\delta^{18}O$ of rainfall also exhibits distinct seasonality, alternating from peak levels in the dry season to nadir levels in the rainy season (Fig. 1; Kurita et al., 2009).

Teak is a deciduous tree that grows only in the rainy season and sheds leaves in the dry season. The wood of the tree is a semi-ring-porous type with rings defined by an initial parenchyma band with large vessels. Our group collected ten teak disk samples from four plantations on Java Island, Indonesia for this research (Fig. 2). Two of the sampling sites were located in the western part of Java (Indramayu, Sumedang); the other two, in the eastern part (Cepu, Madiun). The samples were collected exclusively from the four plantations, all of which seemed to have similar growth environments. The number of tree rings in the ten samples collected ranged from 24 to 72. The harvested and girdled dates are known for every sample (Table 1).

2.2. Ring width measurement and cross-dating

Disk samples were scanned at 1200 dpi after the surfaces were polished with a belt sander or electric planer. The ring width was measured using imaging software (W. S. Rasband, ImageJ, U.S. National Institutes of Health, Bethesda, Maryland, USA). To adjust for uneven radial growth, the ring width data were obtained by measuring the ring width along four radii per disk and then averaging the values. The samples were dated by ring counting based on careful observation to detect locally absent rings (Stokes and Smilley, 1968) and false rings. Additionally, the ring width time series were compared with the master chronology to detect false rings. Each cross-dating was verified using statistical tests (t-test and Gleichläufigkeit (GLK); Schweingruber, 1988 and Speer, 2010) with the master chronology. To prepare for the cross-dating and statistical testing, the ring width data were transformed to index values following the steps described below. The individual ring width data were fitted to a 32-year cubic smoothing spline for standardization after natural logarithmic transformation. Ring width indices were calculated as ratios between the logarithmic transformed