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A 177 Years Extended of Teak Chronology Revealing to the Climate Variability in Phrae Province, Northern of Thailand

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Abstract

Teak ring-width is one of the promising paleoclimate proxies in the tropical region. Tree-ring chronology spanning from 1840 to 2016 (177 years) was derived from 76 trees from Phrae Province, northern Thailand. A total of 141 core samples were cross-dated, a standardized master was constructed, and the tree residual master chronology was developed by ARSTAN program. The tree-ring chronology has a significant positive correlation with the monthly rainfall and relative humidity during the monsoon season (May–June). In addition, the growth of tree-ring width also significantly inversely correlated with Niño 3, Niño 3.4, and Niño 4 indices during the second half of the dry season (January–March). We reconstructed summer monsoon season (May–June) rainfall based on a linear regression model which explained 21.95% of the actual rainfall variance. The trend of the reconstructed rainfall record shows a decrease of 0.6 mm per decade and substantially showed four wet periods and five dry periods. These results suggest that this teak chronology has a good potential to be a high-resolution proxy for reconstructing the past local climate in northern Thailand.

Keywords: Teak (*Tectona grandis* L.f.); Dendrochronology; Tree-ring width

Introduction

Paleoclimatic studies are desirable to find out the dynamics of past climate, in order to composite information to explain past historical evidence, or help in predicting future climate. In Thailand, the climate data are relatively limited. Natural paleoclimate proxy information provides a past record of climate data (e.g. precipitation, temperature, and humidity) when recorded data from meteorological instruments is lacking [1]. The paleoclimatological proxies could be extracted from various kinds of natural sources such as sediments from lakes or oceans, ice cores, pollen, speleothems, coral reefs, and tree-ring [2-5].

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Dendrochronology has powerfully contributed to the reconstruction of past climate as well as to the forecasting of future climate via climate change models. Tree ring measurements are one of the biological proxies which provide annual climate data resolution as a distinctive characteristic, resulting in the potential to reconstruct past climate patterns [2, 6-7].

Dendrochronological studies began in the north and south temperate zones; whereas, the tropical zone is unreliable at providing past climate information accurately from annual ring data because of climate limitations. In the temperate region, a warm growing season alternates with a winter low temperature resulting in distinct annual growth rings in an abundance of tree species, whereas tropical regions do not have such an obvious seasonality making dendrochronological study a challenge in the equatorial zone. Dendrochronology needs to be studied not only on temporal, but also on spatial scale by extending studies from the temperate to the tropical region [8-10]. Teak (*Tectona grandis* L.f.) is one of the few tropical tree species suitable for dendrochronology which has been approved to be a good potential for climate reconstruction because of its different and reliable growth rings affected by climate factors, especially precipitation, in sites where rainfall is the limiting factor for tree growth [11-12]. Consequently, teak has been widely used in dendrochronological research in the tropical area, including Southeast Asia [10, 12-19].

Thailand is a country that has a wide natural teak distribution and its rings have been applied in the dendroclimatology using both physical characteristics such as vessel diameter and tree-ring width [13-15, 17-18, 20] and chemical characteristic such as cellulose oxygen isotope [21-23]. The growth of teak ring width in the north of Thailand is predominantly controlled by rainfall which clearly separates the climate into wet and dry seasons (April–October and November–March, respectively). As a result, the signal of Asia monsoon’s influence on Thailand could be captured by the discernible pattern of tree ring which is noticeable when wet periods alternate with dry periods [24]

The teak chronological network in northern Thailand was originally constructed by Pumijumnong and team and a strong correlation between tree rings growth and the amount of rainfall during the first half of the monsoon season (April–July) was found [18]. Furthermore, in Mae Hong Son Province, 413 years of teak chronology was developed [13], and then extended to a 448-year chronology [10]. These studies show the potential of teak chronologies to reveal paleoclimatic variations over a period of at least four centuries.

However, the teak network in Thailand needs to be extended in both spatial and temporal dimensions to magnify the climate dynamic. Therefore, the aim of the current study is to develop and expand the teak chronological index in Phrae Province, northern Thailand. This teak chronology was examined to see if it can detect the signal of Asia monsoon seasons, and the teak rings index was used to reconstruct the rainfall pattern over almost two hundred years.

Materials and methods

1) Study site

The teak tree specimens were living trees at an elevation of 385-550 m in the area of Mae Yom National Park which occupies a total of 455 km^2 in Lampang Province and Phrae Province, northern Thailand. It is located at latitude 18°44′45″ N and longitude 100°11′45″ E (Figure 1(a)). There are dense naturally grown teak trees and the land is mountainous and fertile. Mixed deciduous forest occupies the area with tree species such as *Tectona grandis*, *Afzelia xylocarpa*, *Xylia xylocarpa*, *Pterocarpus macrocarpus*, and *Lagerstroemia calycarpa*.

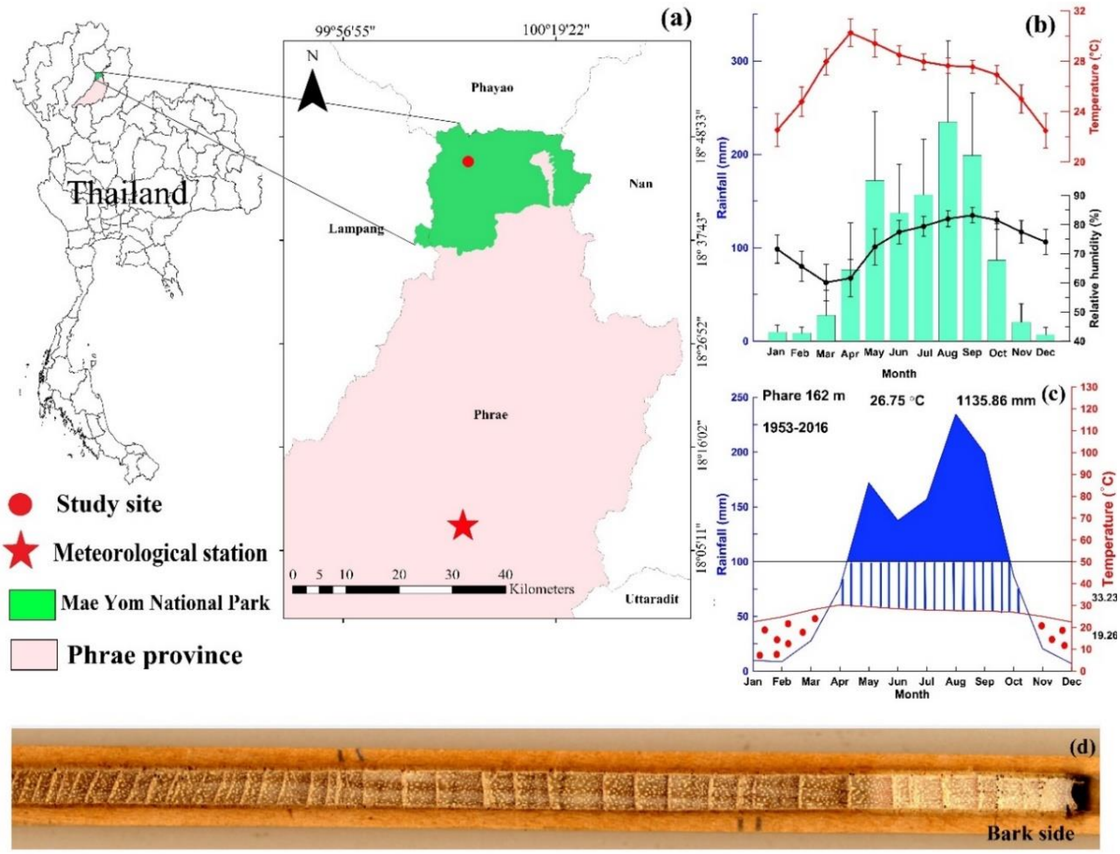

Figure 1 (a) Map of the study site (red circle), Mae Yom National Park (green area), Phrae Province, northern Thailand and Phare meteorological station (red star) 18°07′42″ N,100°09′44″ E; (b) climate condition from 1953-2016; totally monthly rainfall (bars), mean temperature (red line) and mean relative humidity (black line) in Phrae Province; (c) Walter and Lieth climate diagram; total monthly rainfall (blue line), mean temperature (red line), drought period (red dot area), wet period (blue area), and humid period (blue line area); (d) the tree-ring core sample.

The climatological data (total monthly rainfall, mean monthly temperature, and mean monthly relative humidity from 1953 to 2016) were obtained from Phrae meteorological station, Thai Meteorological Department. This station is located at latitude 18º07′42″ N and longitude 100º09'44.1″ E, approximately 80 km from Mae Yom National Park. The height of the instrument that recorded the climate data is 162 m a.s.l. The summer season is from February to May and the rainy season is from June to September. The study site and the plots of monthly rainfall, temperature, and relative humidity that were used to be the climate data of the study site are illustrated in Figure 1(b) and (c).

2) Sample collection and preparation

The teak samples from 76 living trees were taken in October 2016 as thin cylinder cores 5 mm. in diameter using a Swedish increment borer. The samples were collected at approximately 1.30 m above the ground for the purpose of obtaining the longest possible ring sequences with a minimum of individual variability. At least two core samples were collected from each individual tree. Individual tree core samples were stored immediately in a standard plastic sample tube [9]. The sample preparation and measurement were based on standard dendrochronological techniques [25]. The collected cores were checked and then mounted on wooden supports. The sampling cores were cut on the long axis of the cells using a cutter and a scalpel, which is the simplest and fastest method for soft timbers. The sampling cores that had indistinct tree rings, were sanded down to improve visibility [26-27].

3) Measurement of tree-ring width

The core samples, which had tree-ring width clearly visible, were observed under a stereo microscope. The ring width in each core was measured and counted by using a LINTAB™ digital linear positioning table (Frank Rinn Company, Heidelberg, Germany) connected to a stereo microscope (Leica GZ6 microscope) and computer with tree-ring analysis software, TSAP-Win™ software, version 4.64 for Microsoft Windows [28].

4) Cross-dating and chronology construction

The cross-dating process was carried out using tree-ring width data through Math-Graph window of TSAP-Win™ software. The data were then checked by the COFFCHA program v. 3.02P for possible measurement or dating error [29]. This involves statistical cross-dating to test each individual series against a master chronology (mean of all series) on the basis of correlation coefficients. Based on the output of COFECHA, several core samples ring-width data were rechecked and modified to increase cross-dating accuracy (the exact correct ring width in each year and the exact correct of number of tree-ring in each core sample). The ARSTAN (Auto Regression Standardization) software was used to detrend and standardize the dated ring width measurement series in order to produce the master tree-ring chronology [30-31].

5) Climate response on tree-ring width

The DENDROCLIM 2002 software developed by Biondi et al. [32], was used for statistical analyses. The correlations between tree-ring chronology and climate variables (monthly total rainfall, humidity, temperature, and Niño indices) were analyzed. The data of Niño indices, namely Niño 3, Niño 3.4, and Niño 4, were derived from Climate Data Guide: Niño SST Indices (Niño 3, 3.4, 4; ONI and TNI) of the National Center for Atmospheric Research. The correlation between climatic data and tree-ring chronology was calculated using DENDROCLIM2002 that were tested by a bootstrap response function analysis at the 95% significant confidence level.

6) Reconstruction of past climate pattern

Climate factors that gave a high correlation with tree-ring chronology were then evaluated for the potential to reconstruct past variations through statistical analysis. Calibration and verification of the statistical models were always compared in a two-way direction of year period [30]. The actual climate data and tree-ring chronology was tested by dividing into 2 groups of years, half and half. The statistical analysis included the coefficient of correlation (R), the coefficient of determination (R^2), reduction of error statistic (RE), and coefficient of efficiency (CE) determines which climate factors have a high capability to be reconstructed. Following conventional acceptance of verification statistics, the best models had RE values that were positive and greater than CE [33]. Therefore, the data of the above statistics were displayed to confirm the reliability of reconstructed the past climate pattern.

Results

1) Tree-ring chronology

The Mae Yom (MY) chronology, which was dated back of samples, spans from 1840 to 2016 (177 years). The number of sample cores that could be cross-dated is 141. This chronology was constructed using raw data from 76 trees (141 cores). The results of basic statistics are shown in Table 1. The teak residual chronologies and the sample size (the number of tree) through time are illustrated along with the running expressed population signal (EPS) and running mean series intercorrelation (Rbar) using 40-year moving windows with 20-year overlapping (Figure 2). The threshold of EPS at 0.85 was reached at a sample size of 13 trees after 1885; therefore, the reliability years of the index for further reconstructed climate are 1885 to 2016.

Table 1 Statistic description of teak chronology

Statistic	Statistic value
Time-span	1840 – 2016
Year	177
Average ring width (mm)	2.20
Series intercorrelation	0.69
Mean sensitivity	0.49
Autocorrelation	0.53
Standard deviation (SD)	0.15
Correlation between trees	0.44
Correlation within trees	0.57
Signal-to-noise ratio	44
Agreement with population chronology	0.94
Variation in 1 eigenvector (%)	46.80

2) The tree-ring chronology and climate relationship

The tree-ring chronology start from 1840 to 2016, but unfortunately, the available of climate data are start from 1953. Therefore, the climate data and tree-ring growth correlation were analyzed by using the climate data from October of the previous year to December of the current year (15 months) from 1953–2016 and the results are summarized in Figure 3. There is a high correlation between tree-ring chronology and climate data (rainfall, temperature, and humidity) from May to June (early monsoon season). The indices displayed a significant positive correlation with rainfall and humidity, whereas there was a significant negative correlation with temperature (Figure 3(a)). Moreover, the tree chronology is strongly negatively correlated with Niño 3 index during previous December to March, Niño 3.4 index during January to April, and Niño 4 during January to May. Overall, the index is mainly correlated with Niño indices during the second half of the dry season (January–March) (Figure 3(b)).

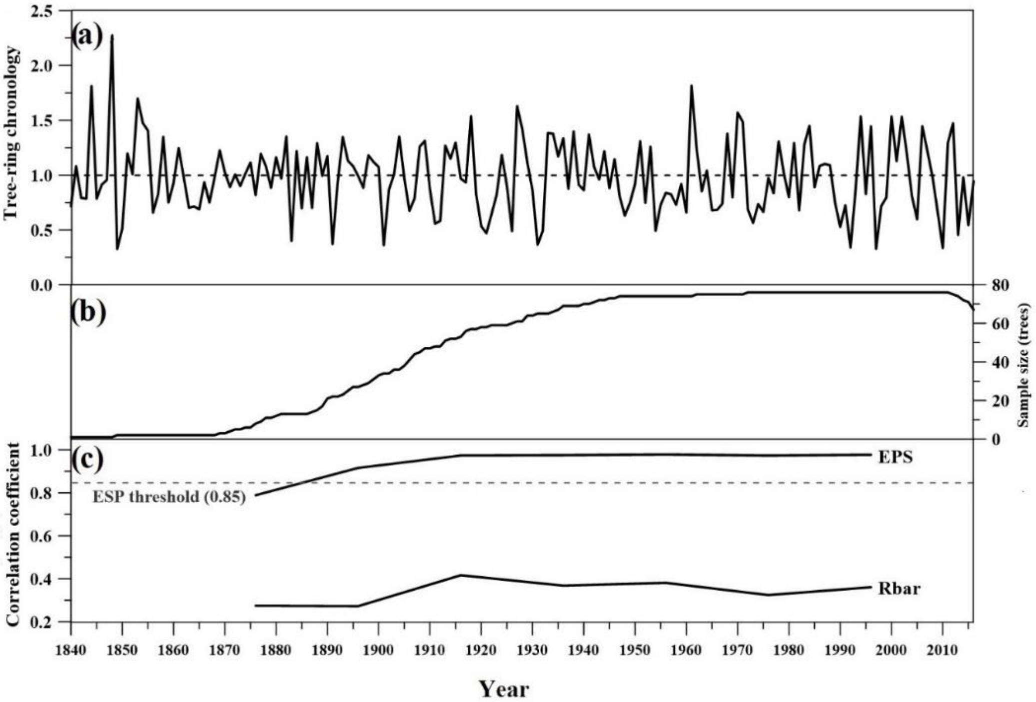

Figure 2 (a) The tree-ring chronology, (b) samples size (the number of trees) and (c) variation in running EPS and running Rbar.

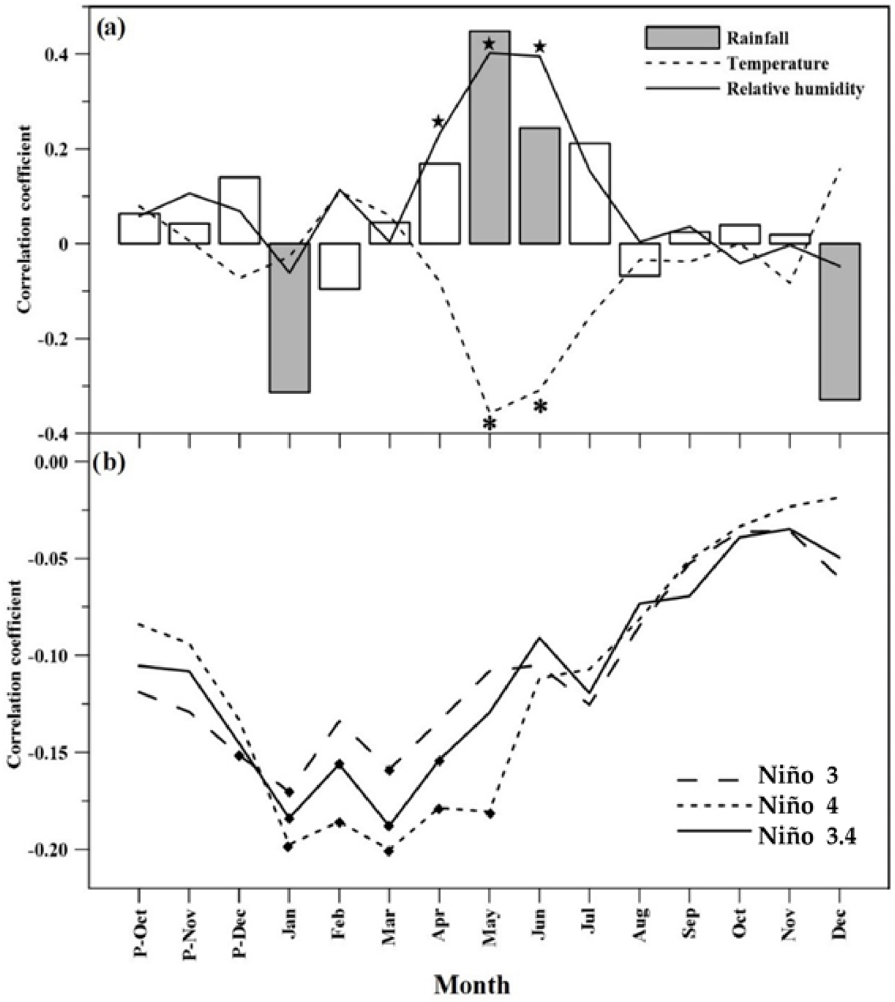

Figure 3 (a) The correlation between climate data (rainfall, temperature, and relative humidity) and tree-ring chronology. The grey bars, ∗, and ★ indicate the significant correlation between the tree-ring chronology and climate factors at $p<0.05$. (b) The correlation between Niño indices and tree-ring chronology. The black diamond symbol (♦) indicates the significant correlation between the tree-ring chronology and Niño indices at $p<0.05$.

3) The rainfall reconstruction from tree-ring chronology

The climate data of the months that significantly correlated with tree-ring chronology were further investigated for reconstructing climate patterns by statistical analysis. The significance of the calibration and verification statistics indicates favorable reconstruction. The statistics involved in the coefficient of correlation (R), the coefficient of determination (R^2), reduction of error statistic (RE), of calibration and verification of two periods (1953–1984 and 1985–2016) are presented in Table 2.

The statistic of tree-ring chronology and the actual rainfall has shown a positive sign test of RE and CE, means that data is reliable [26, 30], although the R^2 values are slightly low. There are slightly different R (0.455-0.497) and R^2 values (0.207-0.247) in different periods of the year. The RE is higher than CE for both two periods; 1953–1984 and 1985–2016 and CE values are more than zero (Table 2). Overall, the rainfall variable showed the greatest potential to reconstruct past patterns, although its R^2 value is low. The scatter plot of observed May to June rainfall and tree-ring width chronology during

1953–2016 is shown in Figure 4(a) with the equation of simple linear regression, total May–June rainfall = (145.80) x tree-ring width chronology + 170, R-squared is 0.2195. The reconstructed May–June rainfall pattern was compared to actual rainfall from 1953 to 2016 (Figure 4(b)).

The reconstructed rainfall tendency is similar to tree-ring chronology, but slightly different to actual rainfall pattern. The mean of reconstructed rainfall is 308 mm per year that is close to the mean of observed rainfall (1953–2016) (312 mm per year). The reconstructed May–June rainfall (1840–2016) was displayed with the smoothed lines of 11-year moving averages and the mean rainfall in Figure 5. The equation of simple linear regression of the trend -line reconstructed rainfall through the years 1840–2016 is $y = -(0.06)x + 317.88$; y is the amount of rainfall, and x is the year (the 1st to 177th year). According to the above equation, the rate of decreasing amount of rainfall is approximately 0.06 mm per year or 0.6 mm per decade. The results suggest that rainfall has a higher variability after 1920. The four periods of high amounts of rainfall above the mean and the five periods of the noticeable decrease in the amount of rainfall are clearly seen in Figure 5.

Table 2 The statistic description of tree-ring chronology and actual May–June total rainfall from 1953 to 2016

Statistic	Calibration 1953-1984	Verification 1985-2016	Calibration 1985-2016	Verification 1953-1984	Calibration 1953-2016
R	0.455	0.497	0.497	0.455	0.469
R^2	0.207	0.247	0.247	0.207	0.220
Significant test	22/10	19/13	22/10	21/11	44/20**
RE		0.220		0.187	
CE		0.193		0.164	

Remark: ** denotes significance with $p<0.01$

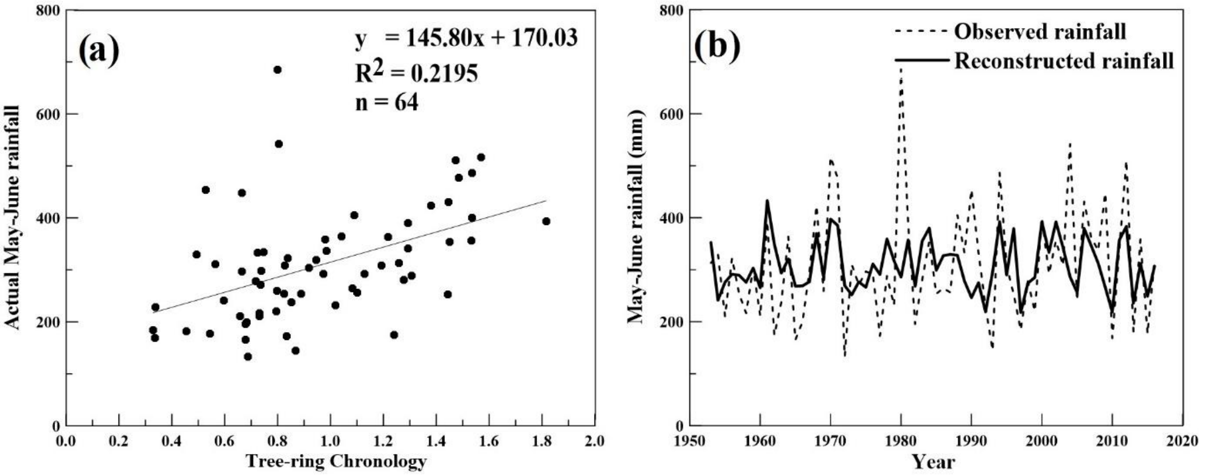

Figure 4 (a) Scatter plot of Mae Yom (MY) tree-ring chronology and actual total May–June rainfall (1953–2016). May–June rainfall = 145.80 x Tree-ring chronology + 170.03 and (b) the comparison between actual rainfall and reconstructed May to June rainfall from 1953 to 2016.

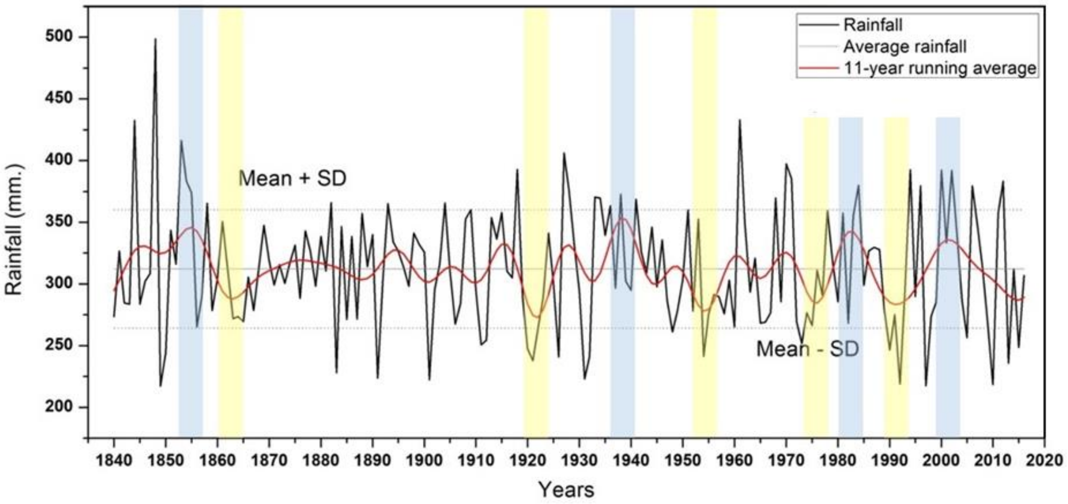

Figure 5 Reconstructed May–June rainfall for years 1840–2016. Yellow highlights indicate the notable five dry periods. Four notable wet periods are highlighted in blue.

Discussion

1) Tree-ring width data and chronology characteristics

The raw data of tree-ring width showed a high potential to construct chronologies. Series inter-correlation and mean sensitivity of tree indices are high at 0.69 and 0.49, respectively, and the autocorrelation is fairly low at 0.53, which indicates a good characteristic of tree raw data [34]. The chronology was constructed using a total of 141 sample cores taken from 76 trees. The number of trees meets the standard criteria that tree-ring width chronology should be composited using at least 10 trees on site with a consistent site-level chronology [6]. The levels of signal-to-noise ratio (SNR) (44) and expressed population signal (EPS) (0.98) are considerably high. The high values of SNR and EPS indicated the strong common climate signals of the trees [35]. It is clearly seen that the chronology is a suitable index to correlate with climate data, although the correlation between trees is fairly low at 0.44.

This chronology was compared with the chronology of Pumijumnong and team [18] derived from teak in Phrae Province, northern Thailand (PHR) (time spanning 1855–1991, 137 years) which was developed from 28 samples. The most noticeable similarity between these two chronologies is the period of years around 1961 when the tree indices levels reach a peak. Other distinctive points occur during the years from 1917 to 1931. The index values dramatically decline from 1917 to 1920 and then gradually rise to the year 1924. After that, they fall as a small loop at 1925 before sharply doubling by the year 1927 and, finally, decline substantially to the year 1931. The close overlap of this constructed chronology and Pumijumnong and team [18] chronology from 1855 to 1991 indicates the reliability and the accuracy of the cross-dating of the tree-ring data which were collected in 2016. As a result, tree-ring data in this study have the capability to extend the old chronology of Phrae Province and the surrounding area not only forward to the near future, but also backward to the past. The addition of more tree samples to the composited data will make the reconstructed climate pattern more accurate.

2) Climate variations and tree-ring growth response

Teak indices mainly showed a positive correlation with total rainfall, particular during the early monsoon month indicating that the growth of ring width occurs mostly in the monsoon season. Moreover, a significant positive relationship with rainfall was obtained during the first half of the wet season (April–June) (Figure 3). The finding of this study provides substantial support that ring growth is influenced by the amount of rainfall in the monsoon season. There is a high positive correlation between the teak index and the rainfall during the first half of the wet season since the size and the number of vessels generated to transport water increases during wet conditions. This strong relationship denotes that the amount of rainfall limits the growth of tree-ring width. Similar results were obtained from several previous studies on teak growth in the tropical region. Teak indices correlate positively with rainfall in most of the months in India [36-37], Myanmar [17, 38], and Thailand [10, 13, 15, 18, 39]. Shah et al. [37] showed a strong positive relationship between the precipitation during Monsoon season (June–September) and tree-ring width in India, resulting from southwest monsoon rainfall [37]. Similarly, in this study, the positive correlation of tree growth and rainfall was presented during monsoon season, although only gave a significant correlation in May and June, it might indicate that southwest monsoon plays an important role in the growth of teak. In the case of northern Thailand, although there is some variation between studies, most of the tree-ring growth positively correlated with rainfall in the first half of the wet season (April–July) [15, 18, 39], which conforms to this study and support the reliable of this tree-ring chronology. Pumijumnong and team [18] presented a high relationship between teak index with rainfall in April to June in Phrae Province, northern Thailand and also in May to July in Mae Hong Son Province, northwest Thailand [16]. Teak tree-ring chronologies from Tak Province, had a positive correlation with April–May rainfall during pre-monsoon season [15]. Lumyai et al [14] also exhibited a direct relationship with rainfall in the Umphang Wildlife Sanctuary from March to June in which the months of March and June showed a significant correlation. In the first half of the wet season, the first rain in monsoon season may stimulate an increase in cambium activities [11, 18] and Priya et al. [40] confirmed that cambial dormancy of teak tree is offset by rainfall during pre-monsoon season, stimulating cambial reactivation [40]. The teak wood vessel formation in India was studied by Sinha and team [41] and Bhattacharyya and team [42], they revealed that the climate of the month in early monsoon period plays a role for building the early wood vessels. Moreover, the high temperature during pre-monsoon also dramatically effects cambium activity and earlywood vessel formation [43]. Consequently, teak chronology generally correlates with rainfall during the first half of the monsoon season and slightly correlates with rainfall after July, the second half of wet season, even though there is a high amount of rainfall in August followed closely by September. However, unexpectedly, the growth of teak considerably correlates negatively with rainfall in the previous December and current January. Pumijumnong et al. [17] presented the inverse correlation of teak in Myanmar with rainfall only in the month of the preceding October. In fact, the cambium activity offsets after the beginning of November [20, 40].

In contrast, the teak chronology demonstrated a significant negative correlation with May temperature, which is monsoon season, similarly to Pumijumnong et al. [18] and Pumijumnong [16], although the teak growth in tropical zones is not directly influenced by some factors including temperature [36] and humidity, similar to studies in temperate zones. Shah et al. [37] also reported that there was no any significant relationship between temperature and the growth of teak in tropical forest in India [37]. The fluctuation in the correlation between the tree-ring width and temperature supports the notion that temperature is not the limiting factor for tree-ring width in these study sites located in the tropical zone. In the case of tree growth in the temperate zone, the temperature is the dominant factor to limit the width of tree-ring, the increasing of ring growth during warm seasons resulted in a positive correlation between temperature and ring width [44-45]. For example, in temperate region, tree-ring width generally had a significantly positive correlation with the average monthly temperature [46-48]; while in tropical forest, the tree-ring width commonly positively correlated with rainfall [12, 49]. The growth of rings in different regions is forced by different environmental conditions. In temperate zone, earlywood is usually produced in spring and early summer while latewood is formed in the late summer [35]. In tropical zone, earlywood is usually generated in early rainy season, and latewood is generated in late rainy season [12]. Consequently, the temperature is the primary climate factors that affected the tree-ring width in temperate region, while the rainfall limits the tree-ring width in tropical regions.

Regarding humidity, there is a strong positive correlation with the tree ring chronology from April to June which is the period of rainfall that gave a sharp negative correlation with tree ring chronology. Since, humidity is certainly dependent on the amount of rainfall, the relationship and mechanism between the teak ring width and humidity is interesting and should be further investigated.

Although there are several teak chronological studies in Thailand [11-18] by investigating the relationship between the tree-ring chronology and climate factor (such as rainfall, humidity, temperature), the teak chronology network should be expanded to examine that some areas are influenced by local climate or regional climate. This study could extend the chronology from living tree in Phrae Province, northern Thailand dating back to be 177 years, which is not only correlated with rainfall and temperature, but also significantly correlated with Niño index. We noted that this is the first dendrochronological study in Thailand that show the significant strong relationship between tree-ring chronology and Niño indices. The Niño indices (Niño 3, Niño 3.4, and Niño 4) inversely correlated with tree-ring width and a significant negative relationship was found in most months of the second-half of the dry season (January–March). The trend of Niño 3, Niño 3.4, and Niño 4 influence in the tree-ring chronology is the same; the correlation reaches a high from January to April (Figure 3(b)). This evidence indicates that El Niño-Southern Oscillation (ENSO) might influence the northern Thailand region, particularly in the dry season. These results confirm [50] that Pacific Sea surface temperatures have an inverse relationship with the summer monsoon rainfall in the northern regions of Thailand. ENSO is a phenomenon involved in the cycle of warm and cold temperatures in the equatorial zone of the Pacific Ocean that is influenced by unusual sea surface temperature (SST) changes [51]. Generally, in Thailand, El Niño leads to a decrease in rainfall and then drought; on the other hand, La Niña leads to heavy rain. Conversely, La Niña phenomena have a high chance of happening when the SST decreases in the equatorial zone of Niño 3, Niño 3.4, and Niño 4, resulting in a high amount of rainfall and wider tree-ring width. The results suggest that increasing SST in all regions of Niño 3, Niño 3.4, Niño 4 from average normal SST brings an El Niño event causing a depletion of rainfall during the summer monsoon [41]; consequently, the teak growth is limited. The results from this study related to reports by D'Arrigo et al. [52] and Roy and Roy [53] that found an inverse relationship between teak growth and Niño 3 index, confirming that El Niño warm conditions lead to teak ring width reduction over southeast Asia because of the migration of the Walker circulation forward to the east zone of the Pacific Ocean.

In conclusion, teak ring-width in this study could extract the signal of monsoon season's effect on Thailand's climate. Tree-ring width measurements may reasonably support and broaden the idea that northern Thailand's climate might be influenced not only by southwest monsoons and northeast monsoons, but also influenced by ENSO, especially during the dry season.

3) Past climate pattern reconstruction

The total amount of rainfall in May to June was reconstructed backward to 1840 (177 years) which based on a linear regression model. This summer monsoon rainfall reconstruction could explain 21.95% of the actual rainfall variance (Figure 4-5). This percentage is quite low when compared with other study [14]. Reasons for low reliability may come from: 1. the meteorological station data is not located near the study area. 2. The factors that control the growth of teak, there are other factors involved human activities. Therefore, in order to improve the reliability, such as 1. the weather data should be close to the sampling area, which this study is limited to the location of the meteorological station which is quite far from the study area. 2. the increase in the number of trees that are expected to grow in the most influential climates. However, the trends of fluctuation between tree-ring chronology and the reconstructed rainfall is closely similar. The reconstructed rainfall and actual rainfall has a significant positive correlation (r=0.469, p<0.01). The mean of May - June reconstructed rainfall is 308 mm per year which is close to the mean of observed rainfall (1953-2016) (312 mm per year). The trend of the amount of reconstructed rainfall declined 0.06 mm per year and we would assume that the total May–June rainfall decreased 0.60 percent per decade. A long-term decreasing trend in rainfall in Thailand is also reported by the Intergovernmental Panel on Climate Change (IPCC) [54]. Thus, the diverging trends in rainfall volume are different in each region of Thailand and this study supports the negative trend of rainfall over one hundred years in northern Thailand. According to our results, the rainfall seems to have a low variability from 1840 to 1915 (Figure 5). The amount of rainfall tends to remain stable before 1915, and there is only one remarkable period (1852–1857) showing a substantial change in rainfall. After 1915, the amount of rainfall seems to fluctuate considerably. There are four periods of noticeably increasing rainfall and five periods of decreasing rainfall. The most striking decline in rainfall is from 1919 to 1924. In 1920, it is clearly seen that the amount of rainfall obviously reaches a low leading to drought condition. The causes of decreasing rainfall are not only ENSO events but also the Indian Ocean Dipole (IOD). IOD is the same phenomena with ENSO but occurred in Indian Ocean. This may influence the amount of rainfall in the rainy season [55].

The rainfall pattern fluctuation of this study appears to resemble the May-July reconstructed rainfall of Pumijumnong [16] in Mae Hong Son Province showed the cycle of the amount of rainfall that dropped during 1920–1930 and then substantially raises before decreasing in 1945–1955 [16]. Some dry periods of these results such as during 1953–1957 and 1972–1978 tend to synchronize with the teak chronology of Buckley et al. [10] in northwest Thailand [10]. The May–June reconstructed rainfall also seems to be similar to May and June rainfall reconstruction in the study of Lumyai and Duangsathaporn [14] particularly in 1935-1945; the rising of rainfall [14].

In addition, remarkably, the reconstructed rainfall also showed a similar trend with the annual rainy season rainfall (1804–1999) reconstructed by tree ring oxygen isotopes, which was aligned well with actual amount of rainfall, although it derived from *Pinus merkusii* in Tak Province, western Thailand [56]. The pattern between our reconstructed rainfall in Phrae and reconstructed rainfall in Tak from Xu et al. [56] was noticeably similar, particularly in rainy season during 1935–1945, dry season during 1915 and 1925 and after 1990. Since the Phrae chronology in this study matches fairly well with other previous studies, it seems that the northern Thailand climate was influenced by monsoon signal with effects on both local and regional scales.

Therefore, the teak chronology seems to have the potential to reconstruct the past amount of rainfall. These results denote a strong potential of teak for regional climate reconstruction, particularly the precipitation variable. However, the tree-ring chronology networks need to be expanded in terms of both temporal scale (e.g. using archaeological evidence, historical wood ruins, tree stumps) and spatial scale (e.g. expanding study site) because it allows us to construct the long climate pattern with more precision to broaden our understanding of the past climate dynamics. The implication of this finding is to apply the results to be the database for monitoring the climate change from past to present and to predicting the climate in the future. The prediction can be an early warning for handling the upcoming disaster in agricultural field and can be used with teak forest management because it is known that the amount of rainfall affects the tree-ring width which it is a product of the wood.

Conclusions

The living tree samples were collected from Mae Yom National Park, Phrae Province, northern Thailand and then they were processed through dendrochronological techniques. The tree-ring width data showed the conventional acceptance quality to construct the chronologies. The chronology has a positive significantly correlation with rainfall and humidity during the first half of the monsoon season (May–July). Conversely, tree-ring chronology is negatively correlation with temperature from May to June. Furthermore, there is an inverse relationship between tree-ring chronology and Niño indices (Niño 3, Niño 3.4, and Niño 4) especially in the second half of the dry season (January–March).

Regarding reconstruction of the past climate, the actual rainfall and the master tree-ring chronology was analyzed. The reconstructed rainfall, spanning the year from 1840 to 2016 (177 years), showed a decreasing rate in the amount of rainfall at 0.6 mm per decade. The variability of rainfall was low during 1840–1915, and then the trend substantially fluctuated after 1915. This research highly suggests that teak responds to the climate, in particular rainfall which is the limiting factor in the tropical region.

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