

Climatic fluctuations trigger false ring occurrence and radial-growth variation in teak (*Tectona grandis* L.f.)

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The objective of this study was to examine the interaction of extreme growth years in teak (*Tectona grandis*) with climatic conditions of current, antecedent and subsequent years, in order to explain the nature and the effects of climatic variability on teak growth in northeastern Thailand. A 33-year tree-ring index was constructed and extreme growth years during the period 1976-2008 were identified. A superposed epoch analysis (SEA) was used to study the interaction of climatic data and extreme growth years. Extreme growth years were derived from eight wider and seven narrower annual rings identified using the Cropper's method. Seventeen false rings were detected using the threshold value $\geq 80\%$ of false ring occurrence for all samples in each growth year. False ring occurrence was associated with narrow ring width formation and triggered by increasing maximum and mean temperatures at the beginning of the rainy season (May to August). In the third year after false ring formation, we observed a pattern of wet year occurrence when annual rainfall and relative humidity in September to December were higher than in adjacent years. Moreover, in the sixth year before false ring formation, a wet year was observed when relative humidity in September to December was higher than in adjacent years. Wider ring width index occurring in a particular year was found to be triggered by a decrease in maximum and mean temperatures in May to August of the current year, suggesting that wet years promote teak growth. The third year after the formation of wider rings was characterized by a low annual rainfall. Our results showed that drought years trigger false ring and narrow ring formation, while wet years trigger wide ring formation in teak. A cycle of wet years between the sixth year prior to, and the third year after, the formation of false rings was also observed, as well as the occurrence of drought in the third year since the formation of wide rings. False ring, narrow ring and wide ring occurrences appear to be good indicators of a 3-6 year climate fluctuation pattern, similar to that of the El Niño-Southern Oscillation (ENSO) cycle in this region.

Keywords: Extreme Event, False Ring, Pointer Year, Superposed Epoch Analysis, Teak (*Tectona grandis*), Tree-ring

Introduction

Teak (*Tectona grandis* L.f.) is one of the most well known tropical tree species for its high-quality and prized timber (Rao & Rajput 1999, Bhat & Priya 2004). Teak wood is suitable for multiple uses due to its

various favorable characteristics and properties, including fine grain, beautiful golden color, and durability with respect to weather, insects and fungi (Kaosa-ard 1986). Archaeological studies showed that teak was widely used in Egypt, India and

China more than 2500 years ago (Forest Research Office 1994). Teak is naturally distributed in tropical monsoon Asia, including India, Myanmar, Laos PDR, Indonesia and Thailand (Tangmitcharoen & Owens 1997, White 1991). However, the increasing demand of this quality timber has caused widespread planting even in areas outside the natural distribution regions, such as the plantations in Southeast Asia, Africa and South America (Katwal 2005).

It is important to understand factors affecting teak growth, to ensure sustainable production of high-quality teak wood and appropriate forest management practices. Several studies indicate that teak is a deciduous to semi-deciduous tree growing in a wide range of climatic and edaphic conditions (Sousa et al. 2012). Kaosa-ard (1998) also reported some environmental factors controlling the distribution and growth of teak such as rainfall (500-5000 mm year⁻¹), soil (best on deep and well-drained alluvial soils with relatively high mineral salts), light intensity (75-90%) and temperature

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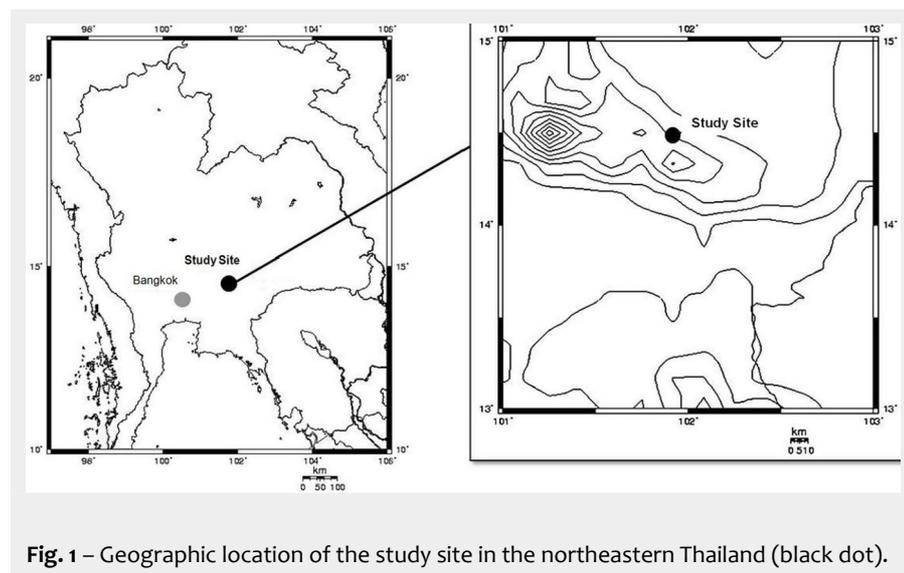


Fig. 1 – Geographic location of the study site in the northeastern Thailand (black dot).

(27–36 °C).

Recently, IPCC (2013) reported global average surface temperature increasing over the period 1880–2012 by about 0.85°C. Analysis of Thailand meteorological data in the past six decades indicated little changes in rainfall and increases in annual mean, minimum and maximum temperature, especially in the last decade (Vongvisessomjai 2010). The fluctuation of some climatic variables may affect tree growth and adaptation because they are important environmental factors determining ecological niches of tree species and their distribution patterns (Trisurat et al. 2009).

Several researchers have suggested that drought causes significant losses in growth of teak and other plants (Prasad et al. 2008, Almeselmani et al. 2011, Deepak et al. 2010, D'Arrigo et al. 2011). A growth study of juvenile teak, which involved 20 days drought followed by 5 days rehydration treatments, indicated that growth declined due to drought stress and rapidly recovered a few days after rehydration (Husen 2010). In rainy season, pre-monsoon showers broke the cambial dormancy and ra-

dial-growth was initiated (Priya & Bhat 1999). Wood formation started after the budding and continued until the end of the rainy season (Nobushi et al. 1996), while drought during active growing season caused false ring formation in teak (Priya & Bhat 1998, Palakit et al. 2012). Rao & Rajput (1999) found the maximum radial-growth of teak during the monsoon period, while Kokutse et al. (2010) reported that annual ring width is strongly depended on mean monthly temperature and is associated with bud break during the rainy season.

Teak has been widely used for tree-ring analysis, to determine climate-growth response. Several studies discovered the significant positive relationship between rainfall and teak growth in the monsoon season (Pumijumnong et al. 1995, Shah et al. 2007, Ram et al. 2008, Borgaonkar et al. 2009). Ram et al. (2011) also found that the moisture availability in the post-monsoon period of the previous year had a significant role in the development of teak growth in the current year.

In this paper, we identified extreme events (pointer years), which were derived

from the variation of teak ring width index and false ring formation. The interaction of these pointer years with antecedent and subsequent climatic conditions were then examined with the aim of understanding the nature and effects of climatic variability on teak growth in northeastern Thailand. Instead of analyzing the climate-growth response using simple correlation and multiple regression analysis, we used the superposed epoch analysis (SEA) to establish the climatic fluctuations triggering false ring occurrence and radial-growth variation in teak.

Material and methods

Study site

The study site was located at the Wang Nam Kiao Forestry Student Practice Station (WNKFSPS) of the Faculty of Forestry, Kasetsart University in the Nakhon Ratchasima province, lower northeastern Thailand (14° 29' N, 101° 56' E) at 339 m a.s.l (Fig. 1). Most of the teak growing on this site formed false rings, which normally are obstacles for tree-ring analysis. However, they provided an opportunity to study factors triggering false ring formation.

Climatic data

The longest climatic data of total monthly rainfall (RF), relative humidity (RH) and monthly temperature – maximum (Tmax), minimum (Tmin), and mean (Tmean) temperature – for forty years (1969–2008) were derived from the nearest meteorological station at the Sakaerat Environmental Research Station (SERS). Based on RF and Tmean, climate was classified into wet and dry periods during March to November and December to February, respectively (Fig. 2). Total monthly rainfall rapidly increased at the beginning of wet period (March to May), followed by a short period of drought during June to August. The highest rainfall was recorded at the end of the wet period in September–October, and the rainfall amount rapidly decreased from November to February (Fig. 2). Maximum, minimum, and mean monthly temperature slightly increased from the beginning of the year in the dry period to the highest temperature at the beginning of the wet period in April, and gradually decreased to the lowest temperature in the dry period at the end of the year (Fig. 3).

Methods

A total of seven natural teak trees that were dominant and had a symmetrical crown and straight trunk were selected from a small forest stand of approximately 15 teak trees growing on well drained soil. From each sample tree, four increment cores were taken at breast height (1.3 m) in cardinal directions (north, east, west and south) using an increment borer. Following the standard procedures of dendrochronology (Stokes & Smiley 1996), twenty eight increment cores were carefully fixed on

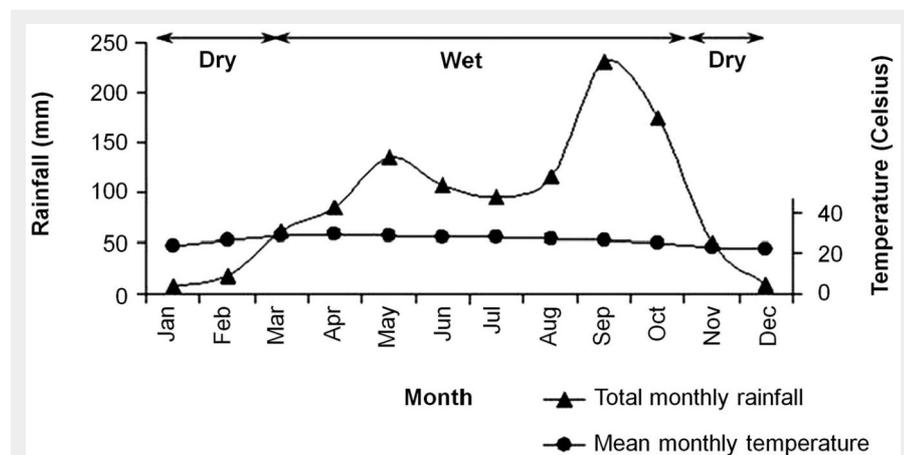


Fig. 2 - Mean monthly total rainfall and temperature in the period 1969–2008, with indications of wet and dry periods (source: Sakaerat Environmental Research Station, Nakhon Ratchasima province, Thailand).

support wood slabs and gently polished until tree-rings on transverse surfaces were clearly visible. This was done at the Laboratory of Tropical Dendrochronology (LTD), Kasetsart University, Faculty of Forestry (KUFF) in Bangkok (Thailand). Annual rings and intra-annual rings were identified using the techniques of visual cross-matching (Fritts 1976) and vessel size investigation (Palakit et al. 2012). Annual ring widths were measured at a resolution of 0.001 mm with the accuracy of 0.010 mm m⁻¹ using the TA Unislide Tree-Ring Measurement System (Velmex Inc., New York, USA) interfaced with a microcomputer and a 4x to 40x magnified stereo microscope. Measurement errors were corrected with a computer-assisted software of cross-dating and quality control procedures, namely the COFECHA program (Holmes 1983). Annual ring width series were standardized to minimize age effect and maximize the observation of the environmental factors of interest using the ARSTAN software package (Cook 1985). Expressed Population Signal (EPS) was calculated to determine the usefulness of the standardized annual ring width index based on their sample sizes and correlation values. Wigley et al. (1984) suggested that the index supported by EPS values ≥ 0.85 could be accepted as reliable chronology for tree-ring analysis. Additionally, the number of identified false rings in each year of all sample cores was counted and converted to the percentage of false ring frequencies in each year.

Extreme growth fluctuations, called pointer years, were extracted from the standardized tree-ring chronology using the Cropper's method (Cropper 1979, Schweingruber et al. 1990). Pointer years were calculated as the normalized differences between the standardized growing value in the year i and the mean of the standardized growing values within a five-year moving average, called moving windows, as follows (eqn. 1):

$$Z_i = X_i - \frac{\text{mean}[\text{window}]}{\text{stdev}[\text{window}]}$$

where Z_i is the pointer year index value in the year i ($i = 1964, 1965, \dots, 2006$), X_i is the standardized growing value in the year i , $\text{mean}[\text{window}]$ is the arithmetic mean of ring width within the moving windows of $X_{i-2}, X_{i-1}, X_i, X_{i+1}, X_{i+2}$, and $\text{stdev}[\text{window}]$ is the standard deviation of ring width within the moving windows of $X_{i-2}, X_{i-1}, X_i, X_{i+1}, X_{i+2}$.

Values of Z_i which were ≥ 0.75 or ≤ -0.75 were defined as positive (wider ring) or negative (narrower ring) pointer years, respectively (Vitas 2004). In the case of false-ring occurrence, pointer years were detected using the threshold of 80% or higher in each year. Using this threshold, at least 6 trees from the total of 7 teak sample trees were found to have false rings in year i .

Superposed epoch analysis (SEA) is a statistical method originally used to test for significant relationships between the oc-

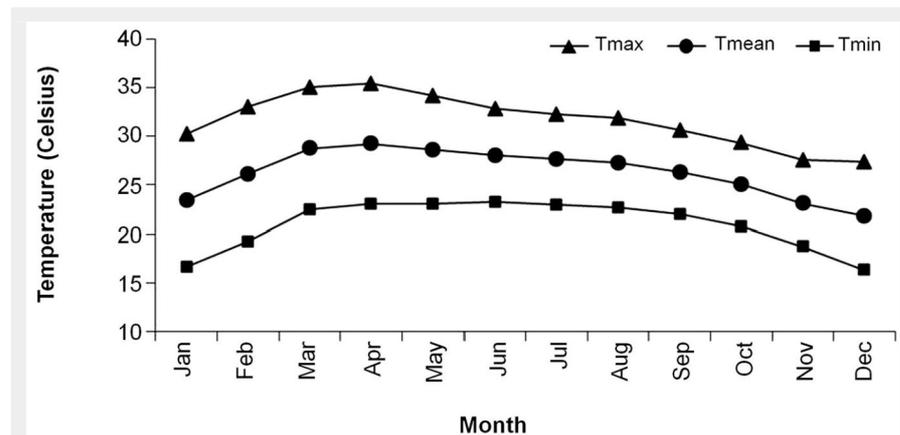


Fig. 3 - Monthly variation of maximum (Tmax), minimum (Tmin) and mean (Tmean) temperature in the period 1969-2008 (source: Sakaerat Environmental Research Station, Nakhon Ratchasima province, Thailand).

currence of a specific event and the strength of recruitment in the corresponding years (Prager & Hoenig 1989). SEA was used to examine the relationship between extreme events ($-0.75 \geq Z_i \geq 0.75$) and false ring frequencies ($\geq 80\%$) and time series of annual and seasonal climatic data (January to April, May to August and September to December). The climate data, included RF, Tmax, Tmean, Tmin and RH. The relationship between false ring pointer years and standardized annual ring width index was also examined. SEA compared these time series with extreme events by superposing windows of concurrent and lagged climatic conditions for each extreme growth year. Simulations for 1000 trials with 28376 random seed values were used to develop confidence intervals of the mean s , with the aim of determining whether climate was significantly different from average during six years prior and four years after extreme growth years. In this study, SEA was carried out using the EVENT software package (Holmes & Swetnam 1994).

Results

Tree-ring width data

Cross-dating was successful in all 28 teak cores, though the identification of false rings was difficult and time consuming. False rings occurred in both earlywood and latewood, as one or more rows of paratracheal parenchyma and small vessels scattered

nearby dense fibers without paratracheal parenchyma (Fig. 4). The average annual ring width series and the standardized annual ring width index are shown in Fig. 5. Mean sensitivity (MS, the mean relative change between adjacent ring widths – Fritts 1976), standard deviation, and autocorrelation of these ring width series were 0.422, 0.421 and 0.170, respectively. The average annual ring width series rapidly increased during the period 1962-1964, gradually decreased during the period 1965-1979, and stabilized during the period 1980-2008 (Fig. 5b). When the age trend at the beginning of tree growth was removed, the standardized ring width index fluctuated around and close to the mean value of 1 (Fig. 5b). During 1976-2008, the EPS values were at least 0.85, indicating a reliable chronology, while EPS values obtained for previous periods were lower than such threshold, likely due to the reduced sample sizes, indicating unreliable chronologies (Fig. 5c, Fig. 5d). Thus, the low EPS chronologies were discarded from this study.

Pointer year identification

The pointer years of fast (wider annual ring) and slow (narrower annual ring) growth derived using the Cropper's method are shown in Fig. 6. Teak rapid growth with pointer year index value ($Z_i \geq 0.75$) occurred in 1964, 1967, 1971, 1976, 1978, 1983, 1986, 1991, 1994, 1999 and 2000, while growth suppression ($Z_i \leq -0.75$) oc-

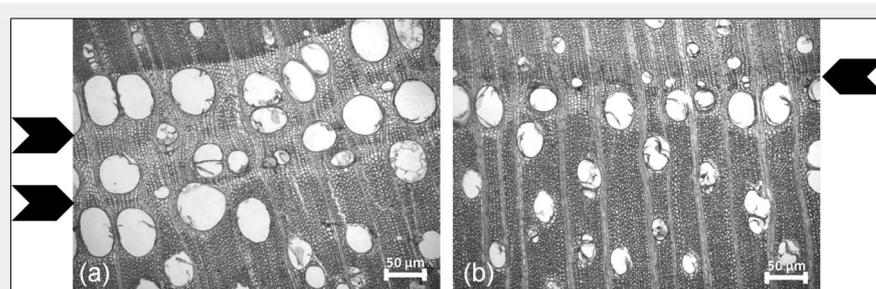


Fig. 4 - False ring formation in teak: (a) earlywood; (b) latewood.

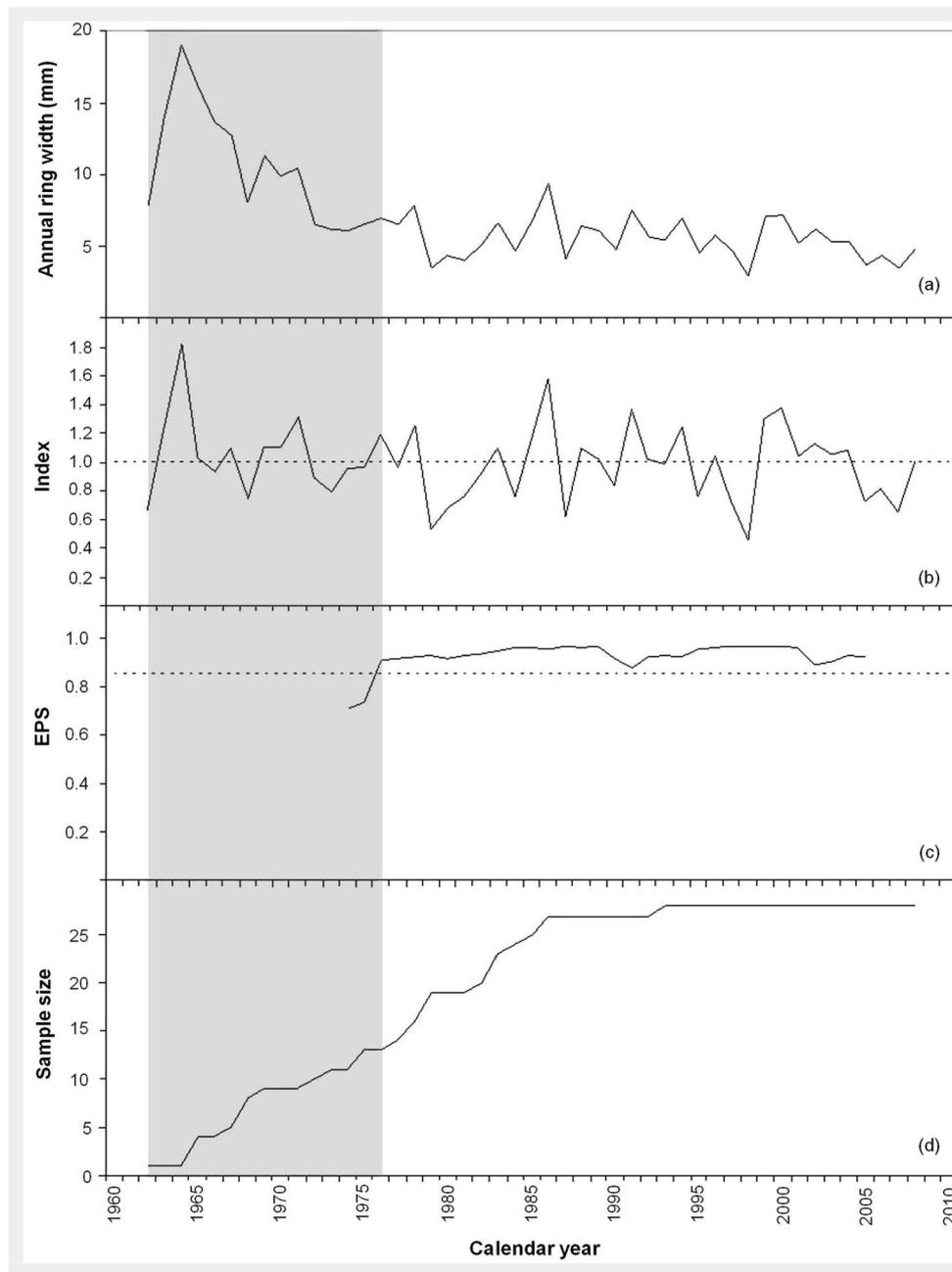


Fig. 5 - Annual ring width index of teak (*Tectona grandis*) in the period 1962-2008. (a) average annual ring width series; (b) annual ring width index; (c) EPS values; (d) sample sizes. The gray shaded area indicates the period of lower reliability of the annual ring width index due to smaller sample sizes.

occurred in 1968, 1973, 1979, 1984, 1987, 1990, 1995, 1998 and 2001. Due to the unreliability of annual ring width index prior to 1976, previous pointer years in the period

1962-1975 were not considered in this study.

Visual cross-matching and vessel size investigation indicated that intra-annual

growth rings occurred within actual annual rings (Fig. 4). The successful cross-dating using the COFECHA software also confirmed the accuracy of the intra-annual

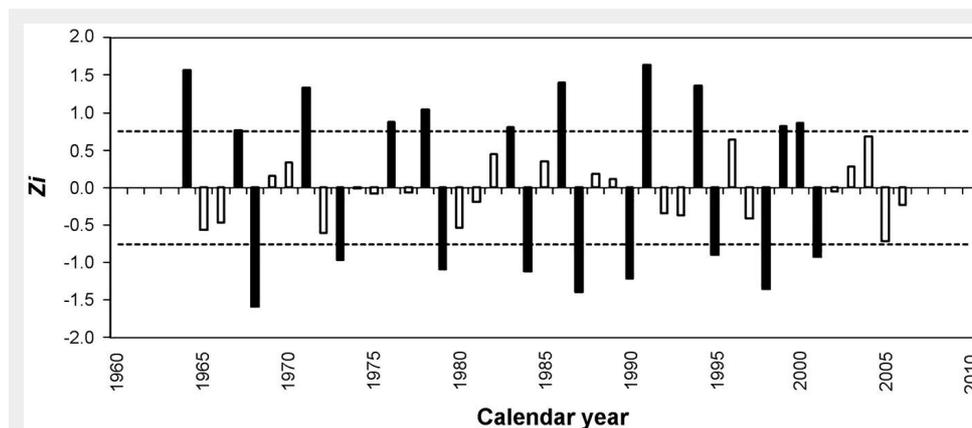


Fig. 6 - Pointer years derived from annual ring width index of teak (*Tectona grandis*). Years with significant pointer year index values ($-0.75 \geq Z_i \geq 0.75$) above the upper and below the lower dashed lines (black column) indicate the wide and narrow ring width pointer years, respectively.

growth ring identification. The years 1968, 1970, 1972, 1977, 1979, 1980, 1981, 1982, 1984, 1987, 1988, 1989, 1990, 1993, 1996, 1997, 1998, 2002, 2005 and 2006 were defined as false ring pointer years, when false ring occurrence was at least 80% (22 sample cores - Fig. 7). As previously mentioned, the pointer years before 1976 were rejected from this study due to the unreliability of the annual ring width index.

Climate-pointer year interaction

The superposed epoch analysis (SEA) indicated the existence of a climate-pointer year interaction, as reflected by the significant relationship between the increase of Tmean and Tmax in the rainy season (May to August: $p \leq 0.05$ - Fig. 8b, Fig. 8c) with the occurrence of false rings and the negative values of annual ring width index ($p \leq 0.05$ - Fig. 8a). Additionally, there was a significant positive relationship between the false ring occurrence and the relative humidity (RH) in the transition period to the rainy and cold season (September to December - Fig. 8d). A cycle of wet periods in the sixth year prior to, and the third year

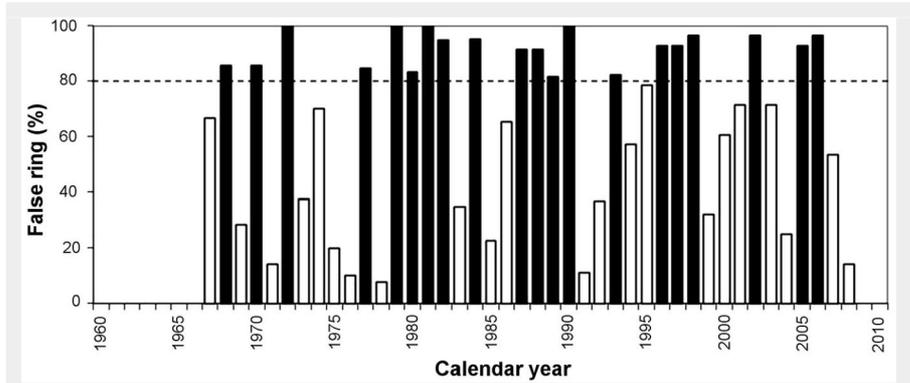


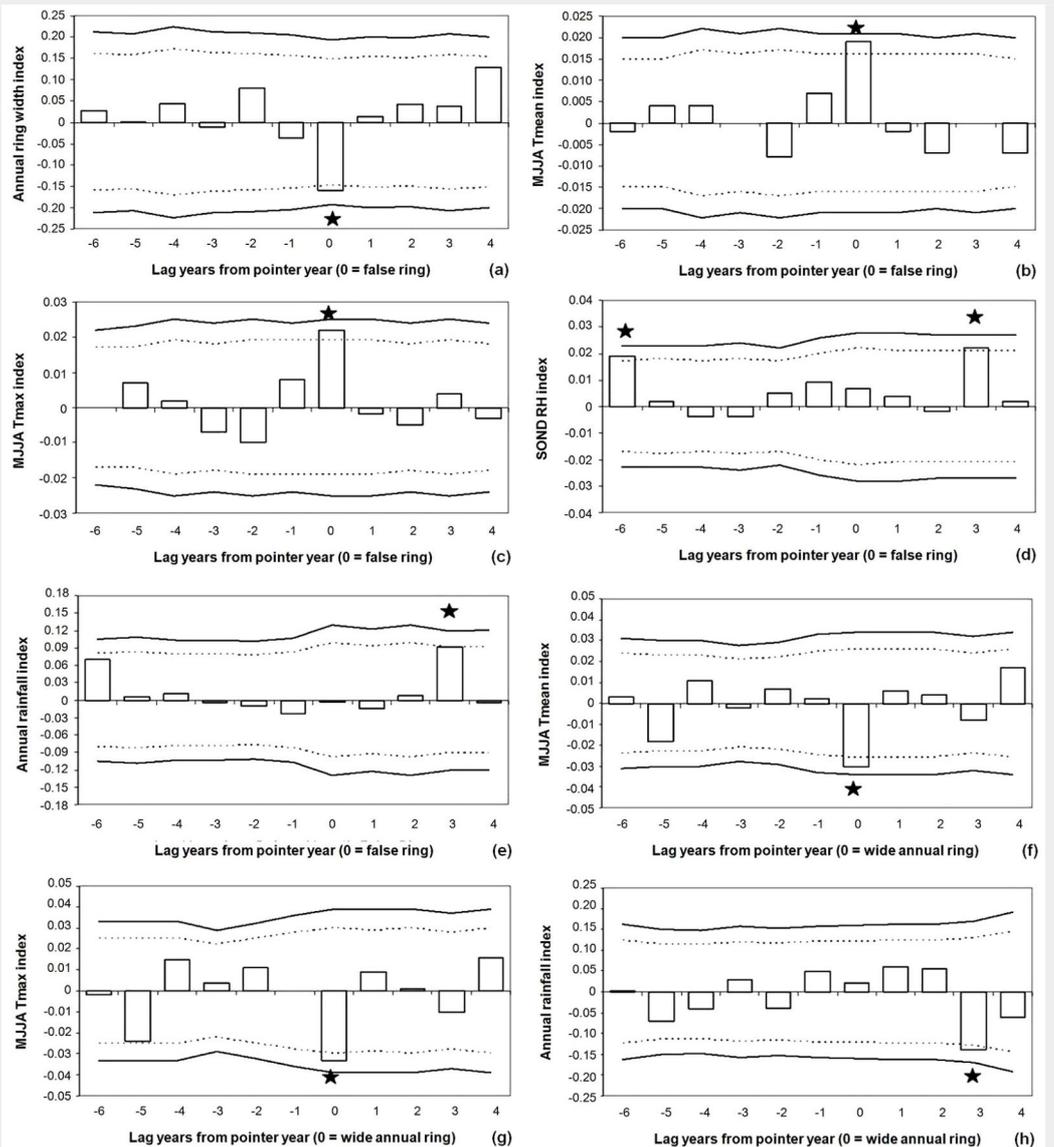
Fig. 7 - False ring frequencies in each growing year. False ring pointer years ($\geq 80\%$ false ring occurrences) are represented by black columns.

after, the occurrence of the false rings was detected. Moreover, an increasing annual rainfall departure from the mean of annual rainfall index was found in the third year after false ring occurrence ($p \leq 0.05$ - Fig. 8e). In years in which Tmean and Tmax for the rainy season (May to August) were significantly lower ($p \leq 0.05$ - Fig. 8f, Fig. 8g),

annual ring width index values were larger than those of other adjacent years. In the third year after the occurrence of a wider annual ring, the annual rainfall was significantly lower than that of other adjacent years ($p \leq 0.05$ - Fig. 8h).

Although the narrow annual rings generally occurring in drought years were signif-

Fig. 8 - Superposed epoch analysis (SEA) showing the departures of actual from simulated events: (a) annual ring width index; (b) Tmean (May to Aug); (c) Tmax (May to Aug); (d) RH (Sep to Dec); (e) annual rainfall of years with false ring pointer year occurrence; (f) Tmean (May to Aug); (g) Tmax (May to Aug) and annual rainfall were significantly related with wide annual ring occurrences. Dashed and solid lines indicate confidence intervals at 95% and 99%, respectively based on 1000 random simulations. Significant departures ($p \leq 0.05$) from random expectations are indicated by stars.



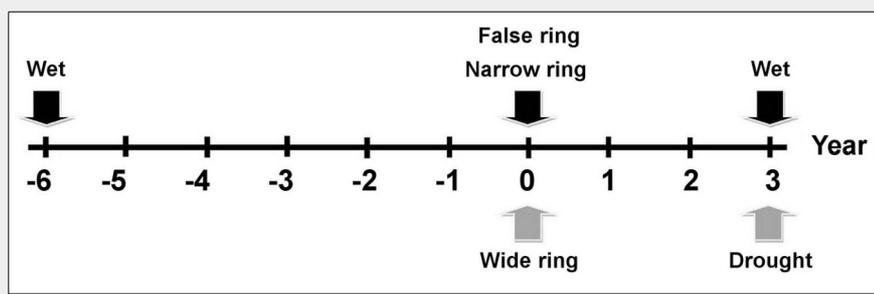


Fig. 9 - Cycle of false ring formation, narrow ring and wide ring formations in teak, related to the cycle of drought and wet occurrences.

icantly associated with false ring formation, there was no significant relationship with the recorded climatic data. Fig. 9 summarizes the patterns of formation of false rings in teak, and their association with the narrow ring width and drought conditions in the growing year, and with the wet conditions in the sixth year prior to false ring occurrence, as well as with the third year after. The formation of wider annual rings was found to be linked with wet conditions in the growing year and with drought conditions in the third year after the occurrence of the wider annual rings.

Discussion

Teak in this study area was appropriate for investigating environment-growth interaction, especially in term of climate fluctuation, because it formed wide and narrow rings intermixed through time (a phenomenon called sensitivity). The teak annual ring width index showed a high mean sensitivity (MS) value of 0.42, fairly close to MS values (0.5) observed for natural teaks growing in mountainous areas of northern Thailand (Pumijumnong et al. 1995). Interestingly, the MS of Thai teak in northwestern Thailand was only 0.27 (Buckley et al. 2007), and that of the Indian teak varied by site ranging from 0.22 to 0.43 (Bhattacharyya et al. 2007, Shah et al. 2007, Ram et al. 2008, 2011, Borgaonkar et al. 2009). Although Bhattacharyya et al. (2007) suggested that MS value of 0.22 was a moderate value, the amount of variation that could be explained by climate was approximately 57.15%. In case of MS value = 0.5, Pumijumnong et al. (1995) suggested that growth variability of northern Thailand teak triggered by climate was approximately 61%.

In this study, SEA results showed that teak false rings were associated with narrow ring width, and drought during the rainy season. Priya & Bhat (1998) and Palakit et al. (2012) reported false ring formation in both earlywood and latewood teaks. Artificial drought during the early growing season also induced false ring occurrence in teak (Priya & Bhat 1999). Palakit et al. (2012) also confirmed that increasing temperature followed by increasing rainfall at the end of the monsoon period stimulated teak false ring occurrence. As for other tree species, Cherubini et al. (2003) sug-

gested that false ring formation in Mediterranean trees was caused by the interruption of the normal growth during the season caused by either a dry or wet period. These false rings could be identified by carefully studying xylem cells at the transition from the thin band of latewood to earlywood cells. This transition was gradual, diffuse, and not as abrupt or sharp as in annual ring boundaries. It was similar to the variation of vessel lumen area in *Erica arborea*, whose annual rings with intra-annual density fluctuations (IADFs) suddenly decreased in vessel lumen size at the middle of earlywood and formed a band of latewood-like cells (De Micco et al. 2014). Battipaglia et al. (2010) also found false ring formation in earlywood or latewood related to drought. Nabais et al. (2014) suggested that the correlation between climate and IADFs is driven by site conditions and is less related to the species. Copenheaver et al. (2006) suggested that false rings in intermediate and co-dominant trees were due to tree growth suppression more than climatic conditions.

False ring occurrence in each growing year was related to the occurrence of narrow annual ring and increasing temperature, but no relationships were detected with annual rainfall and relative humidity (RH). The relationship between false ring occurrence and climatic data in the adjacent years was unclear at this time. A spectral analysis of the northwestern Thai teak chronology over the past 448 years indicated a significant range of teak growing cycle related to El Niño-Southern Oscillation (ENSO) variability spanning 2.2-4 years (Buckley et al. 2007). This was similar to the cycle of Moisture Index (MI) in each of 3.5 years reconstructed from teak ring index in India (Ram et al. 2011). Solomon et al. (2007) also suggested that historical El Niño events occurred about every 3-7 years, while Singhrattna et al. (2005) found a significant correlation between summer monsoon precipitation and large scale climatic features of the Pacific sea surface temperatures (SSTs) and ENSO. Therefore, the fluctuation of ENSO causing precipitation might induce the variation of tree growth, and foster cycles of 3 to 6 years annual rainfall and RH.

Tree growth rates are also related to cli-

matic fluctuation. This study found an increasing annual ring width index of teak with decreasing Tmean and Tmax in the rainy season. These results were similar to other dendroclimatological studies of teak. In Thailand, Buckley et al. (2007) found a significant relationship of teak growth rate with reduced Tmean at $p \leq 0.05$. Moreover, it was consistent with the study of Pumijumnong et al. (2000), who reconstructed temperature from teak ring index, and found a negative relationship between temperature and teak growth. Teak annual ring variation in India also showed a significant negative correlation with temperature (Shah et al. 2007, Ram et al. 2008, Ram et al. 2011).

In this study, the decrease in annual rainfall in the third year after the occurrence of a wide annual ring width was another interaction between climate and pointer years, suggesting the existence of an underlying climatic cycle. D'Arrigo et al. (2006a, 2006b) found a strong correlation of the reconstructed Palmer Drought Severity Index (PDSI) and warm pool sea surface temperature (SST), based on Indonesian teak ring width series, representing approximately 5-7 year ENSO cycle. This could mean that the cycle of extreme wet or dry year occurred every 5-7 years, similar to our study of the interaction between annual rainfall and wide annual ring width index. The interpretation is that false ring associated with narrow ring width occurred in a dry year (high temperature) followed by wet year in the third year. As well, wider rings occurred in a wet year of low temperature followed by a cycle of drought year three years later.

Although this study could not find a significant relationship between rainfall and teak growth in any particular year, several studies have suggested increasing tree growth with abundant rainfall and moisture (Shah et al. 2007, Bhattacharyya et al. 2007, Ram et al. 2008, Pumijumnong et al. 2000, Pumijumnong et al. 1995). After the occurrence of a wider annual ring width, the amount of annual rainfall three years later was significantly lower than other adjacent years. This cycle covered six year intervals, similarly to the climatic fluctuation due to ENSO effect describe above. Although Tmean and Tmax which were below the average induced wider annual ring formation in teak, the study of Vongvisessomjai (2010) indicated increasing trends of annual mean, minimum and maximum temperatures in Thailand, especially during the last decade. Therefore, teak growth rate may decrease due to the limitation of increasing temperature. This is particularly important for the growth of trees in both natural forest and plantations, which provide direct benefit in terms of timber and indirect benefit in terms of carbon sequestration. On the other hand, the formation of false rings is an indicator of unfavorable environmental factors affecting tree growth during the growing

periods, as well as the formation of narrow rings. These observations can contribute to the development of strategies for adaptation to global warming and climate change mitigation, especially on plants which are primary producers (autotrophic) in terrestrial ecosystems.

Conclusions

This study extracted pointer years of large, small, and false ring occurrences from teak annual ring width series. High maximum and mean temperatures in May to August triggered the formation of false rings due to drought occurrences during the beginning of the growing period. Additionally, false ring occurrence was found to be associated with small annual ring widths. In the third year after the occurrence of false rings in a particular drought year, relative humidity in September to December and annual rainfall were higher than in other adjacent years; and in the sixth year before false ring formation, annual rainfall was higher than in other adjacent years. Decreased maximum and mean temperature in May to August (wet period) in a particular year induced large annual ring width formation. In the third year after large annual ring occurrence in a particular wet year, annual rainfall was lower than in other adjacent years. Climatic fluctuation patterns were found not to be significantly associated with the pointer years of small annual ring widths. While climatic cycles are not fully understood, the observations in this study appear to suggest that the cycle swings back and forth every 3-6 years, similarly to the ENSO cycle.

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References

- Almeselmani M, Abdullah F, Hareri F, Naesani M, Ammar MA, Zuher Kanbar O, Saud AA (2011). Effect of drought on different physiological characters and yield component in different varieties of Syrian Durum wheat. *Journal of Agricultural Science* 3 (3): 127-133. - doi: [10.5539/jas.v3n3p127](https://doi.org/10.5539/jas.v3n3p127)
- Battipaglia G, De Micco V, Brand WA, Linke P, Aronne G, Saurer M, Cherubini P (2010). Variations of vessel diameter and $\delta^{13}C$ in false rings of *Arbutus unedo* L. reflect different environmental conditions. *New Phytologist* 188 (4): 1099-1112. - doi: [10.1111/j.1469-8137.2010.03443.x](https://doi.org/10.1111/j.1469-8137.2010.03443.x)
- Bhat KM, Priya PB (2004). Influence of provenance variation on wood properties of teak from the Western Ghat region in India. *IAWA Journal* 25 (3): 273-282. - doi: [10.1163/22941932-90000365](https://doi.org/10.1163/22941932-90000365)
- Bhattacharyya A, Eckstein D, Shah SK, Chaudhary V (2007). Analyses of climatic changes around Perambikulam, south India, based on early wood mean vessel area of teak. *Current Science* 93 (8): 1159-1164. [online] URL: http://www.researchgate.net/profile/Santosh_Shah/publication/260843653
- Borgaonkar HP, Sikder AB, Ram S, Pant GB (2009). El Niño and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L. F.) trees from south India. *Palaeogeography, Palaeoclimatology, Palaeoecology* 285 (1-2): 74-84. - doi: [10.1016/j.palaeo.2009.10.026](https://doi.org/10.1016/j.palaeo.2009.10.026)
- Buckley BM, Palakit K, Duangsathaporn K, Sanguantham P, Prasomsin P (2007). Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors. *Climate Dynamics* 29: 63-71. - doi: [10.1007/s00382-007-0225-1](https://doi.org/10.1007/s00382-007-0225-1)
- Cherubini P, Gartner BL, Tognetti R, Braker OU, Schoch W, Innes JL (2003). Identification, measurement and interpretation of tree rings in woody species from Mediterranean climates. *Biological Reviews of the Cambridge Philosophical Society* 78 (1): 119-148. - doi: [10.1017/S1464793102006000](https://doi.org/10.1017/S1464793102006000)
- Cook ER (1985). A time series analysis approach to tree ring standardization. PhD Dissertation, University of Arizona, Faculty of the school of renewable natural resources, Tuscon, AZ, USA, pp. 171. [online] URL: <http://hdl.handle.net/10150/188110>
- Copenheaver CA, Pokorski EA, Currie JE, Abrams MD (2006). Causation of false ring formation in *Pinus banksiana*: a comparison of age, canopy class, climate and growth rate. *Forest Ecology and Management* 236: 348-355. - doi: [10.1016/j.foreco.2006.09.020](https://doi.org/10.1016/j.foreco.2006.09.020)
- Cropper JP (1979). Tree-ring skeleton plotting by computer. *Tree-Ring Bulletin* 39: 47-59. [online] URL: <http://hdl.handle.net/10150/260438>
- D'Arrigo R, Palmer J, Ummenhofer CC, Kyaw NN, Krusic P (2011). Three centuries of Myanmar monsoon climate variability inferred from teak tree rings. *Geophysical Research Letters* 38: L24705. - doi: [10.1029/2011GL049927](https://doi.org/10.1029/2011GL049927)
- D'Arrigo R, Wilson R, Palmer J, Krusic P, Curtis A, Sakulich J, Bijaksana S, Zulaikah S, Ngkoimani LO (2006a). Monsoon drought over Java, Indonesia, during the past two centuries. *Geophysical Research Letters* 33: L04709. - doi: [10.1029/2005GL025465](https://doi.org/10.1029/2005GL025465)
- D'Arrigo R, Wilson R, Palmer J, Krusic P, Curtis A, Sakulich J, Bijaksana S, Zulaikah S, Ngkoimani LO, Tudhope A (2006b). The reconstructed Indonesian warm pool sea surface temperatures from tree rings and corals: linkages to Asian monsoon drought and El Niño-Southern oscillation. *Paleoceanography* 21: PA3005. - doi: [10.1029/2005PA001256](https://doi.org/10.1029/2005PA001256)
- Deepak MS, Sinha SK, Rao RV (2010). Tree-ring analysis of teak (*Tectona grandis* L.f.) from Western Ghats of India as a tool to determine drought years. *Emirates Journal of Food and Agriculture* 17 (1): 388. - doi: [10.9755/ejfa](https://doi.org/10.9755/ejfa)
- De Micco V, Battipaglia G, Cherubini P, Aronne G (2014). Comparing methods to analyse anatomical features of tree rings with and without intra-annual density fluctuations (IADFs). *Dendrochronologia* 32 (1): 1-6. - doi: [10.1016/j.den](https://doi.org/10.1016/j.den)
- dro.2013.06.001
- Forest Research Office (1994). The study of teak important sources in Thailand. Royal Forest Department, Bangkok, Thailand, pp. 169.
- Fritts HC (1976). *Tree rings and climate*. Academic Press, London, UK, pp. 567.
- Holmes RL (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43: 69-78.
- Holmes RL, Swetnam T (1994). Program EVENT user's manual: superposed epoch analysis in fire history. University of Arizona, Tucson, AZ, USA, pp. 7.
- Husen A (2010). Growth characteristics, physiological and metabolic responses of teak (*Tectona grandis* Linn. F.) clones differing in rejuvenation capacity subjected to drought stress. *Silvae Genetica* 59 (2): 124-136. [online] URL: http://www.sauerlaender-verlag.com/fileadmin/content/dokument/archiv/silvaegetica/59_2_010/Heft2/_10_Husen_2361.pdf
- IPCC (2013). *Climate change 2013: the physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 1535.
- Kaosa-ard A (1986). *Tectona grandis* Linn. f. nursery techniques with special reference to Thailand. Danida Forest Seed Centre, Denmark, pp. 42.
- Kaosa-ard A (1998). Overview of problems in teak plantation establishment. In: Proceedings of the "Second Regional Seminar on Teak for the Future" (Kashio M, White K eds). Yangon (Myanmar), 29 May - 3 Jun 1995. FAO Regional Office for Asia and the Pacific (RAP) Publication, Dharmasarn, Bangkok, Thailand, pp. 49-60.
- Katwal RPS (2005). Teak in India: status, prospects and perspectives. In: Proceedings of the "International Conference of Quality Timber Products of Teak from Sustainable Forest Management" (Bhat KM, Nair KKN, Bhat KV, Muralidharan EM, Sharma JK eds). Peechi (Kerala, India), 2-5 Dec 2003. Kerala Forest Research Institute, Kerala, India, pp. 1-18.
- Kokutse AD, Stokes A, Kokutse N, Kokou K (2010). Which factors most influence heartwood distribution and radial growth in plantation teak? *Annals of Forest Science* 67 (4): 407. - doi: [10.1051/forest/2009127](https://doi.org/10.1051/forest/2009127)
- Nabais C, Campelo F, Vieira J, Cherubini P (2014). Climatic signals of tree-ring width and intra-annual density fluctuations in *Pinus pinaster* and *Pinus pinea* along a latitudinal gradient in Portugal. *Forestry* 87 (4): 598-605. - doi: [10.1093/forestry/cpu021](https://doi.org/10.1093/forestry/cpu021)
- Nobushi T, Janmahasatian S, Sakai M (1996). Seasonal changes of wood formation and some characteristics of heartwood formation in teak (*Tectona grandis* L.) plantation. *Kasetsart Journal (Natural Science)* 30 (2): 254-263.
- Palakit K, Siripattanadilok S, Duangsathaporn K (2012). False ring occurrences and their identification in teak (*Tectona grandis*) in north-eastern Thailand. *Journal of Tropical Forest Science* 24 (3): 387-398. [online] URL: <http://www.jstor.org/stable/23617123>
- Prager MH, Hoenig JM (1989). Superposed epoch analysis: a randomization test of envi-

- ronmental effects on recruitment with application to chub mackerel. Transactions of the American Fisheries Society 118: 608-618. - doi: [10.1577/1548-8659\(1989\)118<0608:SEAART>2.3.CO;2](https://doi.org/10.1577/1548-8659(1989)118<0608:SEAART>2.3.CO;2)
- Prasad PVW, Staggenborg SA, Ristic Z (2008). Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In: "Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes" (Ahuja LR, Reddy VR, Saseendran SA, Yu Q eds). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA, pp. 301-356. - doi: [10.2134/advagricsystemodel1.c11](https://doi.org/10.2134/advagricsystemodel1.c11)
- Priya PB, Bhat KM (1998). False ring formation in teak (*Tectona grandis*) and the influence of environmental factors. Forest Ecology and Management 108: 215-222. - doi: [10.1016/S0378-1127\(98\)00227-8](https://doi.org/10.1016/S0378-1127(98)00227-8)
- Priya PB, Bhat KM (1999). Influence of rainfall, irrigation and age on the growth periodicity and structure in teak (*Tectona grandis*). IAWA Journal 20 (2): 181-192. - doi: [10.1163/22941932-90000678](https://doi.org/10.1163/22941932-90000678)
- Pumijumnong N, Eckstein D, Sass U (1995). Tree-ring research on *Tectona grandis* in northern Thailand. IAWA Journal 16 (4): 385-392. - doi: [10.1163/22941932-90001428](https://doi.org/10.1163/22941932-90001428)
- Pumijumnong N, Eckstein D, Sass U, Park WK (2000). Tree-ring network on teak (*Tectona grandis* L.) and its use for climatic reconstruction. In: "New Horizons in Wood Anatomy" (Kim YS ed). Chonnam National University Press, Kwangju, Korea, pp. 278-281.
- Ram S, Borgaonkar HP, Munot AA, Sikder AB (2011). Tree-ring variation in teak (*Tectona grandis* L.) from Allapalli, Maharashtra in relation to moisture and Palmer Drought Severity Index, India. Journal of Earth System Science 120 (4): 713-721. - doi: [10.1007/s12040-011-0090-5](https://doi.org/10.1007/s12040-011-0090-5)
- Ram S, Borgaonkar HP, Sikder AB (2008). Tree-ring analysis of teak (*Tectona grandis* L.F.) in central India and its relationship with rainfall and moisture index. Journal of Earth System Science 117 (5): 637-645. - doi: [10.1007/s12040-008-0058-2](https://doi.org/10.1007/s12040-008-0058-2)
- Rao KS, Rajput KS (1999). Seasonal behaviour of vascular cambium in teak (*Tectona grandis*) growing in moist deciduous and dry deciduous forests. IAWA Journal 20 (1): 85-93. - doi: [10.1163/22941932-90001553](https://doi.org/10.1163/22941932-90001553)
- Schweingruber FH, Eckstein D, Serre-Bachet F, Bräker OU (1990). Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8: 9-38. [online] URL: <http://www.cabdirect.org/abstracts/19930665561.html>
- Shah SK, Bhattacharyya A, Chaudhary V (2007). Reconstruction of June-September precipitation based on tree-ring data of teak (*Tectona grandis* L.) from Hoshangabad, Madhya Pradesh, India. Dendrochronologia 25: 57-64. - doi: [10.1016/j.dendro.2007.02.001](https://doi.org/10.1016/j.dendro.2007.02.001)
- Singhrattana N, Rajagopalan B, Kumar KK, Clark M (2005). Interannual and interdecadal variability of Thailand summer monsoon season. Journal of Climate 18: 1697-1708. - doi: [10.1175/JCLI3364.1](https://doi.org/10.1175/JCLI3364.1)
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 996. [online] URL: <http://books.google.com/books?id=8-m8nXB8CB4C>
- Sousa VB, Cardoso S, Quilhó T, Pereira H (2012). Growth rate and ring width variability of teak, *Tectona grandis* (Verbenaceae) in an unmanaged forest in East Timor. Revista de Biologia Tropical 60 (1): 483-494. [online] URL: <http://www.revistas.ucr.ac.cr/index.php/rbt/article/view/2783>
- Stokes MA, Smiley TL (1996). An introduction to tree-ring dating. University of Arizona Press, Tucson, AZ, USA, pp. 73. [online] URL: <http://books.google.com/books?id=SvBF2Ora-eUC>
- Tangmitcharoen S, Owens JN (1997). Floral biology, pollination, pistil receptivity, and pollen tube growth of teak (*Tectona grandis* Linn f.). Annals of Botany 79 (3): 227-241. - doi: [10.1006/anbo.1996.0317](https://doi.org/10.1006/anbo.1996.0317)
- Trisurat Y, Alkemade R, Arets E (2009). Projecting forest tree distributions and adaptation to climate change in northern Thailand. Journal of Ecology and Natural Environment 1 (3): 55-63. [online] URL: http://www.researchgate.net/profile/Eric_Arets/publication/40799500
- Vitas A (2004). Dendroclimatological research of Scots Pine (*Pinus sylvestris* L.) in the Baltic coastal zone of Lithuania. Baltic Forestry 10 (1): 65-71. [online] URL: [http://www.balticforestry.mi.lt/bf/PDF_Articles/2004-10\[1\]/65_71AdomasVitas.pdf](http://www.balticforestry.mi.lt/bf/PDF_Articles/2004-10[1]/65_71AdomasVitas.pdf)
- Vongvisessomjai S (2010). Effect of global warming in Thailand. Songklanakarin Journal of Science and Technology 32 (4): 431-444. [online] URL: <http://rdo.psu.ac.th/sjstweb/journal/32-4/0125-3395-32-4-431-444-20092553.pdf>
- Wigley TML, Briffa KR, Jones PD (1984). On the average value of correlated time series with applications in dendroclimatology and hydro-meteorology. Journal of Climate and Applied Meteorology 23 (2): 201-213. - doi: [10.1175/1520-0450\(1984\)023<0201:OTAVOC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2)
- White KJ (1991). Teak: some aspects of research and development. RAPA Publication, Bangkok, Thailand, pp. 70. [online] URL: <http://www.cabdirect.org/abstracts/19920663145.html>