OXYGEN ISOTOPE (δ^{18}O) OF TEAK TREE-RINGS IN NORTHWEST THAILAND

S Buajan[1], N Pumijumnong[2, *], Q Li[3] & Y Liu[3]

[1]*College of Forestry, Fujian Agriculture and forestry University, Fujian 350002, China*
[2]*Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170,Thailand*
[3]*Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China*

**nathsuda@gmail.com*

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BUAJAN S, PUMIJUMNONG N, LI Q & LIU Y. 2016. Oxygen isotope (δ^{18}O) of teak tree-rings in northwest Thailand. We investigated the relationship between the oxygen isotopes in teak (*Tectona grandis*) tree-ring cellulose and climatic factors, i.e. rainfall, temperature and relative humidity. Four cores of teak from northwest Thailand were used to analyse the oxygen isotope values in α-cellulose. The oxygen isotopic composition of teak tree-ring α-cellulose ranged from 21.38‰ to 25.58‰. The mean tree-ring α-cellulose δ^{18}O values and standard deviations were 23.4 ± 0.7‰. The δ^{18}O value was positively correlated with rainfall in the February to April dry season ($r = 0.234$, $p < 0.5$) and negatively correlated with total rainfall ($r = -0.350$, $p < 0.01$), average rainfall ($r = -0.321$, $p < 0.01$) and relative humidity ($r = -0.282$, $p < 0.05$) in the late rainy season. The δ^{18}O values were negatively correlated with the annual mean Palmer Drought Severity Index (PDSI) from 1948 to 2005 ($r = -0.491$, $p < 0.001$) based on the mean of 4 grids. Oxygen isotope values in the α-cellulose of teak from northwest Thailand were significantly related to the hydrological cycle in these areas.

Keywords: α-cellulose, PDSI, hydrological cycle, wood cellulose, teak tree-rings

INTRODUCTION

Oxygen isotope values in α-cellulose can be used to analyse past climates. Oxygen isotope (δ^{18}O) ratios of tree-ring cellulose are related to climatic conditions such as temperature, relative humidity, and especially precipitation (Burk & Stuiver 1981, Edwards & Fritz 1986, Yakir et al. 1993, Lipp et al. 1996, Saurer et al. 1997, Anderson et al. 1998, Roden et al. 2000, Robertson et al. 2001, Treydte et al. 2006). A portion of the water acquired by trees comes from precipitation. Tree roots uptake water from soil, and evaporation of water from leaves during transpiration is important for determining the oxygen isotopic ratios in tree-rings (McCarroll & Loader 2004). Thus, oxygen isotope ratios in wood reflect climatic conditions.

Many researchers have studied oxygen isotopes in cellulose, related to climates (Gray & Thompson 1976, Anderson et al. 2002, Saurer et al. 2002, Liu et al. 2004, Battipaglia et al. 2008, Roden et al. 2005). Oxygen isotopes have been studied in cellulose of fossil wood (Richter et al. 2008) and comparisons made between wood and cellulose (Ferrio & Voltas 2005, Szymczak et al. 2011). Most previous studies were made in high latitude regions. Research on isotopes in low latitude tree species is less common, because these species usually lack clear growth ring structure. However, a few species with clear tree rings do occur in tropical areas and one of these is teak (*Tectona grandis*). Pumijumnong et al. (1995) studied teak tree-ring width in relation to climate data in Thailand and found that teak growth correlated with rainfall during the first half of the wet season (April–July). Buckley et al. (2007) studied teak trees from Mae Hong Son province and found that teak tree-ring widths correlated with the length of drought period. Ram et al. (2008) demonstrated that teak tree-ring series from India could be used as high resolution proxy for past precipitation and moisture levels. Borgaonkar et al. (2010) examined teak from India and related growth to the El-Niño weather phenomena. There have been several tree-ring isotope studies conducted in Thailand (Poussart et al. 2004, Poussart &

Schrag 2005, Ohashi et al. 2009, Zhu et al. 2012a, Xu et al. 2015). However, no studies have so far been conducted on Thai teak cellulose. Moreover, palaeoclimatic data in Thailand and other countries in South-east Asia are needed to better understand past climate variability.

In this study, we used teak from the Mae Hong Son province in northwest Thailand to study oxygen isotopes in tree-ring cellulose. We investigated the relationship between the oxygen isotope ratio in tree-ring cellulose and both local and global climatic variables. We hypothesised that variation in the oxygen isotopes of teak tree-ring cellulose were correlated with hydroclimatic parameters and differed from the teak tree-ring index.

MATERIALS AND METHODS

Sampling site and local climate

Samples were collected from Mae Hong Son province in northwest Thailand, about 940 km north of Bangkok. The study site is located in the Pai wildlife sanctuary which is a mountainous region along the Kong River (19° 26' N, 98° 8' E) (Figure 1). The sanctuary has a large population of teak that escaped from the forest concessions. The elevation of study site ranged from 500–600 m above sea level (m asl).

A total of 30 trees were sampled with preference given to the oldest and largest trees for core samples. Core samples were taken at breast height 1.30 m using a 5 mm diameter increment borer for age determination and ring-width measurement. Samples were collected in January 2010 which is the dry season in Thailand. The soil moisture content in the study area ranged from 16.2 to 42.7%. Meteorological data from the Mae Hong Son station (19° 18' N, 97° 50' E) provided rainfall (1950–2009), relative humidity, and temperature (1954–2009) data. The station is located about 40 km from the sample site. The mean annual rainfall was 1265 mm during the observation period. Rainfall was the highest in August (254 mm) and lowest in February (5 mm). Mean annual temperature was 26.7 °C (Figure 2a). Variations in mean temperature and total precipitation during the rainy monsoon season (May–October) are illustrated in Figure 2b. Mean temperatures in the study area showed an increasing trend, since the 1970s. Negative correlations between temperature and precipitation ($r = -0.265$, $p < 0.02$, $n = 56$) and between temperature and relative humidity ($r = -0.411$, $p < 0.001$, $n = 56$)

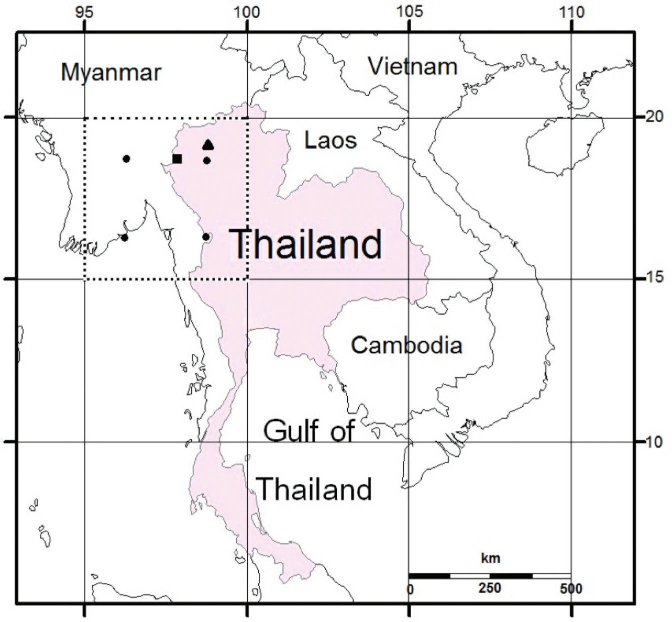

Figure 1 Map of the study area; black triangles (▲) = sampling locations, black square (■) = meteorological station, black dots (●) = four Palmer Drought Severity Index (PDSI, Dai et al. 2004) grid points and dash line (····) = the area covered by four grid points

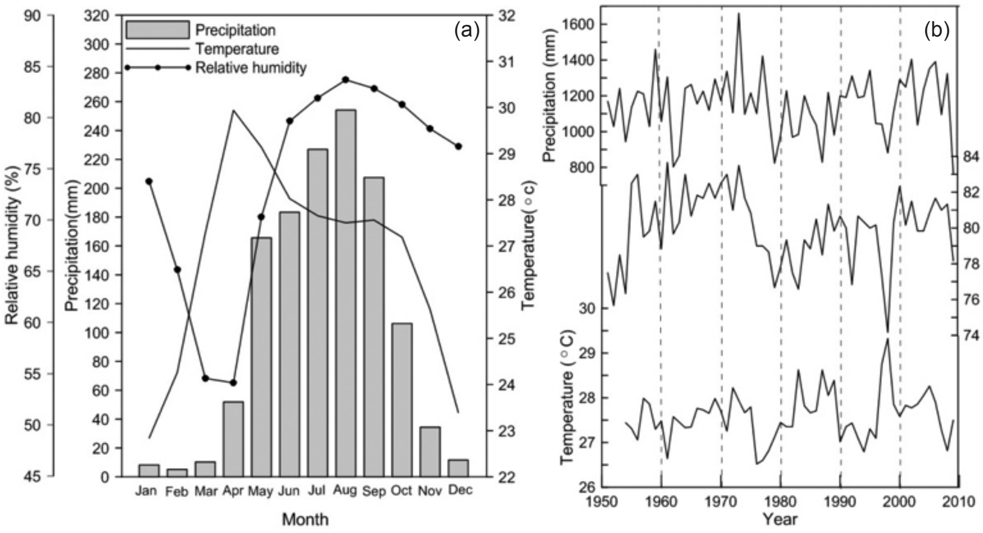

Figure 2 Rainfall and relative humidity records at the Mae Hong Son meteorological station (1951–2009), temperature data were from 1954–2009; (a) = monthly mean precipitation and temperature and (b) = inter-annual variations of total precipitation, mean temperature and mean relative humidity during the rainy monsoon season (May–October)

have also been documented. It is obvious that relative humidity is positively correlated with precipitation ($r = 0.604$, $p < 0.001$, $n = 59$).

The study site is located on the mainland. Thailand is influenced by two monsoon periods. The southwest monsoon brings moisture from the Indian Ocean and Andaman Sea. This occurs from May to October, and the rainfall covers more than 80% of the mainland. The following northeast monsoon brings cold air masses from China mainland through Thailand. At the same time, interaction between the Indian monsoon and the East Asian summer monsoon, including South China Sea, provides moisture for rainfall to remote areas through teleconnection (Ding & Chan 2005). Thailand is under East Asian monsoon influence during the latter part of rainy season (September–October). This combination of rainfall/moisture sources has the greatest influence on teak growth and variations of teak oxygen isotopes.

Cross-dating

For this study two cores from each of 30 teak trees were measured using TSAP-Win program (Rinn 2005). Cross-dating was conducted exclusively on the light table with plotted raw tree-ring series with cores under a binocular microscope and confirmed with the COFECHA program (Holmes 1992). The Arstan program was used for fitting a 66-year spline function to each tree-ring series to eliminate the age trend (Cook 1985). Dendroclim 2002 was used to calculate the relation between the teak index and climate data (Biondi & Waikul 2004). The raw tree-ring series was well synchronised.

Sample preparation and cellulose extraction

Four cores from each of 4 trees, judged to be of relatively equal age, were sampled for isotope analysis. The tree-ring records spanned from AD 1890 to 2009, a period of 119 years. Whole annual rings were used, including earlywood and latewood. Each annual ring of sample cores was split into thin sections with a scalpel. Rings from different cores and different trees (for each year) were combined because of logistic constraints. α-cellulose was extracted from the combined thin sections of the same ring using a 3 step process. A 1:1 mix of toluene-ethanol was first used to remove resins in the sample. Then a 1:1 solution of sodium chlorite ($NaClO_2$) and acetic acid (CH_3COOH) was used to remove lignin. Finally, the hemicellulose component was removed through washing with sodium hydroxide (NaOH) to produce homogeneous α-cellulose which was washed thoroughly and dried prior to analysis. α-cellulose was extracted by a modified Jayme-Wise method (Green 1963, Leavitt & Danzer 1993, Loader et al. 1997). For $\delta^{18}O$ measurements, 2 replicate samples, each containing 120–140 µg of α-cellulose, were loaded into silver capsules which were manually crimped to exclude air. Cellulose $\delta^{18}O$ was then determined using a continuous flow system with a pyrolysis-type elemental analyser at 1350°C connected to a mass spectrometer via open split interface. The standard deviation for repeated analysis of standard material was 0.2‰. The oxygen isotope ratios were expressed as $\delta^{18}O$, representing per mil deviation relative to Vienna Standard Mean Ocean Water (VSMOW) as:

$$\delta^{18}O\ (‰)$$

where $\delta^{18}O = \{[R_{sample}/R_{standard}]-1\} \times 1000$ and $R = {}^{18}O/{}^{16}O$. The value of the oxygen isotope ratios were obtained as the mean of duplicate analyses on individual annual tree-ring cellulose samples. The laboratory work was conducted at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China.

RESULTS AND DISCUSSION

By pooling, a $\delta^{18}O$ time series from 4 sample cores were obtained. The measured tree-ring α-cellulose $\delta^{18}O$ values of teak from 1890 to 2009 is shown in Figure 3. The oxygen isotope composition of tree-ring α-cellulose ranged from 21.38‰ to 25.58‰. The mean tree-ring cellulose $\delta^{18}O$ value was 23.4 ± 0.07‰, which was lower than teak from India (Managave et al. 2011) but higher than teak in Indonesia (Poussart et al. 2004, Schollaen et al. 2013). The variation of $\delta^{18}O$ in precipitation resulted from six major factors, i.e. latitude, altitude, continental, amount effects, seasonality and local temperature (Dansgaard 1964). Feng et al. (2009), using global climate models, concluded that atmospheric circulation patterns affect seasonal cycles of isotopes in precipitation. Lekshmy et al. (2014) analysed 654 samples of daily rain at 9 stations in south India and demonstrated that relatively higher ^{18}O-depletion in monsoon rain is unrelated to rainfall amount but rather to large scale convection.

Oxygen isotope and climatic factors

Correlation analysis was carried out on climatic factors, i.e. total monthly rainfall, average monthly temperature and average monthly relative humidity at the Mae Hong Son meteorological station. The correlation between the monthly data sets with $\delta^{18}O$ values of tree-ring cellulose for rainfall and relative humidity (1951–2009)and temperature was (1955–2009) was determined. Correlation coefficients (r) for rainfall, temperature and relative humidity for the current years are shown in Figure 4. The $\delta^{18}O$ tree-ring cellulose values showed significant positive correlation with rainfall occurring in the February to April dry season ($r = 0.234$, $p < 0.05$, mean monthly rainfall = 25.1 mm), but weak correlation with the November to January driest months (mean monthly rainfall = 8.8 mm), and significant positive correlation with temperature in August ($r = 0.236$, $p < 0.05$). There was significant negative correlation with rainfall and

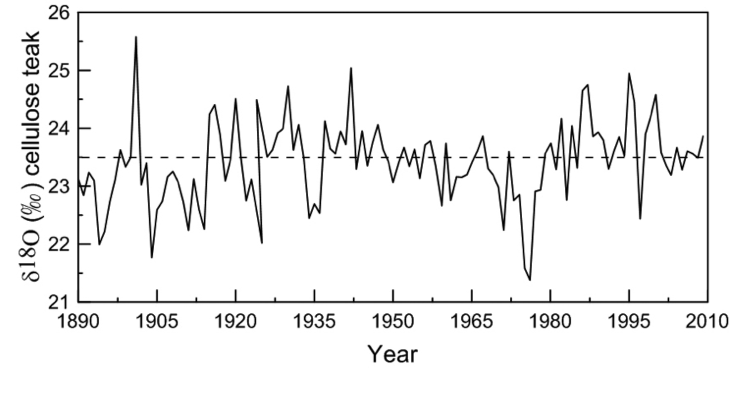

Figure 3 Annual variations of tree-ring cellulose $\delta^{18}O$ of teak between 1890–2009, black dashed line (---) = mean of tree-ring cellulose $\delta^{18}O$ of 23.5‰

relative humidity in August ($r = -0.233, -0.248$, $p < 0.05$) and September ($r = -0.260, -0.266$, $p < 0.05$). Thailand monsoon rains extended from May to October (M–O). The monsoon was divided into early rainy season, May to July (MJJ) and late rainy season, August to October (ASO). The correlation coefficients (r) between monsoon rainfall and $\delta^{18}O$ values of tree-ring cellulose are shown in Table 1 and Figure 4. The results of this study were different from Pumijumnong et al. (1995) and Pumijumnong (2012), who used teak tree-ring width from the same site. It was found that rainfall from the prior December and current March to July directly influenced teak growth (Pumijumnong 2012).

Teak trees are leafless from the end of the rainy season in November until the beginning of the next rainy season in April. The first moisture from the southwest monsoon triggers cambium tissue to become active. Therefore rainfall of the first half of rainy season (April to July) has a strong effect on teak growth (Pumijumnong 2013, Buckley et al. 2007). He et al. (2006) reported that the isotopic variation from low to mid-latitudes are very complicated. The isotopic data ($\delta^{18}O$ and $\delta^{2}D$) in precipitation was analysed at The International Atom Energy Agency World Meteorological Organisation, Bangkok. The results revealed that the source of summer monsoon rainfall originated in Southern Hemisphere Indian Ocean. The El-Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) were positively correlated with Bangkok precipitation $\delta^{18}O$. The Global Network

Table 1 Correlation coefficients of tree-ring $\delta^{18}O$ versus rainfall, temperature and relative humidity (1950–2009).

Mean rainfall (mm)					Mean temperature (°C)			Mean relative humidity		
Dry season		Rainy season								
NDJ	FMA	M–O	MJJ	ASO	M–O	MJJ	ASO	M–O	MJJ	ASO
0.021	0.234*	-0.201	0.054	-0.321**	0.169	0.092	0.186	-0.146	-0.035	-0.282*

M–O = summer monsoon season from May to October, MJJ = early rainy season from May to July and ASO = late rainy season from August to October; * $p < 0.05$, ** $p < 0.01$

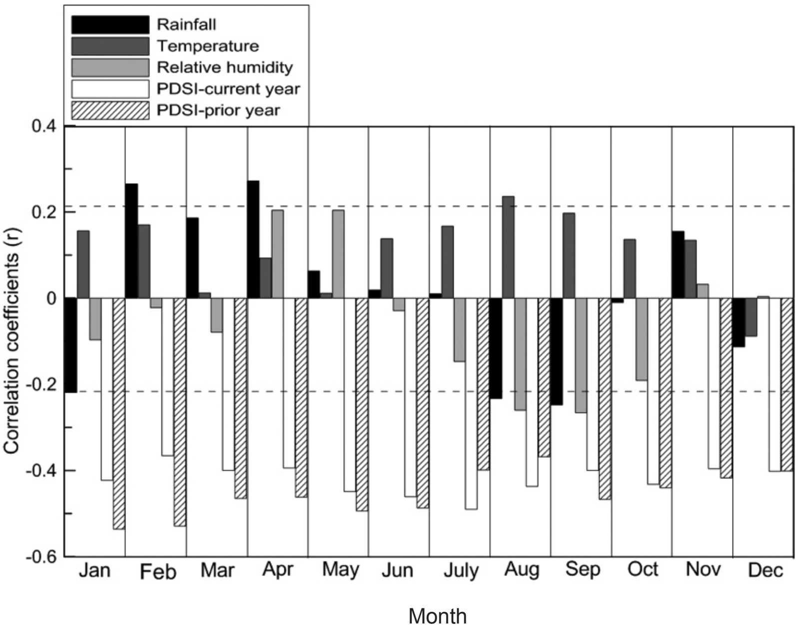

Figure 4 Correlation coefficients between monthly rainfall, monthly mean temperature, monthly mean relative humidity, Palmer Drought Severity Index(PDSI) for current and prior years with $\delta^{18}O$ values of tree-ring cellulose; the horizontal dotted line indicates 95% confidence level

for Isotopes in Precipitation (GNIP) at Bangkok is located 940 km south of the study site (IAEA 2012).The annual value δ^{18}O in precipitation from the GNIP at Bangkok (1968 to 2009 AD) during dry season (November to April) ranged from -4.56 to -3.80‰ during the rainy season (May to October) from -4.97‰ to -8.17‰, respectively. The correlation between δ^{18}O in tree-ring cellulose and δ^{18}O in precipitation at Bangkok was not significant. However, there have been other studies that found strong positive correlation between δ^{18}O tree-ring cellulose and δ^{18}O levels in precipitation from far distance stations. Zhu et al. (2012b) demonstrated a significant positive correlation between δ^{18}O intra-annual cellulose of Cambodia Merkus pine with precipitation δ^{18}O in October at Bangkok station, 450 km away from the sampling site. Brienen et al. (2012) found a significant positive correlation between δ^{18}O of *Cedrela odorata* growing in northern Bolivia with basin-wide precipitation and Amazon River discharge. Brienen et al. (2013) also reported significant correlation between δ^{18}O from tree-rings of *Mimosa acantholoba* and the precipitation isotope at San Salvador, Mexico, 710 km to the southwest.

In Table 1, the tree-ring cellulose δ^{18}O values showed significant negative correlation with total rainfall, average rainfall and average relative humidity in the late rainy season (ASO). In that time the highest amount of rainfall and relative humidity occurred in August. When rainfall and relative humidity were higher, δ^{18}O values of tree-ring cellulose decreased. There are two possible mechanisms to explain this relationship, (1) at high relative humidity, leaf evaporation is low which lowers ^{18}O enrichment in leaf water resulting in lower tree-ring δ^{18}O and (2) 'an amount effect' occurs due to the negative correlation between stable oxygen isotope ratios of rainfall and the amount of rainfall (Dansgaard 1964). Dansgaard (1964) examined the relationship between stable oxygen isotope ratios of precipitation and amount of precipitation in tropical areas and noted that isotopic ratios decreased in the months with greater precipitation. Tree roots take up water without isotopic fractionation and the water is transported to the leaf via the xylem (White et al. 1985, Flanagan & Ehleringer 2006). In the leaf, the δ^{18}O is biologically mediated (isotope fractionation) and altered as a result of transpiration (Barbour & Farquhar 2000). As a result, lighter isotope of hydrogen and oxygen (with lower atomic mass) in leaf water escaped form liquid surface more easily than heavy isotope, thus, leaf water appeared enriched in heavy isotope (Dongman et al. 1974). This mechanism suggested that the δ^{18}O of cellulose was mainly controlled by the δ^{18}O of rainfall and relative humidity.

The current study found that the correlation with rainfall was higher than relative humidity, indicating that rainfall amount was the dominant factor for δ^{18}O values of tree-ring cellulose. Managave et al. (2011) examined δ^{18}O in Indian teak tree-ring cellulose sampled from different locations in India. Teak from western and central India showed a significant positive correlation with the rainfall amount while teak from southern India showed a significant negative correlation with the amount of rainfall. These relationships were used to reconstruct rainfall amounts back to AD 1743. Schollaen et al. (2013, 2014) examined δ^{18}O in Java teak tree-ring cellulose in a low-lying area, on 108-year-old trees. The δ^{18}O in Java teak correlated significantly with regional precipitation over Java and detected signals of different ENSO. Zhu et al. (2012a) investigated δ^{18}O in *Pinus kesiya*, at Doi Chiang Dao in northern Thailand. The δ^{18}O value showed negative correlation with rainfall in ASO. Zhu et al. (2012b) used 3 *Pinus merkusii* from south Cambodia growing during 1867 to 2006. The intra-annual cellulose δ^{18}O exhibited regular seasonal cycles, with annual minima associated with precipitation δ^{18}O in October. It was concluded that pine cellulose δ^{18}O was directly correlated with precipitation and global climate variability, in particular, outgoing long-wave radiation, Indo-Pacific Warm Pool and ENSO since 1867. Xu et al. (2015) examined δ^{18}O in four cores of *Pinus merkusii* from northwest Thailand. It was found that δ^{18}O in Thai pine showed negative correlation with July–October precipitation, July–September river flow and also a close relationship with ENSO from 1871 to 2000. The results revealed that main driver period were AD 1630–1660, AD 1900–1940 and AD 1954–2002, respectively. The δ^{18}O in Thai teak were examined with NINO 3.4 index. The δ^{18}O tree-ring cellulose values showed significant positive correlation with NINO 3.4 index occuring in February to April

($r = 0.171$, $p < 0.01$), May to July ($r = 0.154$, $p < 0.01$) and February to July ($r = 0.177$, $p < 0.01$), respectively. It implied that $\delta^{18}O$ in Thai teak had some influence from equatorial pacific sea sureface temperature.

Temperatures during the monsoon season were not correlated with $\delta^{18}O$ values of tree-ring cellulose. Therefore it was suggested that temperature did not influence $\delta^{18}O$ values of tree-ring cellulose in tropical areas. In the tropical zone, temperature alone was not a primary factor influencing tree growth, in contrast to the effect of temperature on $\delta^{18}O$ values of trees in temperate zones. Gray and Thompson (1976) studied $\delta^{18}O$ of cellulose in tree-rings at Edmonton, Alberta from 1982 to 1969. $\delta^{18}O$ levels in cellulose were best correlated to the mean annual temperature from September to August. Battipaglia et al. (2008) found that the cellulose fraction of *Fagus sylvatica* and *Acer pseudoplatanus* correlated strongly with monthly temperature during the growing season.

Oxygen isotope and PDSI

The average (2.5° × 2.5°) of four gridded (16° 25' N, 96° 25' E; 18° 75' N, 96° 25' E; 16° 25' N, 98° 75' E and 18° 75' N, 98° 75' E) global monthly PDSI (Palmer 1965) data from a published dataset (Dai et al. 2004) was used for correlation with $\delta^{18}O$ values of teak tree-ring cellulose. Correlation coefficients are shown in Figure 4. PDSI measured dryness based on recent precipitation, temperature and soil moisture. Positive and negative values of PDSI corresponded to wet and dry conditions, respectively. The $\delta^{18}O$ values of tree-ring cellulose were negatively correlated with monthly PDSI from 1948 to 2005 for both the current and the prior year. In the current year, for all monsoon months, correlation was strongest in July. January showed the highest correlation during dry season. These results indicated that both wet and dry conditions effected $\delta^{18}O$ levels in tree-ring cellulose.

High temperatures resulted in increased evaporation and the soil water taken up by tree roots became enriched in heavier oxygen isotopes (Gazis & Feng 2004). Tang and Feng (2001) found that deep soil water was restored during large storms and shallow soil water was isotopically enriched. High temperatures resulted in low relative humidity leading to increased evapotranspiration, causing enrichment of oxygen isotopes in leaf water (Roden et al. 2000). High PDSI values indicated wet conditions. High rainfall resulted in lower isotope levels in rainfall. The soil water taken up by tree roots was therefore lighter, and this lead to a negative correlation with tree-ring cellulose $\delta^{18}O$. Previous research documented tree-ring cellulose reflecting a long term drought in northern Laos (Xu et al. 2011) and northern Vietnam (Sano et al. 2012).

In this study, a significant negative correlation ($r = -0.491$, $p < 0.001$, $n = 58$) was found with yearly averaged PDSI (Figure 5a). Simple linear regression was used to determine the yearly mean PDSI. The relationship between yearly mean PDSI and tree-ring cellulose $\delta^{18}O$ was recorded as follows:

$$\text{Yearly mean PDSI} = -1.7516 \times \text{tree-ring cellulose } \delta^{18}O + 39.7183$$

where $r = -0.491$, $p < 0.001$. The relationships between average $\delta^{18}O$ values for teak tree- ring and yearly mean PDSI is illustrated in Figure 5b.

The values of PDSI can be reconstructed back to 1890 and the yearly mean PDSI estimates are shown in Figure 6. The correlation coefficient between actual value and estimated values of PDSI was 0.491, $p < 0.001$. Xu et al. (2011) studied tree-ring cellulose $\delta^{18}O$ chronology of *Fokienia hodginsii* in northern Laos. Results showed that $\delta^{18}O$ in tree-ring cellulose was negatively correlated with PDSI of the monsoon season and that the data could be used to reconstruct PDSI in other parts of South-east Asia. Sano et al. (2012) studied cypress trees from northern Vietnam and found that $\delta^{18}O$ in tree-ring cellulose had highest correlation with PDSI during May to October with results useful for reconstruction of PDSI. Correlations between $\delta^{18}O$ in tree-ring cellulose and PDSI, suggested that $\delta^{18}O$ in tree-ring cellulose of teak from northwest Thailand was a functional response to PDSI. $\delta^{18}O$ in tree-ring cellulose of teak could be used as a proxy for the study of paleoclimates in northwest Thailand.

CONCLUSIONS

Levels of $\delta^{18}O$ in the growth rings of teak from 1890 to 2009 in northwest Thailand were

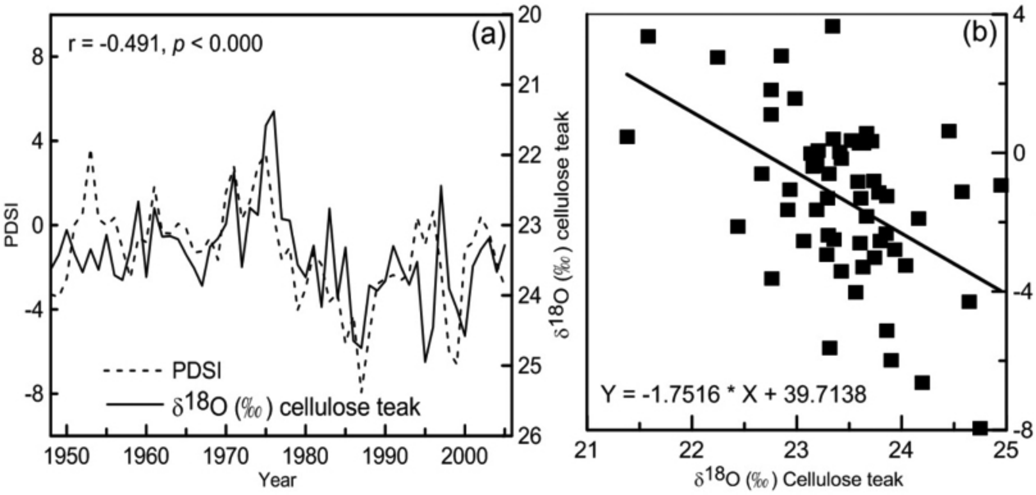

Figure 5 (a) = correlation between annual variations of teak tree-ring cellulose $\delta^{18}O$ and yearly mean PDSI from 1948 to 2005 and (b) = relationships between average $\delta^{18}O$ values for teak tree-ring and yearly mean PDSI. PDSI = (-1.7516) × $\delta^{18}O$ + 39.7183, $r = -0.491$, $p < 0.001$ n=58

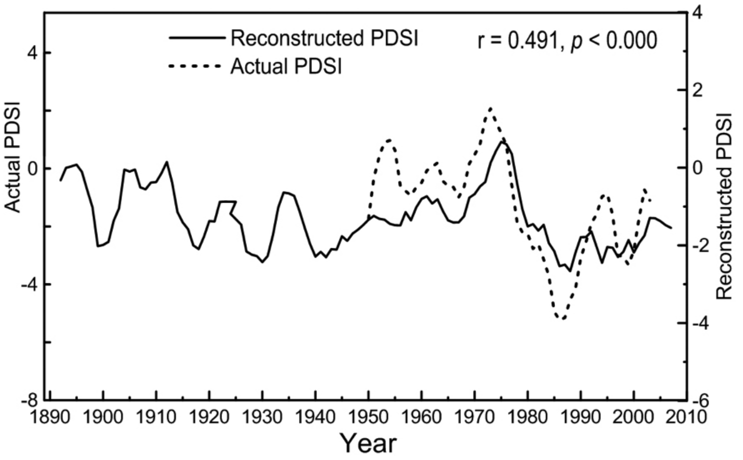

Figure 6 Actual and reconstructed PDSI value, black line(—) = reconstructed PDSI and dash line (----) = actual PDSI

determined. The $\delta^{18}O$ cellulose levels were positively correlated with rainfall during the February to April dry season and negatively correlated with rainfall and relative humidity during the late rainy season. These data were compared to studies conducted in nearby regions such south India (Managave et al. 2011), northern Laos (Xu et al. 2011) and northern Vietnam (Sano et al. 2012). The $\delta^{18}O$ in tree-ring cellulose was negatively correlated with PDSI (mean from 4 grids). The relationship between $\delta^{18}O$ in teak tree-ring cellulose and PDSI was used to estimate the PDSI in northwest Thailand from present back to 1890 AD. It was concluded that $\delta^{18}O$ in tree-ring cellulose of teak from northwest Thailand responded to PDSI and that $\delta^{18}O$ in tree-ring cellulose was useful for study of hydrological cycles in northern Thailand.

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REFERENCES

Anderson WT, Bernasconi SM, McKenzie JA & Saurer M. 1998. Oxygen and carbon isotopic record of climatic variability in tree ring cellulose (*Picea abies*): an example from central Switzerland (1913–1995). *Journal of Geophysical Research* 103: 31625–31636.

Anderson WT, Bernasconi SM, McKenzie JA, Saurer M & Schweingruber F. 2002.Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century. *Chemical Geology* 182: 121–137.

Barbour MM & Farquhar GD. 2000. Relative humidity- and ABA-induced variation in carbon and oxygen isotope ratios of cotton leaves. *Plant, Cell and Environment* 23: 473–485.

Battipaglia G, Jäggi M, Saurer M, Siegwolf RTW & Cotrufo MF. 2008. Climatic sensitivity of δ^{18}O in wood and cellulose of tree rings: Results from a mixed stand of *Acer pseudo platanus* L. and *Fagus sylvatica* L. *Palaeogeography, Palaeoclimatology, Palaeoecology* 261: 193–202.

Biondi F & Waikul K. 2004. Dendroclim 2002. A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computer and Geosciences* 30: 303–311.

Borgaonkar HP, Sikder AB, Ram & Pant GB. 2010. El Niño and related monsoon drought signals in 523 year-long ring width records of teak (*Tectona grandis* L.F.) trees from south India. *Palaeogeography, Palaeoclimatology, Palaeoecology* 285: 74–84.

Brienen RJW, Hietz P, Wanek W & Gloor M. 2013. Oxygen isotopes in tree rings record variation in precipitation δ^{18}O and amount effects in the south of Mexico. *Journal of Geophysical Research: Biogeosciences* 118: 1604–1615.

Brienen RJW, Helle G, Pons L, Guyot JL & Gloor M. 2012. Oxygen isotopes in tree rings are good proxy for Amazon precipitation and El Niño-Southern Oscillation variability. *Proceedings of the National Academy of Science (PNAS)* 109: 16957–16962.

Buckley BM, Palakit K, Duangsathaoprn K, Sanguantham P & Prasomsin P. 2007. Decadal scale droughts over northwestern Thailand over the past 448 year: links to the tropical Pacific and Indian Ocean sectors. *Climate Dynamics* 29: 63–71.

Burk RL & Stuiver M. 1981. Oxygen isotope ratios in trees reflect mean annual temperature and humidity. *Science* 211: 1417–1419.

Cook ER. 1985. A time-series analysis approach to tree-ring standardization. PhD. thesis, University of Arizona, Tucson.

Dai A, Trenberth KE & Qian T. 2004. A global data set of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5: 1117–1130.

Dansgaard W. 1964. Stable isotopes in precipitation. *Tellus* 16: 436–468.

Ding Y & Chan JCL. 2005. The east Asian summer monsoon: an overview. *Meteorology and Atmospheric Physics* 89: 117–142.

Dongmann G, Nurnberg HW, Förstel H & Wagner K. 1974. On the enrichment of $H_2{}^{18}O$ in the leaves of transpiring plants. *Radiation and Environmental Biophysics* 11: 41–52.

Edwards TWD & Fritz P. 1986. Assessing meteoric water composition and relative humidity from ^{18}O and ^{2}H in wood cellulose: paleoclimatic implications for southern Ontario. *Canadian Journal of Earth Sciences* 22: 1720–1726.

Flanagan LB & Ehleringer JR. 2006. Stable isotope composition of stem and leaf water: Applications to the study of plant water use. *Functional Ecology* 5: 270–277.

Feng X, Faiia AM & Posmentier ES. 2009. Seasonality of isotopes in precipitation: a global perspective. *Journal of Geophysical Research* 114, D08116.

Ferrio JP & Voltas J. 2005. Carbon and oxygen isotope ratios in wood constituents of *Pinus halepensis*as indicators of precipitation, temperature and vapour pressure deficit. *Tellus* 57B: 164–173.

Gazis G & Feng X. 2004. A stable isotope study of soil water: evidence for mixing and preferential flow paths. *GEODERMA* 119: 97–111.

Gray J & Thompson P. 1976. Climatic information from ^{18}O/^{16}O ratios of cellulose in tree-rings. *Nature* 262: 481–482.

Green JW. 1963. Wood cellulose. Pp 9–21 in Whistler RL (ed) *Method in Carbohydrate Chemistry*. Academic Press, New York.

He Y, Pang H, Theakstone WH, Zhang Z & Lu A. 2006. Isotopic variations in precipitation at Bangkok and their climatological significance. *Hydrological Processes* 20: 2873–2884.

Holmes RL. 1992. *Dendrochronology Program Library, Installation and Program Manual*. Laboratory of Tree-Ring Research. University of Arizona, Tucson.

IAEA (International Atomic Energy Agency). 2012. *The GNIP Database*. International Atomic Energy Agency, Vienna.

Leavitt SW & Danzer SR. 1993. Method for batch processing small wood samples to holocellulose for stable-carbon isotope analysis. *Analytical Chemistry* 65: 87–89.

Lekshmy PR, Midhun M, Ramesh R & Jani RA. 2014. δ^{18}O depletion in monsoon rain relates to large scale organized convection rather than the amount of rainfall. *Science Reports* 4: 5661.

Lipp J, Trimborn P, Edwards T, Waisel Y & Yakir D. 1996. Climatic effects on the δ^{18}O and δ^{13}C of cellulose in the desert tree *Tamarix jordanis*. *Geochimica et Cosmochimica Acta* 60: 3305–3309.

Liu W, Feng X, Liu Y, Zhang Q & An Z. 2004. δ^{18}O values of tree rings as a proxy of monsoon precipitation in arid Northwest China. *Chemical Geology* 206: 73–80.

Loader NJ, Robertson I, Barker AC, Switsur VR & Waterhouse JS. 1997. An improved technique for the batch processing of small whole wood samples to α-cellulose. *Chemical Geology* 136: 313–317.

Managave SR, Sheshshayee MS, Ramesh R, Borgaonkar HP, Shah SK & Bhattacharyya A. 2011. Response of cellulose oxygen isotope values of teak trees in differing monsoon environments to monsoon rainfall. *Dendrochronologia* 29: 89–97.

McCarroll D & Loader NJ. 2004. Stable isotope in tree rings. *Quaternary Science Reviews* 23: 771–801.

Ohashi S, Okada N, Nobuchi T, Siripatanadilok S & Veenin T. 2009. Detecting invisible growth rings of trees in seasonally dry forests in Thailand: isotopic and wood anatomical approaches. *Trees* 23: 813–822.

Palmer WC. 1965. *Meteorological Drought. Research Paper No.45* U.S. Weather Bureau, Washington.

Poussart PF & Schrag DP. 2005. Seasonally resolved stable isotope chronologies from northern Thailand deciduous trees. *Earth and Planetary Science Letters* 235: 752–765.

Poussart PF, Evans MN & Schrag DP. 2004. Resolving seasonality in tropical trees: multi–decade, high-resolution oxygen and carbon isotope records from Indonesia and Thailand. *Earth and Planetary Science Letters* 218: 301–316.

Pumijumnong N. 2013. Dendrochronology in Southeast Asia. *Trees* 27: 343–358.

Pumijumnong N. 2012. Teak tree ring widths: ecology and climatology research in northwest Thailand. *Science, Technology and Development* 31: 165–174.

Pumijumnong N, Eckstein D & Sass U. 1995. Tree-ring research on *Tectona grandis* in Northern Thailand. *IAWA Journal* 16: 385–392.

Ram S, Borgaonkar HP & Sikder AB. 2008.Tree-ring analysis of teak (*Tectona grandis* L.F.) in central India and its relationship with rainfall and moisture index. *Journal of Earth System Science* 117: 637–645.

Richter SL, Johnos AH, Dranoff MM, LePage BA & Williams CJ. 2008. Oxygen isotope ratios in fossil wood cellulose: isotopic composition of eocene- to holocene-aged cellulose. *Geochimica et Cosmochimica Acta* 72: 2744–2753.

Rinn F. 2005. *TSAP-WinTM. Time Series Analysis and Presentation for Dendrochronology and Related Applications*. Version 4.6. Heidelberg.

Robertson I, Waterhouse JS, Barker AC, Carter AHC & Switsur VR. 2001. Oxygen isotope ratios of oak in east England: implications for reconstructing the isotopic composition of precipitation. *Earth and Planetary Science Letters* 191: 21–31.

Roden JS, Lin G & Ehleringer JR. 2000. A mechanistic model for the interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. *Geochimica et Cosmochimica Acta* 64: 21–35.

Roden JS, Bowling DR, McDowell NG, Bond BJ & Ehleringer JR. 2005. Carbon and oxygen isotope ratios of tree cellulose along a precipitation transect in Oregon, United States. *Journal of Geophysical Research* 110, G02003.

Sano M, Xu C & Nakatsuka T. 2012. A 300-year Vietnam hydroclimate and ENSO variability record reconstructed from tree ring δ^{18}O. *Journal of Geophysical Research* 117, D12115.

Saurer M, Borella S, Schweingruber F & Siegwolf R. 1997. Stable carbon isotopes in tree rings of beech: climatic versus site-related influences. *Trees* 11: 291–297.

Saurer M, Schweingruber FH, Vaganov EA, Shiyatov SG & Siegwolf R. 2002. Spatial and temporal oxygen isotope trends at northern tree-line Eurasia. *Geophysical Research Letters* 29: 10–14.

Schollaen K, Karamperidou C, Krusic PJ, Cook ER & Helle G. 2014. ENSO flavors in tree-ring δ^{18}O record of *Tectona grandis* from Indonesia. *Climate of the Past* 10: 3965–3987.

Schollaen K, Heinrich I, Neuwirth B, Krusic PJ, D'Arrigo RD, Karyanto O & Helle G. 2013. Multiple tree-ring chronologies (ring width, δ^{13}C and δ^{18}O) reveal dry and rainy season signals of rainfall in Indonesia. *Quaternary Science Review* 73: 170–181.

Szymczak S, Joachimski MM, Bräuning A, Hetzer T & Kuhlemann J. 2011. Comparison of whole wood and cellulose carbon and oxygen isotope series from *Pinus nigra*s sp. *Laricio* (Corsica/France). *Dendrochronologia* 29: 219–226.

Tang K & Feng X. 2001. The effect of soil hydrology on the oxygen and hydrogen isotopic compositions of plants' source water. *Earth and Planetary Science Letters* 185: 355–367.

Treydte K, Schleser GH, Helle G, Frank DC, Winiger M, Haug GH & Esper J. 2006. Millennium-long precipitation record from tree-ring oxygen isotopes in northern Pakistan. *Nature* 440: 1179–1182.

White JWC, Cook ER, Lawrence JR & Broecker WS. 1985. The D/H ratios of sap in trees implications for water sources and tree ring D/H ratios. *Geochimica et Cosmochimica Acta* 49: 237–246.

Xu C, Sano M & Nakatsuka T. 2011. Tree ring cellulose d^{18}O of *Fokienia hodginsii* in northern Laos: A promising proxy to reconstruct ENSO?. *Journal of Geophysical Research* 116.

Xu C, Pumijumnong N, Nakatsukaa T, Sanoa M & Li Z. 2015. A tree-ring cellulose δ^{18}O-based July–October precipitation reconstruction since AD 1828, northwest Thailand. *Journal of Hydrology* 529: 433–441.

Yakir D, Berry JA, Giles L & Osmond CB. 1993. The δ^{18}O of water in the metabolic compartment of transpiring leaves. Pp 529–540 in Ehleringer JR et al. (eds) *Stable Isotopes and Plant Carbon–Water Relations*. Academic Press, New York.

Zhu M, Stott L, Buckley B & Yoshimura K. 2012a. 20th century seasonal moisture balance in Southeast Asian montane forests from tree cellulose δ^{18}O. *Climate change* 115: 505.

Zhu M, Stoll L, Buckley B, Yoshimura K & Ra K. 2012b. Indo-Pacific warm pool convection and ENSO since 1867 derived from Cambodian pine tree cellulose oxygen isotopes. *Journal of Geophysical Research* 117, D11307.