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Seasonally resolved stable isotope chronologies from northern Thailand deciduous trees

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Abstract

Despite the existence of a number of climate proxies, the terrestrial expression of tropical climate variability over the past few centuries remains poorly resolved. We explore the applicability of stable isotope dendroclimatology as a tool for chronology and paleo-hydrology reconstruction on deciduous trees from monsoonal northern Thailand. Analysis of 11 trees coming from 4 different regions of northern Thailand yielded 7 records with varying degrees of $\delta^{18}O$ and $\delta^{13}C$ seasonality. We develop age models for trees lacking visible rings based on the seasonality of the $\delta^{18}O$ and find agreement to within ≤ 3 years with radiocarbon age estimates. We use the isotopic age models to reconstruct estimates of growth rates and find a significant positive correlation between growth and amplitude of the oxygen and carbon seasonal isotopic signals. A comparison of a reconstructed dendro-isotopic index from Pangmapa with regional rainfall records indicates significant correlations consistent with the locally derived patterns but with decreased representation of the variance. Individual isotopic chronologies stemming from different tree species share common trends, which are also consistent with patterns of rainfall variability. We see an increase in the amplitude of the seasonal $\delta^{18}O$ cycle along with an increase in $\delta^{18}O_{max}$ over the past few decades suggesting a tracking of the recent drying trend of Thailand's monsoon.

Keywords: oxygen isotopes; carbon isotopes; cellulose; dendroclimatology; Thailand

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1. Introduction

Reconstructing the terrestrial expression of the hydrologic cycle in the tropics over the last several centuries remains a challenge despite the recent development of a variety of proxy records (e.g. corals, speleothems, ice cores). Tropical paleo-hydrology is poorly constrained because rainfall is spatially heterogeneous and variable on seasonal timescales that may not be captured by common terrestrial proxies. In addition, observational records are often limited to the last few decades and stations are sparsely distrib-

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uted. As changes in climate are often expressed on seasonal timescales, there is a real need for better time-resolved proxies.

Trees are obvious candidates for paleo-rainfall reconstruction as they hold the potential for subannual resolution and are widely distributed in the tropics. Traditional dendrochronological techniques are hindered in the tropics because annual banding is usually irregular, indistinct, or not present at all. The seasonality in rainfall and relative humidity in the tropics, while not large enough to cause the creation of visibly distinct rings, may still generate seasonal signals in the oxygen and carbon isotopic composition of tree cellulose. Greenhouse and field experiments show that the δ^{18}O of tree cellulose is largely controlled by the isotopic signature of the tree's source water [1–4]. This value is typically offset following an evapotranspiration enrichment of the leaf water used for photosynthesis [5]. Empirical isotopic models developed by Roden et al. [5] outline the pathways by which trees relying on rainfall rather than groundwater for growth can record variations in the seasonally modulated δ^{18}O composition of precipitation. As described in detail in [6,7], these models suggest that tropical environments such as northern Thailand, where rainfall and relative humidity are highly seasonal, can impress on their forests sequential records of hydrological variability on subannual timescales.

Summer monsoon rains in Thailand are typically 4‰ lighter than in winter, despite the higher summer temperatures [8]. This amount effect is commonly observed for regions heavily influenced by monsoon activity (typically south of the maximum northward extent of the Intertropical Convergence Zone (ITCZ) (Fig. 1 in [8]) whereas the reverse is true for northern regions where temperature effects dominate and yield heavy (light) δ^{18}O rainfall values in summer (winter) [9–11]). In addition, δ^{18}O of precipitation varies with altitude (depletion in heavy isotopes with increased elevation) and with the distance travelled over land relative to the source region (preferential condensation of heavy isotopes).

Recent analytical advances in sample preparation, chemical extraction and continuous flow gas-source mass spectrometry have made possible the recovery of long term seasonal isotopic records in tropical trees [6,7]. Based on high-resolution sampling, Poussart et al. [7] demonstrated that seasonally resolved δ^{18}O (as well as δ^{13}C) cycles recovered from a Thai *Podocarpus nerrifolius* could be used effectively for chronology, despite the lack of visible annual growth rings.

In this paper, we survey the potential of 9 common and widespread tree species from northern Thailand with no visible growth rings for stable isotope chronology. We investigate the extent to which complementary δ^{13}C measurements can assist with age model development and growth rate estimates when seasonal variability in δ^{18}O is less distinct. We infer from the presence (or absence) of seasonal isotopic signals in trees with poorly defined growth rings whether the rings are created internally (biology) or externally (climate). We compare the isotopic records from different species grown in the same forest to assess δ^{18}O reproducibility and outline the potential for tree-based isotopic networks to assist in the spatial reconstruction of the hydrological cycle in tropical environments such as Thailand.

2. Methods

2.1. Sample descriptions, locations and climatologies

We collected samples from three provinces of northern Thailand: Lampang, Chiang Mai and Mae Hong Son (Fig. 1). These provinces experience three distinct seasons: cool and dry (November to February), hot and dry (March to May) and warm and wet seasons (May to October). Throughout northern Thailand, more than 85% of the annual precipitation falls between May and October (monsoon season) whereas December through January are virtually rain free. This is less so for Mae Hong Son, whose mountainous location leads to heavier rainfall dispensed over a longer period of time relative to lower elevation sites. The species sampled were selected for their widespread distribution in northern Thailand and their extensive meridional distributions (for future species transects reconstruction). We used the *Field guide to forest trees in northern Thailand* of Gardner et al. [12] for species identification. All samples with no clear visible growth rings were collected as cross-sections from recently felled specimens (either from windfall or lumbering activity) to facilitate the determination of the tree's pit (Table 1). Cross-section surfaces were sanded, and radial sections (~4 mm ×

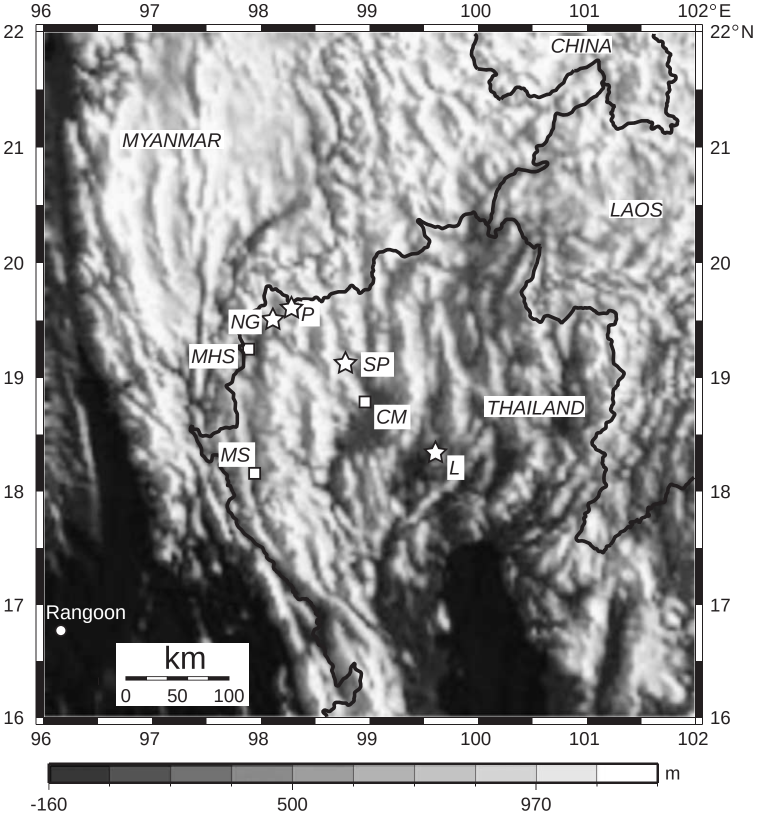

Fig. 1. Map showing the location of sampling and weather stations in northern Thailand. Topographical relief in meters. Sampling locations shown as stars: Nam Gat (NG), Pangmapa (P), Sop Paeng (SP) and Lampang (L). Weather stations with rainfall data (1951–2001) shown as squares: Mae Sariang (MS), Mae Hong Son (MHS) and Chiang Mai (CM). Data from Climatology Division and Meteorological Department, Thailand. Map created using *i*GMT [13].

4 mm × radius of tree) were cut in preparation for microtoming.

A total of 6 species were sampled in the forests of Pangmapa (Fig. 1) (98°16′ E, 19°34′ N). PG1 is a *Quercus kerrii* (Oak), from the Fagaceae family (Thai name: *Goh Pat!*). PG1 is a deciduous tree, typically 6–10 m tall and often found in semi-open forests. It is occasionally associated with dry Dipterocarps. This species exists in northern Myanmar, Vietnam, Laos, and China. The sample was felled recently and had no clear visible rings although some banding was apparent. PK1 is a *Miliusa velutina*, from the Annonaceae family (Thai name: *Kang Huoi Mou*). A common deciduous tree in semi-open forests, *Miliusa* grows between 5–16 m in height. Our sample was felled recently and had no clear visible rings. PP1 is a *Dipterocarpus tuberculatus* from the Dipterocarp family (Thai name: *Pluang*). *Pluang* is a deciduous species, extremely common in dry Dipterocarp forests and sometimes found with *Pinus merkusii*. The cross-section shows some ring structure although the origin of the rings is unclear (biological or environmental). PPR1 is a *Pterocarpus macrocarpus* of the Leguminosae family (Thai name: *Mai Pradu*). *Mai Pradu* is a large deciduous tree which can grow upwards of 30 m. The species has been heavily logged and its current geographical distribution covers south Myanmar, Cambodia, Laos and Vietnam. The tree was cut ~5 yr previous to sampling in moist organic-rich soil. No ring structure is visible. PT1 is a *Lagerstoemia cochinchinensis* of the Lythraceae family (Thai name: *Tabek*). Trees are very large (up to 40 m in height) commonly occupying the upper canopy of moist deciduous forests throughout northern Thailand.

Table 1
Species list from northern Thailand sampling

Sample name	Species	Rings?	Location	Collected on	Felled on	x_0	x_f	Δx
						(cm)		(μm)
LG1	*Lannea coromandelica*	N	Lampang	01.02.03	2003	0	2.6	400
LH1	*Dipterocarpus obtusifolius*	N	Lampang	01.02.03	1990	0	2.6	400
LY1	*Chukrasia velutina*	Y	Lampang	01.02.03	2003	0		125–500
NY1	*Chukrasia velutina*	Y	Nam Gat	23.01.03	2002	1		75–250
PG1	*Quercus kerrii*	N	Pangmapa	22.01.03	2002	0	8.9	400
PK1	*Miliusa velutina*	N	Pangmapa	23.01.03	2000–2002	0	14.1	250
PP1	*Dipterocarpus tuberculatus*	Y	Pangmapa	22.01.03	2002	2.6		125–400
PPR1	*Pterocarpus macrocarpus*	N	Pangmapa	23.01.03	1996–2000	0	2.6	400
PT1	*Lagerstroemia cochinchinensis*	Y	Pangmapa	22.01.03	1992–2002	0		125–500
PTAE2	*Shorea obtusa*	Y	Pangmapa	22.01.03	2003	9.5		125–625
PLPR1	*Pterocarpus macrocarpus*	N	Sop Paeng	24.01.03	2000–2002	?	4.0	250

Samples were collected as cross-sections for isotopic analysis. Sampling locations include Lampang (99°39′ E, 18°20′ N), Nam Gat (98°05′ E, 19°31′ N), Pangmapa (98°16′ E, 19°34′ N) and Sop Paeng (logging concession—original location unknown). The samples were microtomed incrementally toward the pit. x_0 (x_f) represents initial (final) sampling position (cm from cambium) and Δx is sampling interval (μm).

We sampled a cross-section from an in situ stump (unknown felling date but likely recent based on pristine bark condition), on a well-drained southwest facing slope. *Tabek* shows irregular ring structures and a clear heartwood–sapwood boundary. PTAE2 is a *Shorea obtusa* of the Dipterocarp family (Thai name: *Taeng*). This deciduous species is common particularly in dry, degraded areas and is sometimes found at higher altitudes (<1400 m) with *Pinus kesiya*. The sampled tree grew on a ridge and was felled a few days prior to sampling (leaves still fresh). Some banding in the wood was visible.

We acquired an additional sample of *Mai Pradu* from a logging concession in Sop Paeng (PLPR1). The original growing location of the tree is unknown.

A *Chukrasia velutina* sample (NY1 Thai name: *Yom hin*) was collected in Nam Gat (98°05′ E, 19°31′ N), ~20 km west of Pangmapa (Fig. 1). The species is deciduous and belongs to the Meliaceae family. Mature trees can grow up to 25 m and are also common in Myanmar. The sample was felled within the year previous to collection and the sanded surface revealed some ring-like structures.

The closest weather station for these two locations is in Mae Hong Son (MHS ~40 km away) whereas stations in Chiang Mai (CM ~115 km) and Mae Sariang (MS ~150 km) are further away (Fig. 1). All stations have rainfall records which extend back to 1951. Monthly rainfall climatologies (1951–2001) are significantly correlated between stations ($r = 0.5$–0.91, $p < 0.001$) from November through March. However, rainfall amounts during summer months are not consistently correlated with each other. Furthermore, there are large differences in rainfall amounts between all three stations on interannual and decadal timescales.

We collected 3 additional samples in Lampang (99°39′ E, 18°20′ N), which is ~75 km southeast of Chiang Mai (Fig. 1). LG1 is a *Lannea coromandelica* of the Anacardiaceae family (Thai name: *Gook*). Commonly present in semi-open deciduous forests, this deciduous species can grow up to 17 m and its geographic distribution extends to the Malay Peninsula. The sampled tree grew on a ridge of a dry Dipterocarp forest and had no visible ring structure. LH1 is a *Dipterocarpus Obtusifolius* of the Dipterocarp family (Thai name: *Heeang*). This deciduous species is a dominant component of the dry Dipterocarp forest and is fire tolerant. Our sample was taken from a tree stump cut in 1990 ± 3 and had no visible ring structure. LY1 is a *Chukrasia velutina* as was NY1 collected in Pangmapa. The sample was cut from a recently felled tree growing on a ridge. Fire scars were visible on the bark and the wood revealed some ring-like structures.

2.2. Sample preparation for isotopic analysis

2.2.1. $\delta^{18}O$ and $\delta^{13}C$

A rotary microtome was used to manually cut 25 μm wood slivers from the prepared radial sections.

Sampling intervals for individual tree samples ranged from 75 to 625 μm as listed in Table 1. Constant intervals were used for ringless tree samples whereas they were adjusted according to growth rates when rings were visible (~8 samples/year). Wood samples were extracted to α-cellulose using a modified Brendel method [6,14]. Weighted cellulose samples (80–200 μg) were loaded into silver (tin) capsules for δ^{18} O (δ^{13}C) analysis which were pyrolised (combusted) online into elemental CO (CO_2) and measured in a *Delta^{plus}* XL mass spectrometer. The oxygen isotope data are reported as per mil deviations from

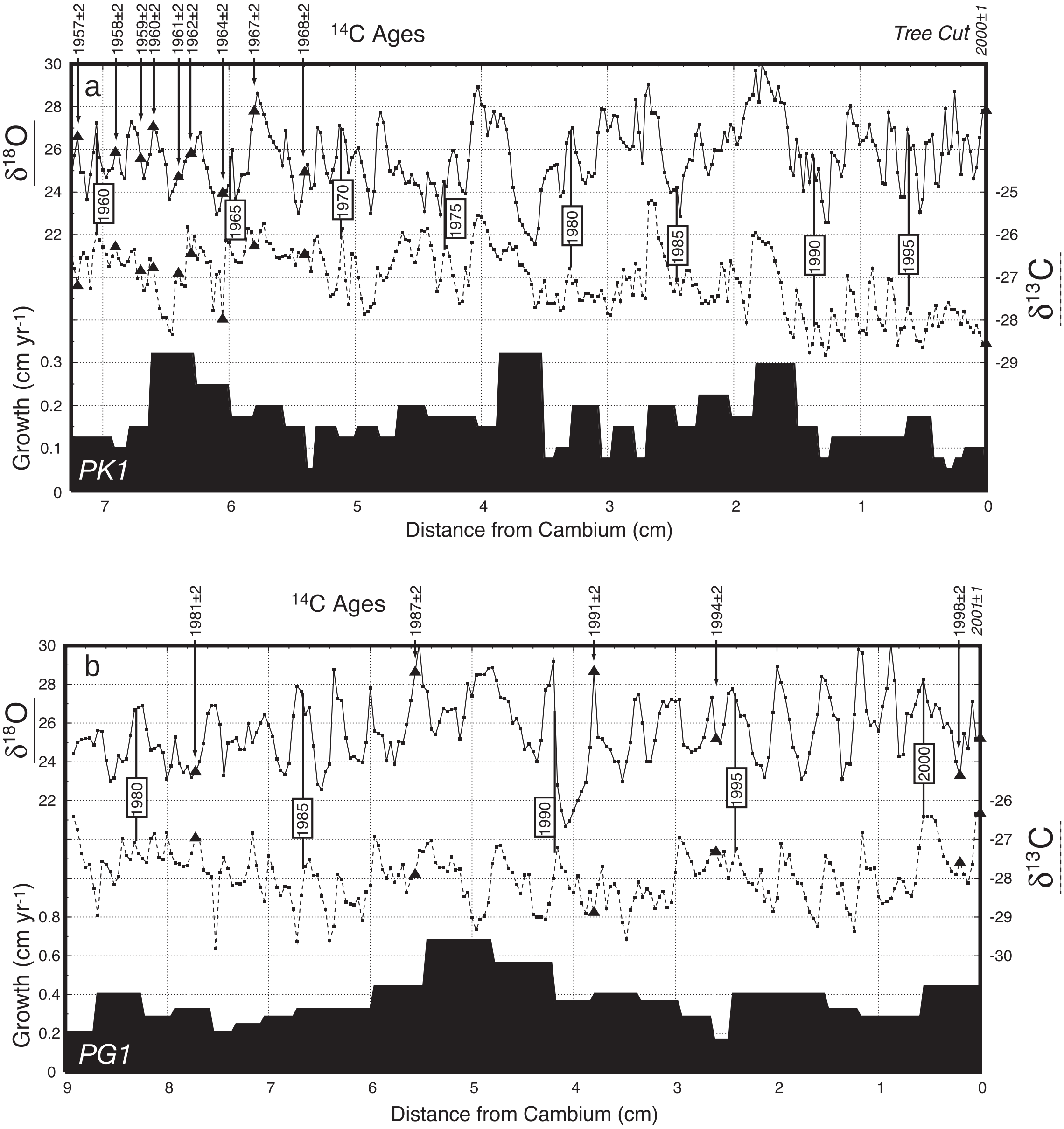

Fig. 2. Construction of δ^{18}O and δ^{13}C age model chronologies, constrained by Δ^{14}C measurements for (a) PK1 and (b) PG1 Pangmapa tree samples. The agreement between radiocarbon and stable isotope chronologies is within ≤3 yr. Growth rate estimates (cm yr^{-1}) are shown as bars.

the standard Vienna standard Mean Oceanic Water (V-SMOW) and the carbon isotope data relative to the Vienna Pee Dee Belemnite (V-PDB) scale. External precision on $\delta^{18}O$ ($\delta^{13}C$) measurements (1 σ) is 0.3 (0.15) ‰.

2.2.2. $\Delta^{14}C$

The $\delta^{18}O$ and $\delta^{13}C$ age models for samples PG1 and PK1 are compared to age estimates derived from $\Delta^{14}C$ measurements of wood samples collected alongside the sample sections. Material is obtained from drilling directly into the tree cross-section with a 1 mm diameter drill bit. We use a modified DeVries ABA (acid–base–acid) pretreatment [15] on the wood samples prior to measuring bomb produced $\Delta^{14}C$ [Westbrook, pers. comm.]. Between 0.5 and 3 mg of pretreated wood samples are combusted at 900 °C in evacuated quartz tubes using 2 g of a 1 : 3 mixture of copper : copper oxide. The resulting CO_2 is cryogenically separated in a vacuum line and later analyzed at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. $\Delta^{14}C$ values are reported following the Stuiver and Polach convention [16] and are $\delta^{13}C$ corrected for biological fractionation effects (measured separately on a Carlo Erba Nitrogen analyzer 1500 inlet system connected to a CF-IRMS *Delta^{plus}* XL mass spectrometer).

3. Results

Of the 9 species studied, the *Quercus kerrii* (PG1) and *Miliusa velutina* (PK1) samples have the most regular and pronounced $\delta^{18}O$ and $\delta^{13}C$ cycles. Measured $\delta^{18}O$ ($\delta^{13}C$) average amplitudes are 5.2 (1.8) ‰ for PG1 and 3.2 (1.0) ‰ for PK1. We develop age models for the two trees based on the oxygen isotopic records by assigning a seasonal timescale to the observed cycles (Fig. 2). We assume isotopic peaks and troughs correspond to times of minima (March) and maxima (August) in relative humidity and that some growth may occur during the dry season. Although both tree species are deciduous and are likely to experience peak growth rates during the rainy season, there are no dendrometer studies to constrain the timing of the growth season.

Age estimates for the remaining data are linearly interpolated between tie points. We use the time of cutting as an exactly dated tie point to the reconstructed time series. As shown in Fig. 2, peaks in

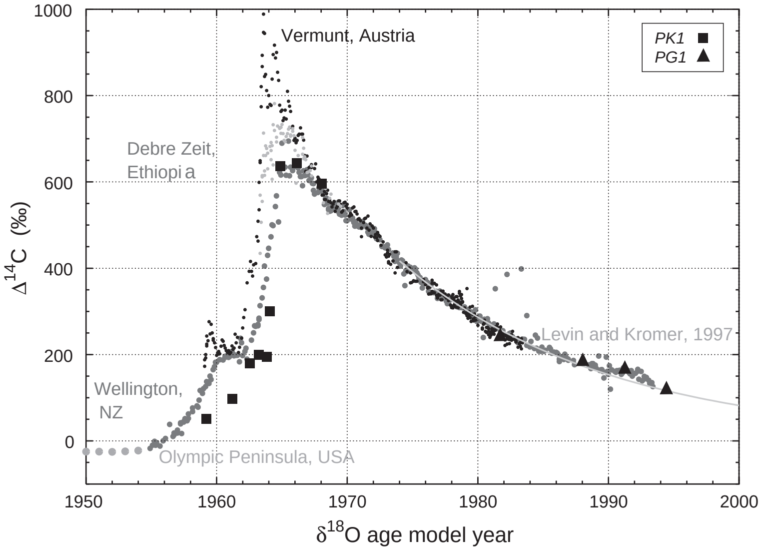

Fig. 3. $\Delta^{14}C$ vs. $\delta^{18}O$ age model years of ringless *Miliusa velutina* (PK1) and *Quercus kerrii* (PG1), northern Thailand. For radiocarbon analysis, wood samples are chemically pretreated following a modified ABA DeVries [15] method. Samples compared to atmospheric $\Delta^{14}C$ records from Olympic Peninsula, USA 47° N [17], Wellington, New Zealand 41° S [18], Debre Zeit, Ethiopia 8° N [19], Vermunt, Austria 47° N [20] and exponential decay curve fitted to atmospheric and tree ring $\Delta^{14}C$ measurements [21].

δ^{18}O coincide with peaks in δ^{13}C to within ± 1 data points for both PK1 and PG1. In the case of PK1, we find a correlation $r^2 = 0.19$ ($p < 0.01$) between amplitudes of the oxygen and carbon isotopic cycles for the period of 1957 to 2001.

We measured the Δ^{14}C of pretreated wood samples along the radial direction of the two samples to test the seasonal timescale of the observed cycles. Fig. 3 shows a comparison between the measured Δ^{14}C values (calibrated with the δ^{18}O age estimates) to the atmospheric Δ^{14}C records. The DeVries pretreated Δ^{14}C data for PK1 defines a curve with amplitude of ~650 ‰.

Fig. 4 shows a compilation of the δ^{18}O time series generated in this study. Samples from Lampang (LG1, LH1 and LY1) and Nam Gat (NY1) did not yield coherent δ^{18}O signals (data not shown). With the exception of PLPR1 (whose growth location is unknown), all of the samples, which revealed large isotopic cycles, were collected in Pangmapa. Isotopic chronologies were calculated as before and were assigned ages based on their time of felling and/or estimated growth rates (see Table 1 for details). Age model errors for PP1, PPR1, PT1 and PTAE2 are within ± 5–10 yr. The large uncertainties in the age models arise from poorly constrained time of felling and from sampling some distance away from the bark (x_0 in Table 1). The top panel of Fig. 4 shows a comparison between the isotopic chronologies. Given the uncertainties in the age models, the records retain some level of coherence. For example, the isotopic low of 1990 is a prominent feature of PK1, PG1 and PLPR1 and the high of 1988 is replicated between PK1, PG1, PP1 and PT1. Common trends are also apparent in the data such as the δ^{18}O increase found in PK1, PG1 and PLPR1 after the early 1980s.

4. Discussion

4.1. High-resolution isotopic chronology

We have identified the species *Miliusa velutina* (PK1) and *Quercus kerrii* (PG1) as two excellent candidates for isotopic chronology development. Measuring both δ^{18}O and δ^{13}C on subannual samples was critical for age model development, as replicated cyclicity provides tighter chronological constraints and further substantiates a common environmental forcing. δ^{13}C variations can assist with chronology

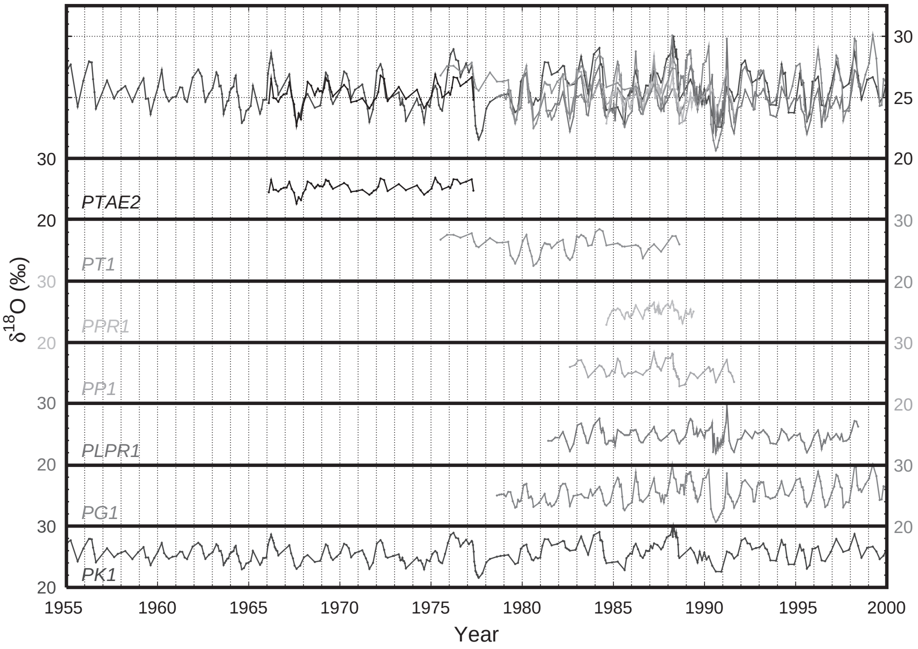

Fig. 4. δ^{18}O time series summary from Pangmapa, northern Thailand.

when variability in $\delta^{18}O$ is less distinct. Although sample preparation and extraction remains labor intensive, the extra $\delta^{13}C$ measurement is technically straightforward and requires little additional material. Both chronologies are tied effectively to a known felling date, providing absolute age control. In addition, the $\Delta^{14}C$ tie points strongly support a seasonal timescale for the observed cycles in the ringless trees. Overall, the results suggest that the DeVries pretreatment is sufficient for radiocarbon measurements. $\Delta^{14}C$ calibration is done most effectively when the tree is >50 yr old (as was the case for PK1, which was ~90 yr old) and the $\Delta^{14}C$ atmospheric bomb peak can be reproduced. We find a ± 3 yr agreement between the PK1 $\delta^{18}O$ and $\Delta^{14}C$ age estimates over the period of 1957 to 2001, confirming the seasonal nature of the isotopic cycles recovered from this ringless tree (Fig. 2). The stable isotopic age model for PG1 extends back to 1979 and is consistent with the DeVries $\Delta^{14}C$ measurements (to ± 1 yr).

Species-specific tree physiologies and growth habits, along with local forest ecology, may in some cases cause discrepancies between the ^{14}C of tree cellulose and atmospheric concentrations of ^{14}C. As described by Grootes et al. [22], such offsets may be passed on from a delay (on the order of weeks) between photosynthate production and incorporation into biomass, by the use of stored photosynthates, or assimilation of biospheric decay. While we cannot assess directly the extent of these effects, such offsets are not likely to dominate the signals recorded by the trees studied here. The forest of Pangmapa has an open canopy and is well ventilated with the boundary layer above. In a study by Trumbore [23] in eastern Amazonia, Brazil, the author found that tropical soil respiration was dominated by C fixed <1 yr ago. Although this finding is likely site-specific, it is suggestive that tropical soils have relatively fast turnover times and that biospheric decay may not cause large offsets between tree cellulose and atmospheric concentrations.

We also found cyclicity in the $\delta^{18}O$ records of *Pterocarpus macrocarpus* (PLPR1), *Dipterocarpus tuberculatus* (PP1), *Lagerstroemia cochinchinensis* (PT1) and *Shorea obtusa* (PTAE2) (Fig. 4). Although unconstrained with $\delta^{13}C$ or $\Delta^{14}C$ measurements and felling dates, the relative agreement of these records with the PK1 and PG1 chronologies indicates that the cycles recovered are also seasonal. Interestingly, we find that the ring boundaries apparent in PP1 coincide >80% of the time with oxygen and carbon isotopic lows (data not shown), suggesting that ring boundaries are produced annually at the end of the peak of the wet season. Additional isotopic work will be required for establishing the origin of the apparent growth rings observed in samples PT1 and PTAE2.

Of the 11 trees analyzed here, 4 did not yield usable isotopic signals. The three samples collected in Lampang (LG1, LH1 and LY1) did not produce coherent $\delta^{18}O$ records and suggest that perhaps the climate of the region is not conducive for this application. Both *Chukrasia velutina* samples (LY1 from Lampang and NY1 from Nam Gat) lacked seasonal isotopic signals implying that the species growth patterns may not agree with recording seasonally modulated isotopic forcings. These results highlight the challenges in developing tropical records in that the approach is both species- and site-sensitive.

4.2. Growth rate estimates

Seasonal isotopic records can be used to estimate past growth rates in trees with no visible growth rings. This application was first demonstrated by Poussart et al. [7] with a Thai *Podocarpus neriifolius*. Based on the distinct and large amplitude cycles in $\delta^{18}O$ and in $\delta^{13}C$ (up to 18‰ and 4‰, respectively) along with absolute age model constraints, the authors estimated seasonal and annual growth rates for the period 1993–1997 and found that ~60% of the annual growth of this evergreen species occurred during the rainy season (May to October).

We estimate the growth rate history of both trees based on the sampling rates and isotopic age models (Fig. 2). Statistical analysis of the present $\delta^{18}O$ records for northern Thailand deciduous trees consistently reveals a significant correlation ($r^2 = 0.39$ and 0.31 with $p < 0.01$) between the isotopic seasonal amplitude ($\delta^{18}O_{max-min}$ and $\Delta^{13}C_{max-min}$, respectively) and estimated annual growth rate (Fig. 5). When samples are lacking visible growth rings and sampling rates are kept constant throughout a radial section, the recovered seasonal $\delta^{18}O_{max}$, $\delta^{18}O_{min}$ and $\Delta^{18}O_{max-min}$ may be subject to sampling biases. Higher growth years (represented by more samples)

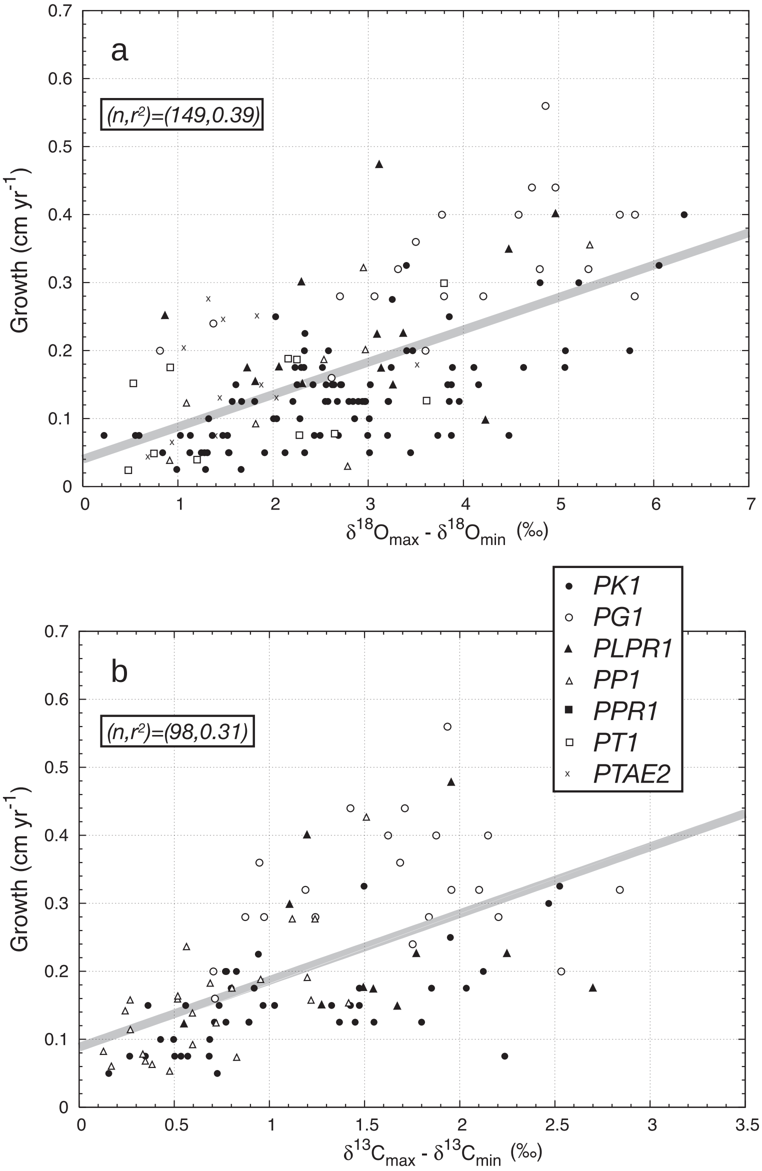

Fig. 5. Scatter plots of estimated annual growth rates (cm yr $^{-1}$) vs. (a) δ^{18}O and (b) δ^{13}C seasonal amplitudes (‰). Annual statistics included if seasonal cycle defined by ≥ 4 data points to avoid potential sampling biases. r^2 significant with $p < 0.01$.

may be more likely to include δ^{18}O extremes at the beginning or end of the growing season. Consequently, biasing should be aggrevated when annual cycles are represented by only a few data points (<4). However, $\delta^{18}O_{max}$ and $\delta^{18}O_{min}$ are never both correlated with growth suggesting that δ^{18}O extremes are not due entirely to higher density sampling. In fact, this pattern indicates that conditions conducive to growth are likely sensitive to the early part of the growing season when maximum cellulose δ^{18}O values are expected to get recorded. Furthermore, the same correlation is found in trees with rings and constant sampling densities between rings (PP1).

The scatter plots shown in Fig. 5 include the years defined by at least 4 data points. The consistency of the relationship across Pangmapa tree species suggests that the measured amplitude of the seasonal isotopic cycles is greater when annual growth rates are high. Given an early start in summer rainfall, trees may initiate growth by recording the heavier δ^{18}O values associated with heavy winter δ^{18}O rainfall and large evapo-transpiration enrichments caused by low relative humidities. Similarly, if the growing season was extended in time or in strength, the δ^{18}O of rainfall may show depleted values relative to dryer wet seasons. The origin of the $\Delta^{18}O_{\max-\min}$-growth relationship could be tested with the use of dendrometer bands and/or on-site rainfall δ^{18}O sampling.

4.3. Relevance to monsoon variability

We compare the Bangkok δ^{18}O rainfall data with the dendro-isotopic records and find no significant correlations. This is not surprising as we expect local effects (topography, distance travelled from source waters) to be a large source of variability for rainfall. The observed range of variability (~4 ‰) agrees with our measurements but year-to-year comparison with the tree records is not possible as much of the rainfall records are short, incomplete and too far away.

Of the 7 isotopic tree records presented here, only PK1, PG1 and PLPR1 have well constrained (uncertainty $\leq$3 years) chronologies (Fig. 4). Nonetheless, we find the same salient features revealed in all of the Pangmapa records when compared to regional rainfall records. In general, we find much better correlation with rainfall stations in Mae Sariang (MS) and Mae Hong Son (MHS) than in Chiang Mai (CM). The topography of the region likely accounts for much of the observed spatial heterogeneities in rainfall by preventing air mass mixing between CM from the other stations to the west (Fig. 1).

We find positive correlations between $\Delta^{18}O_{\max-\min}$ Pangmapa trees PK1, PG1, PLPR1, PT1 and PTAE2 and dry season rainfall patterns. r^2 values ($p<0.01$) explain between 36% and 73% of the variance. When dry seasons have greater than average rainfall, the corresponding amplitude of the δ^{18}O seasonal cycles also increases suggesting that tree growth at that time may be capturing a fraction of annual rainfall δ^{18}O cycle that would otherwise go unrecorded.

In addition, we find negative correlations between $\delta^{18}O_{\min}$ and wet season rainfall patterns for samples PK1, PG1 and PTEA2 as shown in Fig. 6b. The negative correlation suggests that the extent of the rainfall amount effect (monsoon intensity) is at least partially recorded in the minima of the tree cellulose δ^{18}O. Individually, the correlations explain up to 50% of the variance. Slopes are related to amount of rainfall as well as species- and site-specific effects. Fig. 6 (a,b) summarize the greatest correlations found between individual trees and the monthly seasonal rainfall records.

We build Pangmapa isotopic tree indices by taking averages from all available records of the following parameters: Annual maximum, minimum, mean and seasonal amplitude δ^{18}O and growth rate estimates. The isotopic indices are compared to a rainfall index [(MS+MHS)/2] calculated on monthly, seasonal and annual timescales. Although we can replicate the relationships explained above, the regional indexes only explain about 10–20% of the variance (data not shown). This result suggests that the δ^{18}O of tree cellulose is not uniquely sensitive to the δ^{18}O of rainfall (source water) but that it also responds to changes in growing season relative humidity as well as temperature variations [24–26]. In addition, species-specific effects and/or heterogeneities in the rainfall spatial patterns may be responsible for the low correlations found.

Tree ring reconstructions typically rely on a large number of replicated ring width records for the development of significant climate reconstructions. Individual tree ring records rarely explain more than 20–30% of the variance of any particular climate index. Although our limited number of trees only explain 10–20% of the available rainfall records, the δ^{18}O/climate connection is clearly recorded in these time series. Furthermore, the fact that we find similar dendro-isotopic/monsoon rainfall relationships both at the scale of individual trees and at the regional scale of forest indexes, suggests that the amplitude of δ^{18}O-dry season rainfall and $\delta^{18}O_{\min}$-wet season rainfall couples are robust.

Despite the limitations discussed above, we find long term trends that are coherent between the Pangmapa dendro-isotopic anomaly and regional rainfall indexes. Anomalies are calculated by subtracting the full length record average from individual annual indices. As shown in Fig. 7a, the δ^{18}O seasonal amplitude anomaly shows an increasing trend from

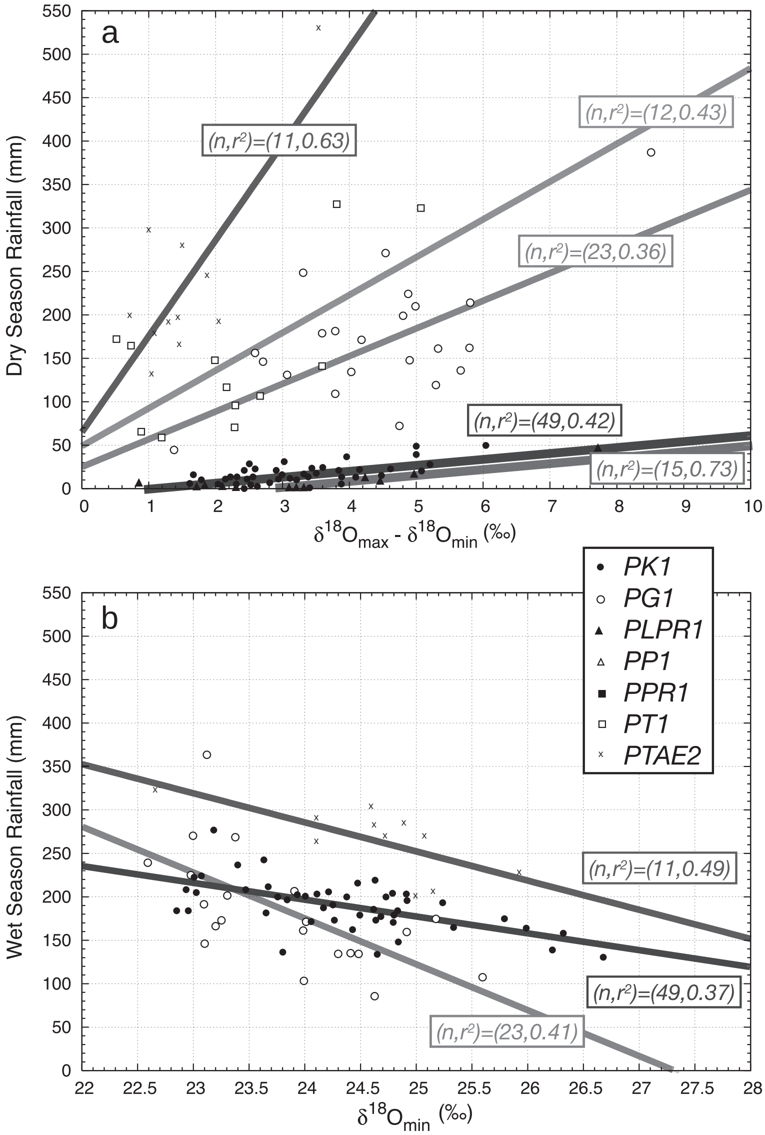

Fig. 6. Scatter plots of individual trees from Pangmapa showing (a) Dry season rainfall (mm) vs. ($\delta^{18}O_{max} - \delta^{18}O_{min}$) (rainfall comparison for PK1 with Mae Sariang (MS) dry season, PG1 with Mae Hong Son (MHS) May, PLPR1 with MS December, PT1 with MS May and PTAE2 to Chiang Mai September) and (b) Wet season rainfall (mm) vs. $\delta^{18}O_{min}$ (rainfall comparison for PK1 with MHS wet, PG1 with MS June and PTEA2 with MS August). All r^2 significant with $p < 0.01$.

the early 1970s onwards. This trend is also apparent in the $\delta^{18}O_{max}$ anomaly (data not shown). Consistent with this increase, we observed a decrease in wet season rainfall throughout that period and an increase in the dry season rainfall index (Fig. 7b). This drying trend in Thailand's monsoonal rainfall over recent decades was observed also by Singhrattna et al. [27]. The authors argued that decrease in summer rainfall is linked to increased ENSO frequency. They suggested that during ENSO events in the tropical Pacific, the Walker circulation's descending branch migrates over Thailand, thereby hindering convection activity and rainfall (see Gill [28] for a review of the Walker circulation). Based on the results

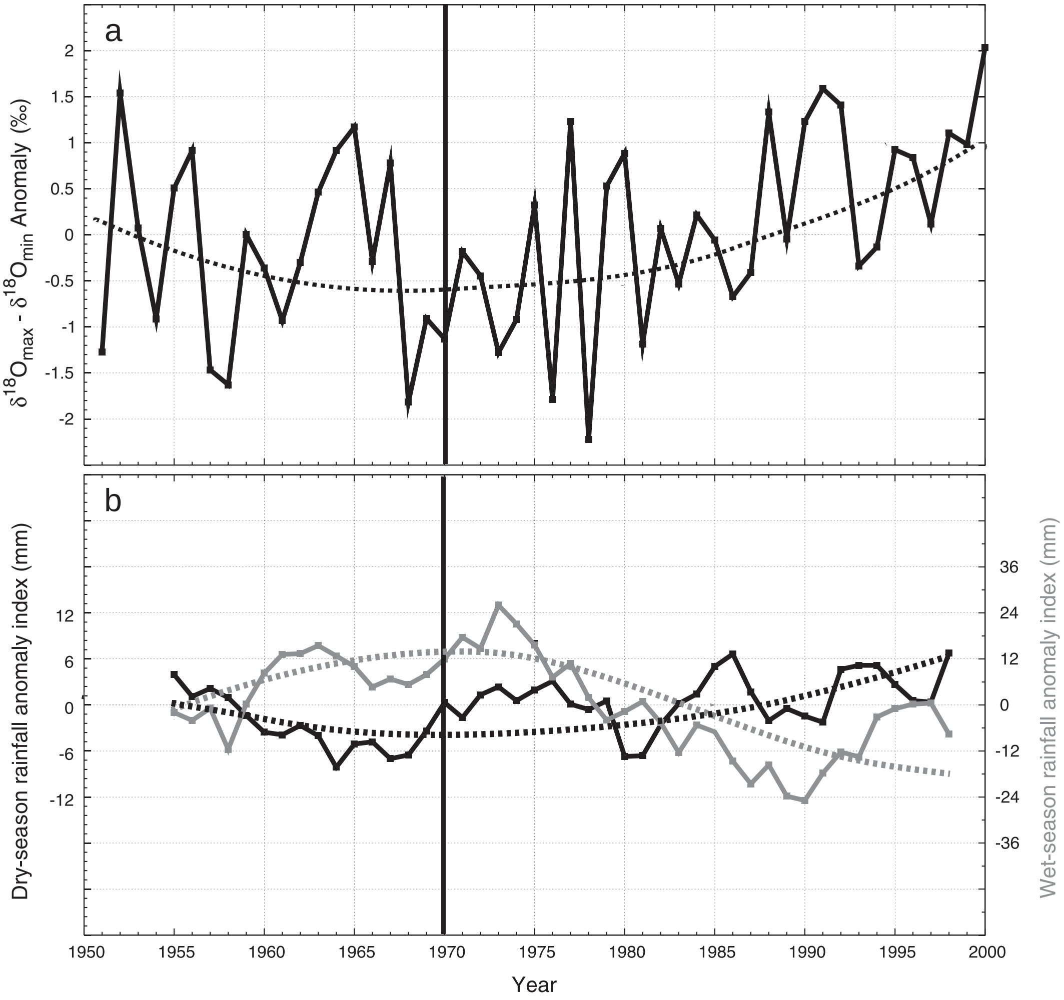

Fig. 7. (a) Pangmapa tree record of $\delta^{18}O_{max} - \delta^{18}O_{min}$ annual anomaly index. (b) Comparison of the 5-yr running average of dry vs. wet season regional anomaly indices (mm). Dotted lines are the color-coded second-order polynomial fits to the time series. Anomalies are calculated by subtracting the full length record average from individual annual indices.

presented here, we suggest that the development of a network of $\delta^{18}O$ tree chronologies across northern Thailand may yield valuable insights into the non-stationary relationship between the country's monsoon variability and ENSO.

Work by Tans and Mook [29], Stuiver et al. [30] and Francey and Farquhar [31] revealed large $\delta^{13}C$ variations (1–4 ‰) around the circumference of a tree as well as amongst neighboring trees. To date, there are no publications that explicitly address this issue for $\delta^{18}O$ signals. However, the amount of reproducibility found in 2 teaks growing in the same forest and 2 suar trees (also from Java, Indonesia) [7] along with low in-ring $\delta^{18}O$ variability measured in Alaskan Sitka spruce samples (Lamie, pers. comm.) support the idea that the $\delta^{18}O$ of cellulose may not be as sensitive as the $\delta^{13}C$ to locally modulated factors such as differing levels of irradiance, nutrient supply, growth rates and water stress. This issue clearly needs further investigation.

5. Conclusion

From the 11 trees sampled across northern Thailand, we identify 7 candidates for isotopic chronology. The samples are from deciduous tree species collected in Pangmapa and at a logging concession in Sop Paeng and show varying degrees of $\delta^{18}O$ and $\delta^{13}C$ seasonality. Stable isotopic age models are developed for ringless tree samples of *Miliusa velutina* (1950–2000) and *Quercus kerrii* (1980–2000) and agree to within ≤3 years with radiocarbon age estimates. The isotopic age models provide estimates of growth rates which are significantly correlated with the amplitude of the oxygen and carbon seasonal isotopic signals. Individual isotopic chronologies from different tree species share common trends, which are also consistent with patterns of rainfall variability. Clearly, additional studies are needed to confirm the climatic relevance of these records. At present, we find tantalizing evidence to suggest that the $\delta^{18}O$ tree chronologies recorded the drying trend of Thailand's monsoons over the past few decades.

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