Teak Tree-Ring Cellulose $\delta^{13}C$, $\delta^{18}O$, and Tree-Ring Width from Northwestern Thailand Capture Different Aspects of Asian Monsoon Variability

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Abstract: The inter-annual variability in tree-ring cellulose $\delta^{13}C$ ($\delta^{13}C_{TR}$, $\delta^{18}O_{TR}$), and tree-ring chronology in teak (TRW) (Tectona grandis L.f.) trees from Northwestern Thailand during 1901–2009 AD was performed. The $\delta^{13}C_{TR}$ and $\delta^{18}O_{TR}$ have a positive correlation, significant at $r = 0.400$, $p < 0.0001$, and both of the stable isotopes were not significantly related to the TRW. The TRW is related to rainfall in the first half of the rainy season and has a strong relationship with the relative humidity. The $\delta^{18}O_{TR}$ captured moisture well throughout the rainy season, and the $\delta^{13}C_{TR}$ had a strong correlation with rainfall in the second half of the rainy season and had a high correlation with cloud fraction and vapor pressure. The $\delta^{13}C_{TR}$ and $\delta^{18}O_{TR}$ were associated with the stomata conductance response, but had no effect on photosynthesis. The three indices of the teak annual ring respond well to the variability in the Asian monsoon, and give us a better understanding of both the hydrological cycle and the factors that contribute to the growing of tropical broadleaf trees under changing climates.

Keywords: $\delta^{18}O_{TR}$; $\delta^{13}C_{TR}$; tree-ring width; Asian monsoon variability; teak

1. Introduction

Tree-ring width (TRW) is the most widely used tree-ring proxy and one of the most useful paleo-climate proxies for reconstructing climate variability during the past millennium. In Southeast Asia, teak (Tectona grandis L.f.) was the first tree species successfully studied in the field of dendrochronology [1–5]. Teak grows naturally in tropical and subtropical climate zones and its natural distribution ranges from India to the Philippines [6]. In addition to being one of the best quality woods in the world, teak is durable and has a beautiful pattern. Teak tree-ring width variations have been used to effectively study climate variability and to reconstruct past climate [7]. Moreover, teak TRW has the potential to record the variability in specific climate events, such as El Niño occurrences [8,9] or variations in the Pacific decadal oscillation (PDO) [10].
Subsequently, the study of stable isotope variations in tree-rings in tropical regions has become possible. Stable isotopes in tree-ring cellulose have improved our understanding of the hydrological cycle and of tree physiological responses to climate events. Tree-ring stable oxygen ($\delta^{18}\text{O}_{\text{TR}}$) and carbon isotope studies ($\delta^{13}\text{C}_{\text{TR}}$) in Southeast Asia have increased in recent decades. Xu et al. [11] reconstructed the local Palmer Drought Severity Index (PDSI) from May to October by studying the $\delta^{18}\text{O}_{\text{TR}}$ of Fokienia cypress in Laos. It was also found that the El Niño southern oscillation (ENSO) has an important effect on the $\delta^{18}\text{O}_{\text{TR}}$ in Laos. Schollaen et al. [12] compared tree-ring width, $\delta^{13}\text{C}_{\text{TR}}$, and $\delta^{18}\text{O}_{\text{TR}}$ responses to the climate on Java Island, Indonesia, and discovered that all three were significantly related to precipitation, but that TRW mainly responded to the early rainy season, whereas isotope ratios mainly reflected precipitation maxima during the rainy season. Three different tropical tree species from different families (Tectona grandis, Samanea saman, and Podocarpus nerifolius) from Indonesia and Thailand have been measured with respect to $\delta^{18}\text{O}_{\text{TR}}$ and $\delta^{13}\text{C}_{\text{TR}}$ [13]. Stable isotope trends in seven analyzed deciduous trees reflected a monsoon drying trend during the past decades in Thailand. In addition, a growth rate model revealed that local rainfall was a significant driving factor [14].

Muangsong et al. [15,16] found that the intra-seasonal variability in teak $\delta^{18}\text{O}_{\text{TR}}$ in the northwest of Thailand is consistent with the pattern of changes in oxygen isotopes in precipitation, providing new insights for investigating seasonal changes in subtropical monsoons. Buajan et al. [17] determined a significant relationship between teak $\delta^{18}\text{O}_{\text{TR}}$ and hydrological cycles in both dry and rainy seasons in Northwest Thailand. Monsoon season rainfall in Northwest and Central Thailand has been reconstructed from pine $\delta^{18}\text{O}_{\text{TR}}$ [18,19]. In addition, pine $\delta^{18}\text{O}_{\text{TR}}$ revealed unstable relationships between inter-annual precipitation fluctuations and ENSO.

While the variation in $\delta^{18}\text{O}$ in tree-ring cellulose in Southeast Asia has revealed a high potential for reconstructing hydroclimate, the number of studies on $\delta^{13}\text{C}$ in tree rings is still limited. Inter-annual analysis on the $\delta^{13}\text{C}_{\text{TR}}$ variations in Pinus mekusii tree rings from Northwestern Thailand showed a strong correlation with monsoon season maximum temperature and enabled the reconstruction of 228 years of monsoon season maximum temperatures [20]. The fractionation of $\delta^{13}\text{C}$ in tree rings is mainly affected by stomatal conductance and the photosynthetic rate [21]. Since stomatal conductance is mainly controlled by moisture conditions (such as relative humidity), the photosynthetic rate is primarily affected by temperature, radiation intensity, and other factors, and hence $\delta^{13}\text{C}_{\text{TR}}$ is a promising proxy for paleoclimate reconstruction [14,22].

In this study, we present a TRW chronology from four teak trees, and generated annual $\delta^{13}\text{C}_{\text{TR}}$ and $\delta^{18}\text{O}_{\text{TR}}$ from these four teak trees to determine what climate factors control the variation in all three chronologies. We hypothesized that the different tree-ring parameters studied respond in different ways to climatic conditions and may be combined to obtain a better understanding of changes in climatic variability throughout the annual cycle. Specifically, we assume that TRW can capture rainfall during the first half of the rainy season, $\delta^{18}\text{O}_{\text{TR}}$ is able to reflect moisture conditions throughout the rainy season and has a strong correlation with ENSO, while $\delta^{13}\text{C}_{\text{TR}}$ has a good correlation with atmospheric vapor pressure deficit, which is mainly driven by the maximum temperatures.

2. Materials and Methods

2.1. Study Area and Sampling Process

Teak (Tectona grandis L.f.) samples that had previously been used to establish a TRW index and a climate reconstruction in previous research in Northwest Thailand [8] were used as study materials. The samples were collected from naturally distributed teak in the Pai wildlife sanctuary (Figure 1), Mae Hong Son province (MHS) (19°35′51″ N 98°11′43″ E; 269 m a.s.l.). Teak was distributed in a mountain range at 300–600 m a.s.l. alongside the Kong River. Approximately 218 cores from 109 trees were collected in January 2010 from trees at breast height using a 5 mm diameter increment borer. The circumference of the studied trees was in the range of 150 to 349 cm.
Figure 1. Map of Mae Hong Son province (on the right), Mae Hong Son meteorological station and the study area (black circle). Colors indicate the altitude of the area.

The core samples were mounted with the cross-section side view facing up. After the glue dried, the cores were sanded until the cross-section side revealed boundaries of tree rings enough to process a tree-ring measurement. The cores were measured on a LinTab measuring system and plotted with the TSAP program [23]. To cross-date the TRW series, each individual series was visually compared with the graph plots on the TSAP program, aided by the simple correlation check using the COFECHA program [24,25].

We selected 4 teak cores from 4 teak trees using the following selection criteria: (1) the specimen is very old, (2) the tree-ring boundaries are clearly visible, (3) the average ring width is not very narrow to provide sufficient cellulose for subsequent stable isotope analyses, and (4) the age determination is correct. For all four samples, cross-correlation was checked using the COFECHA software to ensure that the re-collected samples matched each other well. The Arstan program was used for fitting a 66-year spline function to each tree-ring series to eliminate the biological age trend [26]. Autoregressive modelling was applied and the series were averaged, using the robust means, to a white noise residual chronology.

2.2. Climate Conditions in Northwestern Thailand

According to the climate diagram from Mae Hong Son (MHS) meteorological station (Figure 2), which is located ca. 60 km away from the study sites in Northwestern Thailand, the summer monsoon climate is dominant from May to October. During the rainy season, monthly long-term (1951–2019) average rainfall is in the range of 133.8 to 249.3 mm and has a mean of 192.2 mm, with monthly mean temperature ranging from 26.6 to 29.3 °C, with a seasonal mean of 27.7 °C. Relative humidity in the rainy season is within the range of 74–84%, with a mean of 80%. During the dry season, which lasts from November to April, monthly mean rainfall ranges from 4.6 to 54.9 mm, with a mean of 22 mm. The monthly mean temperature in the dry season ranges from 23.7 to 26.1 °C, with a mean of 24.8 °C.
Relative humidity in the dry season is between 61 and 73%, with a mean of 68% [27] (Figure 2).

Figure 2. (A) Walter and Lieth climate diagram (Walter and Lieth, 1967) monthly rainfall totals and mean temperatures between AD 1951 and 2019 for the MHS (Thai Meteorological Department, 2019). The dark-blue area and blue lines represent rainfall and temperatures, respectively. Values on the left axis of the diagrams are average maximum and minimum temperatures of the warmest and the coldest months, respectively, whereas values on the upper right corner show annual average temperature and total precipitation. Areas shaded in black and gray indicate the moist and the arid periods. The growing season (grey shadow) of teak extends approximately from April to October. (B) MHS rainfall for the rainy season (May to October), and dry season (November to April), and annual sum (1951–2019), 20-year cubic-smoothing splines (thick black line) and linear trends lines (black line) show long-term fluctuations and trends.

2.3. Cellulose Extraction

Each annual ring was cut under a microscope with a sharp knife, then sliced to the smallest possible size and packed in an Eppendorf tube with sample code written on the tube. Alpha-cellulose was extracted following the method described by Wieloch et al. [28]. A detailed process for the alpha-cellulose extraction is described by Pumijumnong et al. [29].

We extracted the alpha cellulose for each annual ring separately instead of pooling the individual samples. This was done to investigate the relationship of isotope variation between trees and to calculate statistical parameters of chronology confidence (mean intercorrelation Rbar, expressed population signal EPS) [30].

Approximately 300 µg of each dried alpha-cellulose sample were weighed and wrapped in silver foil to be processed in mass spectrometry. The cellulose samples were converted to CO at 1450 °C by using an elemental analyzer (EA, HT oxygen analyzer, Thermo Fisher, Erlangen-Nürnberg, Germany) linked to an isotope ratio mass spectrometer (DELTA V Advantage, Thermo Fisher, Erlangen-Nürnberg, Germany). The ratios of $^{18}O/^{16}O$ were measured with respect to the VSMOW standard (Vienna standard mean ocean water) with an analytical precision of ±0.3‰ and expressed as δ$^{18}O$. The δ$^{18}O$ values were referred to as the international standard (Vienna standard marine ocean water: VSMOW): δ$^{18}O = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} \right] - 1 \times 1000$, where $R_{\text{sample}}$ and $R_{\text{standard}}$ are the $^{18}O/^{16}O$ ratios of the sample and standard, respectively. Alpha-cellulose extraction and δ$^{18}O$ analysis were performed at the Institute of Geography, University of Erlangen-Nuremberg, Erlangen, Germany.

For stable carbon isotope analyses, the alpha-cellulose samples were wrapped in tin foil (sample weight: 110–140 µg) and loaded into an auto sampler, in which every eight sample was inserted with a standard sample (IAEA-CH3, −24.724 ‰, VPDB) for
The samples were dropped into the element analyzer (Thermo Fisher flash 2000 organic elemental analyzer) and combusted to gas in oxidation (960 °C) and reduction (660 °C) furnaces. Purified CO₂ gas was separated in a gas chromatography column, then injected into an isotope ratio mass spectrometer (Thermo Fisher DELTA V Advantage) to determine a ¹³C/¹²C ratio. The result was presented in δ¹³C (‰) from the following equation:

\[ \delta^{13}C = \left( \frac{R_{sample}}{R_{standard}} - 1 \right) \times 1000 \]

where \( R_{sample} \) is a ratio of the samples and \( R_{standard} \) is a ratio of the standard deviating from Vienna Peedee belemnite (VPDB).

After each individual δ¹³C value was obtained, the first several decades were removed to avoid possible juvenile effects [21]. Then, the remaining individual δ¹³C were defined as NK3_21B (1910–2009 AD), NK3_19A (1929–2009 AD), NK02_02B (1901–2009 AD), and NK3_13A (1903–2009 AD).

Tree-ring δ¹³C cellulose was analyzed at the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China. In this study, we used a statistical correction for the effects of changing atmospheric δ¹³C (δ¹³C_air) [21]. The equation is as follows:

\[ \delta^{13}C_{corr} (‰) = (\delta^{13}C_{air} - \delta^{13}C)/(1 + \delta^{13}C)/1000) \]

where \( \delta^{13}C_{corr} \) and \( \delta^{13}C \) represent corrected and raw tree-ring δ¹³C, respectively. We used published values of δ¹³C_air for the period 1901–2003 from McCarroll and Loader [21], and extrapolated the near-linear decline of δ¹³C_air over the last decades to estimate the values for 2004–2009.

2.4. Statistical Analysis

Statistical tests for investigating the relationship between the mean δ¹³C_TR series, δ¹⁸O_TR series, and tree-ring chronology and monthly climatic data were computed using SPSS version 21. Monthly climatological data (precipitation, temperature, and relative humidity) during 1951–2019 AD were obtained from the MHS meteorological station, which is approximately 60 km away from the sampling site. In addition, precipitation and temperature data during 1951–2019 from the Climate Research Unit time-series (CRU TS) 4.04 (University of East Anglia Climatic Research Unit, 2008) (http://badc.nerc.ac.uk/data/cru/ accessed on 20 February 2021) and 0.5° × 0.5° gridded data sets averaged from four CRU grid points (18°15′ N, 97°45′ E; 18°15′ N, 97°45′ E; 19°45′ N, 97°45′ E; 19°45′ N, 98°15′ E) were used in this study. Spatial correlation analyses to examine the extensions of the derived climate tree-ring parameter relationships were performed using KNMI Climate Explorer (https://climexp.knmi.nl accessed on 30 March 2021).

3. Results

3.1. The Collection from the Effects of Changing Atmospheric δ¹³C

The mean δ¹³C_TR values of the four sample trees ranged from −26.46‰ to −23.37‰ (Figure 3A). The inter-tree variability showed a range from 0.37‰ to 1.24‰. The inter-correlations between NK3_21b, NK3_19a, NK2_02b, and NK3_13a were significant at the 0.01 level, varying from 0.79 to 0.84. A slightly decreasing trend was due to the increase in atmospheric CO₂ concentration, which has been found in most individual δ¹³C series. The trend-line among the four cores varied between −0.01‰ and −0.02‰ yr⁻¹. The decreasing trend, due to atmospheric CO₂ concentration, has been found in most of the tree-ring δ¹³C studies [21,31–33]; some had reported no decreasing trend in tree-ring δ¹³C related to atmospheric CO₂ increase [34–36].
Table 1. The correlation coefficients among the samples of tree-ring width, tree-ring $\delta^{13}$C, and tree-ring $\delta^{18}$O.

| Samples   | Tree-Ring Width | Tree-Ring $\delta^{13}$C | Tree-Ring $\delta^{18}$O |
|-----------|----------------|--------------------------|--------------------------|
|           | 13a  19a  21b  02b | 13a  19a  21b  02b | 13a  19a  21b  02b |
| TKNK3_13a | 1               | 1                        | 1                        |
| TKNK3_19a | 0.459           | 1                        | 0.764                    |
| TKNK3_21b | 0.627           | 0.339                    | 0.828                    |
| TKNK3_02b | 0.767           | 0.265                    | 0.678                    |

All statistics are significant at the $p < 0.01$ level.

We presented the TRW of four trees and residual chronology, tree-ring $\delta^{13}$C of four trees ($\delta^{13}$C_{TR}), and tree-ring $\delta^{18}$O ($\delta^{18}$O_{TR}) of four trees with EPS and Rbar (Figure 4A). We found that all of the tree-ring parameters had EPS values surpassing the recommended threshold of 0.85 [30]. For TRW, the EPS span a range of 0.83–0.96, and Rbar was in the range of 0.78–0.91. The $\delta^{13}$C_{TR} chronology displays EPS values in the range of 0.83–0.91, and Rbar is in the range 0.61–0.72 (Figure 4B), and the $\delta^{18}$O_{TR} chronology shows EPS and Rbar values in the range of 0.93–0.96 and 0.78–0.91, respectively (Figure 4C).
We found a highly significant correlation between the δ\(^{13}\)C\(_{TR}\) series and δ\(^{18}\)O\(_{TR}\) series, and we found that the two stable isotope series had no significant correlation with the TRW chronology (Table 2).

Table 2. Correlation coefficient between tree-ring chronology (TRW), tree-ring δ\(^{13}\)C (δ\(^{13}\)C\(_{TR}\)), and tree-ring δ\(^{18}\)O (δ\(^{18}\)O\(_{TR}\)).

| Chronology | δ\(^{13}\)C\(_{TR}\) | TRW | δ\(^{18}\)O\(_{TR}\) |
|------------|----------------|-----|----------------|
| δ\(^{13}\)C\(_{TR}\) | 1 | | |
| TRW | 0.060 | 1 | |
| δ\(^{18}\)O\(_{TR}\) | 0.400 ** | 0.022 | 1 |

** Correlation is significant at the p < 0.01 level.

The ages of the four studied teak trees ranged between 98 and 136 years (1874–2009). The important statistics are that the correlation with master chronology is 0.637, standard
deviation (SD) is 1.430, autocorrelation is 0.684, mean sensitivity is 0.344, signal-to-noise ration 1.351, and variance in the first eigenvector is 61.74%. It implies that these teak trees exhibit similar growth patterns and that their TRW responds well to the climate.

Since we did not find any juvenile effects in any of the stable oxygen isotope series, we averaged the δ18O values of contemporaneous tree rings to obtain the mean δ18OTR chronologies. The mean δ18O chronology has a long-term mean of 24.7‰, with values ranging between 22.5 and 26.2‰.

### 3.3. Climate Correlation of Tree-Ring Parameters

TRW was significantly positively correlated with MHS rainfall of the months May, June and July, at a significance at the \( p < 0.05 \) level. The significant relationship between TRW and rainfall in the first half (MJJ, \( r = 0.335, p < 0.001 \)) of the rainy season was higher than that for the whole rainy season (May to October, \( r = 0.286, p < 0.004 \)). Likewise, TRW was significantly positively correlated with relative humidity (RH) for most of the year, except November. The highest significant positive correlation during the rainy season (May to October) was \( r = 0.517, p < 0.0001 \). In turn, TRW was significantly negatively correlated with the maximum temperatures in January, May, and June, at a significance at the \( p < 0.05 \) level, the first half of the rainy season (MJJ, \( r = -0.312, p < 0.016 \)) and throughout the rainy season, at a significance at the \( p < 0.05 \) level.

The \( \delta^{13}C_{TR} \) showed a negative correlation with rainfall in January, September, at a significance at the \( p < 0.05 \) level, the second half of the rainy season (ASO, \( r = -0.299, p < 0.003 \)), and throughout the rainy season, at a significant at the \( p < 0.05 \) level. In turn, the \( \delta^{13}C_{TR} \) has a positive correlation with the maximum temperature in September (\( r = 0.298, p < 0.022 \)). We found that \( \delta^{13}C_{TR} \) was insignificant with relative humidity.

The tree-ring \( \delta^{18}O_{TR} \) showed a positive correlation with rainfall only in April, a negative correlation with rainfall in July, August at a significance at the \( p < 0.05 \) level, the second half of the rainy season (ASO, \( r = -0.270, p < 0.007 \)), and throughout the rainy season (May to October, \( r = -0.309, p < 0.002 \)). The \( \delta^{18}O_{TR} \) showed a negative correlation with relative humidity in July (\( r = -0.306, p < 0.018 \)), and the second half of the rainy season (ASO, \( r = -0.260, p < 0.047 \)) (Figure 5).

![Figure 5](image-url)  
**Figure 5.** Correlation between the tree-ring chronology (TRW) (top panel), tree-ring \( \delta^{13}C \) chronology (middle) and tree-ring \( \delta^{18}O \) chronology (lower panel) with MHS meteorological station data (precipitation, maximum temperature and relative humidity). The black bars indicate significance at \( p < 0.01 \), the gray bars are significant at \( p < 0.05 \), and the white bar graph indicates non-significant correlation values. The yellow frame highlights the growing season. The blue areas indicate the values of precipitation (mm), maximum temperature (°C), or relative humidity (%) in the different columns.
TRW correlated significantly positively with CRU TS4.04 rainfall in May, August, the first half of the rainy season (MJJ), the second half of the rainy season (ASO), and throughout the rainy season (May to October) \( (p < 0.05) \). In turn, TRW and maximum temperature were found to be significantly negatively correlated \( (p < 0.05) \) in January, March, May, the first half of the rainy season (MJJ), throughout the rainy season (May to October), and throughout the dry season (November to April). TRW and potential evaporation were found to be significantly negative correlated \( (p < 0.05) \) in January, May, and throughout the dry season (November to April). TRW correlations were insignificant with the cloud fraction and vapor pressure.

The \( \delta^{13}C_{TR} \) and CRU TS4.04 rainfall were found to be significantly negatively correlated in January, September, and throughout the rainy season (May to October) \( (p < 0.05) \). In turn, \( \delta^{13}C_{TR} \) and the maximum temperature were found to be significantly positively correlated in September \( (r = 0.302) \), and the second half of the rainy season (ASO, \( r = 0.213 \)). \( \delta^{13}C_{TR} \) and CRU TS4.04 potential evaporation were found to be significantly negatively correlated in June \( (p < 0.05) \). In turn, \( \delta^{13}C_{TR} \) and cloud fraction were found to be significantly positively correlated \( (p < 0.05) \) in April, June, July, August, the first half of the rainy season (MJJ), and throughout the rainy season (May to October). \( \delta^{13}C_{TR} \) and vapor pressure were found to be significantly negatively correlated \( (p < 0.05) \) in April, July, August, September, October, and the second half of the rainy season (ASO).

The \( \delta^{18}O_{TR} \) and CRU TS4.04 maximum temperatures were found to be significantly positively correlated \( (p < 0.05) \) in July, September, November, and December, and the second half of the rainy season (ASO). \( \delta^{18}O_{TR} \) and potential evaporation were found to be significantly negatively correlated \( (p < 0.05) \) in April. In turn, \( \delta^{18}O_{TR} \) and cloud fraction were found to be significantly positively correlated \( (r = 0.282) \). \( \delta^{18}O_{TR} \) and vapor pressure were found to be significantly negatively correlated \( (p < 0.05) \) in October, May to October, and throughout the dry season (November to April).

The \( \delta^{18}O_{TR} \) and CRU TS4.04 rainfall were found to be significantly negatively correlated in July \( (r = -0.329) \), August \( (r = -0.247) \), September \( (r = -0.232) \), the first half of the rainy season (MJJ, \( r = -0.301 \)), the second half of the rainy season (ASO, \( r = -0.347 \)), and throughout the rainy season (May to October, \( r = -0.473 \)) (Figure 6).

![Figure 6](image-url). Correlation between the tree-ring chronology (TRW) (top panel), tree-ring \( \delta^{13}C \) chronology (middle) and tree-ring \( \delta^{18}O \) chronology (lower panel) with CRU TS4.04 climate data (precipitation, maximum temperature, potential evaporation, cloud fraction, and vapor pressure). The black bars indicate significance at \( p < 0.01 \), the gray bars are significant at \( p < 0.05 \), and the white bar graph indicates non-significant correlation values. The yellow frame indicates the growing season.

The \( \delta^{18}O_{TR} \) was significantly positively correlated \( (p < 0.0001) \) with El Niño 3.4 region sea surface temperatures (SST) from June to December. This correlation was also found in
the TRW, although relatively weak, but still significant at p < 0.05, whereas no significant correlation was observed between the $\delta^{13}C_{\text{TR}}$ and El Niño (data not shown).

4. Discussion
4.1. Chronology Characteristics of All Tree-Ring Parameters

We developed three chronologies of different teak wood parameters, namely, TRW, $\delta^{13}C_{\text{TR}}$, and $\delta^{18}O_{\text{TR}}$, from the same four sampled trees (TKNK3-13A, TKNK3-19A, TKNK3-21B, and TKNK2-02B) from Mae Hong Son province, Northwest Thailand. The teak tree-ring index covered from 1876 to 2009. The individual TRW series synchronized well, so it was possible to develop a teak TRW chronology.

From the atmosphere-corrected $\delta^{13}C_{\text{TR}}$ series, we created a mean $\delta^{13}C_{\text{TR}}$ series covering the period of 1901–2009. Because the $\delta^{18}O_{\text{TR}}$ did not show any juvenile effect, and each sample has a high coherence, we created a mean $\delta^{18}O_{\text{TR}}$ series from four oxygen isotope samples, which covered the period 1873–2009. The $\delta^{13}C_{\text{TR}}$ and the $\delta^{18}O_{\text{TR}}$ correlated at $r = 0.400$ ($p < 0.0001$), but both the correlations of the stable isotope chronologies and TRW are not significant. The results of this study differ from a study on Acacia species in Ethiopia, where the TRW and $\delta^{13}C_{\text{TR}}$ series had a negative relationship [22]. Under those climate conditions, similar environmental factors influence TRW and carbon isotope fractionation, i.e., photosynthesis rate, stomatal conductance [21,37], or it may depend on species-dependent adaptations [38]. The results of our studies are consistent with [37], who argued that TRW does not correspond to $\delta^{13}C_{\text{TR}}$ because trees have different stomatal conductance and the ability to photosynthesize is the same. Hence, the leaf intercellular CO$_2$ concentration C$_i$ may remain constant. Atmospheric $\delta^{13}C$ is discriminated and imprinted in plant $\delta^{13}C$ under the influence of photosynthesis and stomatal conductance factors related to temperature, light intensity, and moisture. Additionally, tree architecture itself also contributes to inter-tree $\delta^{13}C$ variability (e.g., root system and circumferential shapes [39]). Tree genetics also affect $\delta^{13}C$ variability. Previous studies have reported that inter-tree variability from genetic contributions was at 1–3‰ [40].

We compared our $\delta^{18}O_{\text{TR}}$ chronology with other proxies within the region. The relationship between our $\delta^{18}O_{\text{TR}}$ and a teak $\delta^{18}O_{\text{TR}}$ from Phrae province, which is approximately 400 km away, was $r = 0.446$, $p < 0.001$ [16], and Myanmar teak $\delta^{18}O_{\text{TR}}$ was 0.532, $p < 0.001$ [41]. We also found significant relationships between our teak $\delta^{18}O_{\text{TR}}$ and Pinus merkusii $\delta^{18}O_{\text{TR}}$ from Mae Hong Son ($r = 0.636$, $p < 0.0001$) [19] and Tak province ($r = 0.532$, $p < 0.001$) [18]. We suggest that the reason for the consistency of isotope patterns between sites is the presence of a common moisture source for the studied teak and Pinus merkusii trees within the monsoon region. It is interesting that our teak $\delta^{18}O_{\text{TR}}$ also correlated with Fokieenia hodginsii tree-ring $\delta^{18}O$ chronologies from Vietnam ($r = 0.309$, $p < 0.001$) [42] and Laos ($r = 0.312$, $p < 0.001$) [11].

4.2. Climate Control of the Teak Tree-Ring Parameters

The relationship between our TRW index, and the MHS climate data and CRU TS4.04 data was in the same direction, as follows: rainfall in the first half of the rainy season (MJ) had a significantly positive effect on the TRW index and relative humidity of individual months, and also seasons had a significant positive effect on the TRW index. On the other hand, the maximum temperatures in May and June, during the first half of the rainy season, and the whole rainy season (May to October) had a significant negative effect on the TRW index. These findings are consistent with previous studies [1,3,4,44].

Schollaen et al. [12] found that $\delta^{13}C_{\text{TR}}$ of Java teak was negatively associated with the peak rainfall (December to November). The results of this study differ from ours, since we found a correlation between $\delta^{13}C_{\text{TR}}$ and rainfall almost at the end of the rainy season. The result of our study is consistent with the theory for the carbon fractionation of most broadleaf trees with ring-porous wood anatomy, regarding the process of post-photosynthesis and carbon isotope signals being transmitted from the leaf level to develop wood tissue [38]. Interestingly, $\delta^{13}C_{\text{TR}}$ has a significant positive correlation with the cloud
fraction during the main rainy season (Figure 7D). Conversely, $\delta^{13}C_{TR}$ has a significant negative correlation with vapor pressure during the main rainy season (Figure 7C). Generally, the ratio of $^{13}$C to $^{12}$C in leaves and in the trunk ranges between $−20\%$ and $−30\%$ (VPDB), which is much lower than the $\delta^{13}C$ of air, which is about $−8\%$. The change from $^{13}$C/$^{12}$C sources to a tree is called “fractionation”, much of which is due to the influence of trees responding to the environment. It was therefore concluded that the important environmental factors controlling the proportion of carbon isotope in the tree ring were to control the stomata conductance rate and photosynthesis rate [21]. During the rainy season (May to October) the temperature is quite high, causing high evaporation. However, relative humidity during this period is also high. The enrichment of $\delta^{13}C_{TR}$ is the result of reduced stomatal conductance, due to the high evaporation during the hot rate rainy season.

Figure 7. (A) Correlation of tree-ring $\delta^{13}C$ with July–September averaged CRU TS4.04 precipitation 1901–2009, $p < 10\%$; (B) correlation between tree-ring $\delta^{13}C$ with June–August averaged CRU TS4.04 potential evaporation 1901–2009, $p < 10\%$; (C) correlation between tree-ring $\delta^{13}C$ with August–October averaged CRU TS4.04 vapor pressure 1901–2009, $p < 10\%$; (D) correlation tree-ring $\delta^{13}C$ with June–August averaged CRU TS4.04 cloud fraction 1901–2009, $p < 10\%$.

Ohashi et al. [45] studied a radial file of five-year-old teak at intra-annual resolution and found that the $\delta^{13}C$ value had rapidly increased before decreasing to a minimum near the end of the growing season. The researchers concluded that the variation in isotope carbon value was controlled by changes in the moisture availability, and that the carbon isotope distribution in the tree-ring was confirmed to be dependent on the $^{13}$C-enriched reserve material from the previous year. Although our study used annual rings, the results were consistent. We found a correlation between $\delta^{13}C_{TR}$ and rainfall in the late wet season. We found that the water vapor pressure during the rainy season has a significant negative relationship with $\delta^{13}C_{TR}$. Based on our $\delta^{13}C_{TR}$ value, we assumed that the impact of photosynthesis on intercellular CO$_2$ concentrations (C$_i$) was higher that of stomatal conductance (g$_s$). However, it is interesting to study intra-annual stable isotope variations...
in conjunction with the cambium activity in the same tree, for a better understanding of the physiological and biological mechanisms of teak trees.

Tree-ring $\delta^{13}C_{TR}$ was negatively associated with the second half of rainy season rainfall (ASO). Such findings may explain why, at the beginning of the growing season, teak cambium divides and the formation of wood may be dependent on past-stored carbon material. Because teak shed its leaves in the dry season and the leaves bloom at the beginning of the rainy season, teak does not have any leaves at the beginning of the growing season. After leaf flush, photosynthesis takes place, and the carbon isotope signal appears in the tree ring [12,38]. Hence, correlations between $\delta^{13}C_{TR}$ and rainfall were found in Thai teak, but not in Indonesia [12] and India [46].

The study of the ratio of the net photosynthesis rate and transpiration rate of young teak trees in Panama found that teak continued to demonstrate high carbon absorption efficiency, significant physiological plasticity under different water-constrained conditions, and the ability to recover from stress from rapid drought, thus making teak a species with high water use efficiency [47]. Often, a high water use efficiency goes in line with drought tolerance. However, when the tree takes up soil moisture, there is no fractionation of oxygen isotopes until the water is delivered to the leaves, so isotope fractionation occurs during transpiration, with gas exchange depending on the temperature and ambient humidity. This causes the loss of the lighter oxygen isotope and a consequent enrichment in leaf $^{18}O$.

In the case of our study, teak was grown in an area approximately 300–600 above sea level. So, we expect isotope signaling caused by evaporation enrichment of the upper soil layers to be irrelevant. Since the roots of teak are not very deep, they take up moisture from the falling rain, but not from the deeper soil layers.

The relationship between $\delta^{18}O$ in tree-ring cellulose and climate factors in this study is consistent with previous studies of teak in other regions of Thailand [16]. It exhibits an inverse relationship with the MHS rainfall ($MO, r = -0.309, p < 0.002$), and CRU TS4.04 rainfall ($MO, r = -0.470, p < 0.0001$). This study found no correlation between $\delta^{18}O_{TR}$ and $\delta^{18}O_{rain}$ from Bangkok Station. This could be due to the distance from Bangkok to Mae Hong Son, about more than 700 km, and the moisture source of the rainfall at Bangkok and Mae Hong Son is different. Researches have confirmed that the source of moisture or rainfall at Mae Hong Son during the first half of the rainy season (MJJ) was influenced by the Indian Ocean, whereas the moisture source in the second half of the rainy season (ASO) was influenced by the South China Sea [15,48,49]. The $\delta^{18}O_{TR}$ was significantly positively correlated with the Niño3.4, Niño4 (data not shown), which is consistent with previous studies [44,50,51].

Climate factors modulate trees’ physiology, which governs stable isotope fractionation in plant tissues. Studies of dual stable isotopes are very interesting and add to the understanding of the study of plant adaptation to the changing environment. The two stable isotopes show some correlation, indicating that stomatal conductance is related to the regulation of equilibrium between the supply of carbon dioxide and water loss. Factors controlling moisture loss also cause the fractionation of oxygen isotope leaf water and are not independent of each other [21]. Our results are consistent with the conceptual model of [52], who proposed a positive correlation of $\delta^{18}O_{TR}$ and $\delta^{13}C_{TR}$, concluding that these isotopes were associated with the stomatal conductance response, while photosynthesis had no effect.

5. Conclusions

We developed chronologies of various tree-ring parameters using four teak trees. The tree-ring chronology was significantly positively correlated with rainfall in the first half of the rainy season (MJJ), and significantly positively correlated with relative humidity most of the year, except for November. On the other hand, $\delta^{13}C_{TR}$ and $\delta^{18}O_{TR}$ were significantly negatively associated with rainfall in the second half of the rainy season (ASO). $\delta^{18}O_{TR}$ correlated significantly with the El-Niño. Instead, $\delta^{13}C_{TR}$ correlated significantly with cloud fraction, the potential of evaporation, and vapor pressure during the monsoon
period over the northern part of Thailand. The three indices of teak wood only correlated with the current year climate variables. Further studies should be carried out on a high resolution of dual stable isotopes and the water use efficiency of teak. It will provide a better understanding of the growth of teak under climate change conditions.

Author Contributions: Conceptualization, N.P.; methodology, S.B., C.M. and Q.L.; formal analysis, P.S.; resources, U.C.; data curation, P.P., P.S. and K.P.; writing—original draft preparation, N.P.; writing—review and editing, C.M. and S.B.; Discussion, A.B., Y.L.; funding acquisition, N.P. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the grant number RSA6280017; the grants from the CAS Key Research Program of Frontier Sciences (grant number QYZDJ--SSW--DQC021), (grant number NSFC41630531), (grant number XDPB05), (grant number GJHZ1777); the Key Project of IEECAS and the SKL-LQG.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: To exclude this statement.

Conflicts of Interest: The authors declare no conflict of interest.

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