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Contributed Paper

Influence of Climate on the Growth of Teak (*Tectona grandis* Linn. f.) at a Non-native Distributed Site in Northeastern Thailand

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Abstract

Teak (*Tectona grandis* Linn. f.), which grows naturally in the northern parts of Thailand, is widely used to determine linkages between modern and palaeo-climates. But the knowledge about climate inducing growth of teak planted in other sites of Thailand is still limited. This research attempted to investigate the effect of climate on teak growing in a non-native distributed site with non-silviculture management in Nakhon Ratchasima province, northeastern Thailand, using the techniques of cambial marking and annual ring analysis. The results showed a strong negative correlation between the annual ring formation and the mean temperature (Tmean) in March to August and illustrated a weak correlation between the teak annual growth and regional climates of the Equatorial Southern Oscillation Index (SOI) and the tropical Pacific Sea Surface Temperature (SST). Climate components of *Temperature*, *Precipitation,* and *Soil Moisture* derived from the Principle Component Analysis (PCA) directly induced teak growth through the occurrence of mature dark green leaves. The association of climate components with the occurrence of mature dark green leaves induced increments in teak stem diameter, both of wood and bark. Therefore, it can be concluded that teak growing at the non-native distributed site can be used for investigating climate-growth relationship and climate reconstruction as describe in the principle of dendrochronology.

Keywords: annual ring, cambial marking, dendrochronology, leaf phenology, path analysis

1. Introduction

Teak (*Tectona grandis* Linn. f.) is recognized as the most valuable timber in the world [1]. It is a tropical deciduous tree species distributed naturally in many countries of Southeast Asia such as India, Myanmar, Lao PDR, and Thailand [2], while teak in Java, Indonesia was introduced from India between 14th-16th centuries [1]. In Thailand, teak is naturally distributed and limited in the Northern parts, growing alongside *Pterocarpus macrocarpus*, *Afzelia xylocarpa*, *Lagerstroemia calyculata*, *Xylia kerii,* and bamboo [3]. A National Economic and Social Development Plan and strict law enforcement in 1989 led to a ban on logging in the natural forest. This added with an ever increasing demand for teak wood resulted in the relevant organizations such as the Forest Industry Organization (FIO) and other private sectors to develop teak plantations throughout the country in an area of around

127,300 hectares [4].

Kaosa-ard (1989) explained the climatic factors controlling teak growth and distribution in a warm-moisture tropical climate with rainfall between 1,270-3,800 mm, under relatively high soil moisture conditions with a dry period of 3-5 months. Teak can survive over a wide range of temperatures, from 2-48 °C, with an optimum growth observed in areas with a mean maximum and minimum monthly temperature of 40 and 13 °C, respectively. Using techniques of tree-ring analysis, namely dendrochronology, a positive correlation between teak growth with monsoon rainfall was reported within a naturally distributed zone in Myanmar and Thailand [5, 6, 7]. The correlation increased gradually from the beginning to mid-season and gradually decreased towards the end of the season, confirming that the growth was dependent on the moisture availability

Using one of basic principles and concepts of dendrochronology, the concept of ecological amplitude [8], it was found that the growth of a tree growing around the margins of its natural range may be highly reduced due to variations in climate, far greater than of that growing near the center of its natural distribution. The relative difference between adjacent ring widths, commonly termed as the mean sensitivity, ranges between 0-2 and can be used to indicate the growth response to variations in climate [9]. Studies of the relationship between climate and teak growth response were generally undertaken near the center of the natural distributed zone as in the natural forest of the Northern region, while studies focusing on the influences of climate on teak growth at a non-native distributed site, such as in teak plantations of other regions in Thailand, is still limited.

For this research, teak trees planted using non-silviculture practice, the practice of controlling forest composition, structure, and growth for any purpose, at the Wang Nam Khiao Forestry Student Practicing Station in Nakhon Ratchasima province, northeastern Thailand, were selected. The purpose of this selection, instead of selecting a teak plantation, was to avoid effects of human and other activities on teak growth. Patterns of monthly and annual growth of teak were described and correlated with climate in a non-native habitat in order to explain the effects of climate on teak growth and to confirm the importance of samples collected for tree-ring analysis using the concept of ecological amplitude. Their growing patterns were also discussed and compared with other teaks growing in natural and non-native distributed habitats.

2. MATERIALS AND METHODS

2.1 Site Description

The research site is located at the Wang Nam Khiao Forestry Student Practicing Station, which belongs to the Faculty of Forestry, Kasetsart University. This station is located in Nakhon Ratchasima province, northeastern Thailand, at an elevation of 339 m above the mean sea level (Figure 1). Mature teak trees, approximately 40 years old, were planted with other tree species to serve the practical purposes of forestry students as an arboretum, with non-silviculture practice. The nearest meteorological station is the Sakaerat Environmental Research Station (SERS), which has been recording climatic variables like rainfall, relative humidity, and temperature since 1969. The region experiences two seasons, i.e., dry (December until February) and wet (March until November) seasons. The wet season can be divided further in two intervals of early (March until August) and late (September until November) wet season, due to reduced rainfall during the mid-season (Figure 2). The average annual rainfall and mean temperature was 1074.9 mm. and 26.3 °C, respectively. The total rainfall during the dry and wet season was 31.9 and 1043.0 mm, while the mean temperature during these 2 periods was 23.8 and 27.1 °C, respectively.

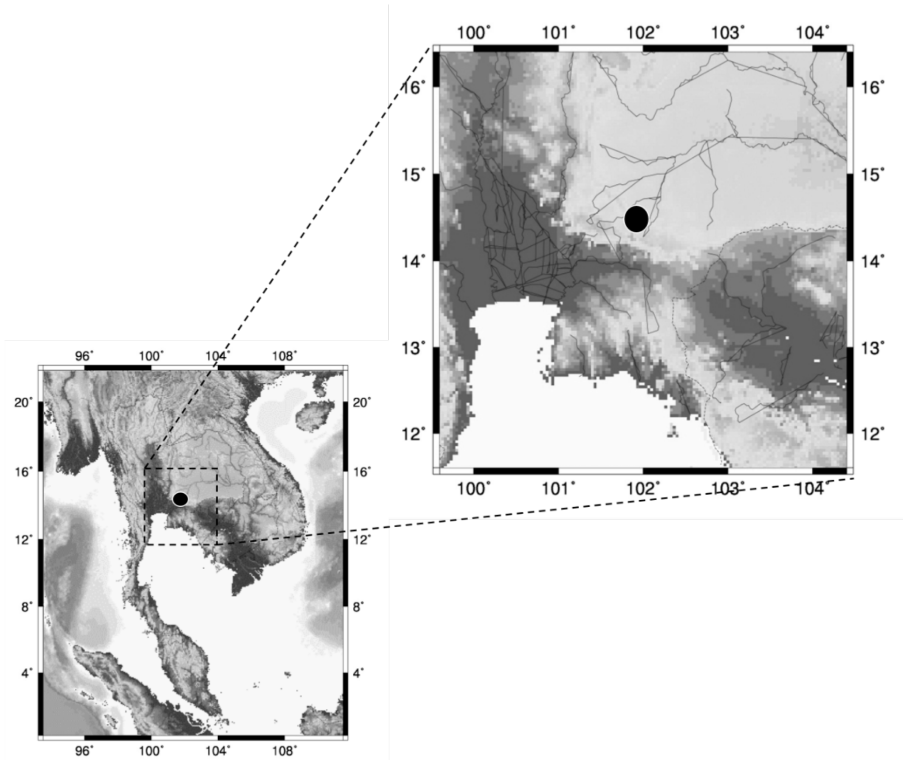

Figure 1 The study site (indicated by black dots) located in northeastern part of Thailand.

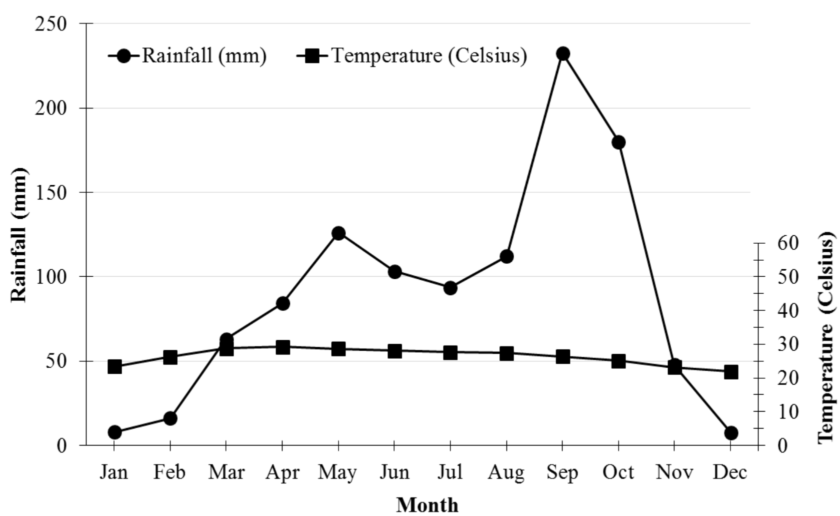

Figure 2 Mean monthly rainfall and temperature from the Sakaerat Environmental Research Station (SERS) during 1969-2014.

2.2 Sample Collection and Preparation

During August 2009 to August 2010, seven mature teak trees with symmetrical crowns and straight trunks (coded WNTG01 to WNTG07), planted with non-silviculture management on well-drained soil, were selected for monthly and annual growth investigation. To study the annual growth, four incremental cores from each tree were taken from the bark through to the pith in the cardinal directions at breast height (1.3 m), using an increment borer. Wood cores were kept in ventilated plastic straws to avoid damage and fungi attack until these samples were transported to the Laboratory of Tropical Dendrochronology in the Faculty of Forestry, Kasetsart University. The core samples were then fixed in wooden supports and polished with several grades of sandpaper until the transverse surfaces were visible under a stereomicroscope.

In addition, the monthly growth of teak trees, in terms of leaf phenology and tree diameter increment, was also investigated. The occurrences of leaf flushing (LF), mature light green leaf (MLL), mature dark green leaf (MDL), and leaf abscission (LA) were investigated on a monthly basis using visual estimation with binoculars for a year. The scoring system for leaf phenology ranged from 0-5 with a 0 indicating absence of leaf, 1 for 1-20 percent, 2 for 21-40 percent, 3 for 41-60 percent, 4 for 61-80 percent, and 5 for 81-100 percent occurrence. Coinciding with the leaf phenological study, the outside and inside bark diameter increments (OBD and IBD, respectively) were recorded monthly. Modified manual band dendrometers with a 0.1 mm accurate vernier scale were installed on the seven selected teak trees at breast height to record the OBD increment. The IBD increments were studied by injuring the cambial zone once a month for a year. Soil moisture content was also monitored on a monthly basis from soil depths of 5, 10, 15, 20, 25 and 30 cms. After a year of monthly investigations, all the cambial injury markings were extracted from the trees and carefully polished using several grades of abrasive papers until the injured zones were smooth and prominently visible under a stereomicroscope.

2.3 Data Analysis

All the core samples were visually cross-matched to determine their ages and annual ring boundaries. The annual ring widths were then measured by using a Velmex measuring system, with a sliding stage micrometer of 0.001 mm accuracy [10], and the measurements were recorded onto a microcomputer by using the MeasureJ2X software [11]. The COFECHA [12, 13] and ARSTAN [14] softwares were used to re-check the dating quality and to construct an annual ring width index, respectively. The running Rbar and the Expressed Population Signal (EPS) were calculated, and an EPS of 0.85 or higher [15] was used to evaluate the average correlation between ring-width series and the acceptable number of annual rings respectively.

The monthly and annual meteorological temperature data (maximum or Tmax, minimum or Tmin, and mean or Tmean), total rainfall, and relative humidity (RH) were obtained from the Sakaerat Environmental Research Station (SERS) (*http://sakaeratsers.weebly.com/3586365736293617364136213629364036053640360936363618361736233636360736183634.html*), with the Equatorial Southern Oscillation Index (SOI) obtained from *http://www.cpc.ncep.noaa.gov/ data/indices/reqsoi.for,* and the tropical Pacific Sea Surface Temperature (SST) from *http://www.esrl.noaa.gov/psd/data/correlation/eofpac.data,* for the climate-growth relationship analysis. These local and regional climate data were correlated with the annual ring width index using correlation and regression analyses to investigate the local and regional climate-growth relationship. The distances between the baseline (the 1st injured marking) and each injured marking derived from the injured cambial samples were measured using the Velmex measuring system and converted into a monthly IBD. The standardized values of OBD and IBD were calculated using a z-score which normalized the growth of all trees in different age classes to a comparable scale. A positive or negative z-score indicated that the actual value was above (greater than) or below (less than) the mean, respectively. Z-score was calculated using the formula given below:

$$Z = \frac{X - \overline{X}}{SD}$$

where X is the measured monthly OBD or IBD , $\overline{X}$ is the mean and SD is the standard deviation of the measurement.

The monthly climate and soil moisture variables were grouped to remove multicollinearity by using the PCA. In the case of multicollinearity, a significant relationship between the independent variables of rainfall, temperature, relative humidity, and soil moisture content, had been detected when the tolerance (TR) values was less than 0.20 and/or the variance inflation factor (VIF) was 5 or above. Based on the criteria of Eigen values ≥ 1, these climatic data were then transformed into components of linearly uncorrelated variables. The relationship among grouped climate variables, leaf phenology, OBD, and IBD were finally analyzed to explain the hierarchical correlation of climate variability on teak growth using the technique of Path Analysis (PA).

3. Results

For annual growth and climatic response, all the increment cores were cross-matched and cross-dated. The annual teak ring width patterns had a rapid increase in the beginning of their growth and declined when they reached maturation. The mean series intercorrelation, mean sensitivity, total length, and mean length of the series were 0.59, 0.43, 47, and 33.4, respectively. The annual ring width index was constructed from the annual ring width series covering the past 47 years, with the EPS ranging from 0.87 to 0.96, indicating sufficient sample size and excellent overall cross-dating of teak ring index (Figure 3).

The correlations were calculated between the annual ring width index and local and regional climatic data to indicate which climate variables controlled the growth of teak and are shown in Figure 4 & 5. The index was significantly correlated with the local mean monthly Tmax, Tmin, and Tmean from March to August. Annual and seasonal temperature during the rainy season from March until November also had a highly significant correlation with the index, while the highest correlation coefficient was found indicating a strong negative correlation between the index and March to August Tmean with $r(38) = -0.75$; $p < 0.01$, as shown in Figure 4a-4c. The total rainfall from March until August exhibited a weak positive correlation with the index with $r(38) = 0.34$; $p < 0.05$, while total rainfall in the dry season (December until February) was moderate positive correlation with the index with $r(38) = 0.50$; $p<0.01$, as shown in Figure 4d. The variations in the annual ring width index were not significantly related with the relative humidity (Figure 4e). The regional climatic data of the Equatorial SOI and tropical Pacific SST during the pre-monsoon months, from January until April, had a weak positive and negative correlation with the annual ring width index with $r(38) = 0.45$; $p < 0.01$ and $r(37) = -0.49$; $p < 0.01$, respectively (Figure 5). Using a regression analysis, it was found that the variations in annual teak growth could be explained by the fluctuations in Tmean during March to August and the pre-monsoon SST with variances of 55.7% and 24.1%, respectively.

Leaf phenology in terms of LF is illustrated in Figure 6 in March until August and November. MLL developed from LF were observed in April until November and were abundantly found during April and May. In June, most of the MLL matured to MDL and appeared until November. The number of MDL continuously decreased from December until May. Leaves started to abscise (LA) as indicated by their color changing to yellowish and brown. LA was rarely found in June-November and generally occurred in December to January. The various phases of teak leaves were rarely observed in February and March, indicating dormancy and transitional period to a

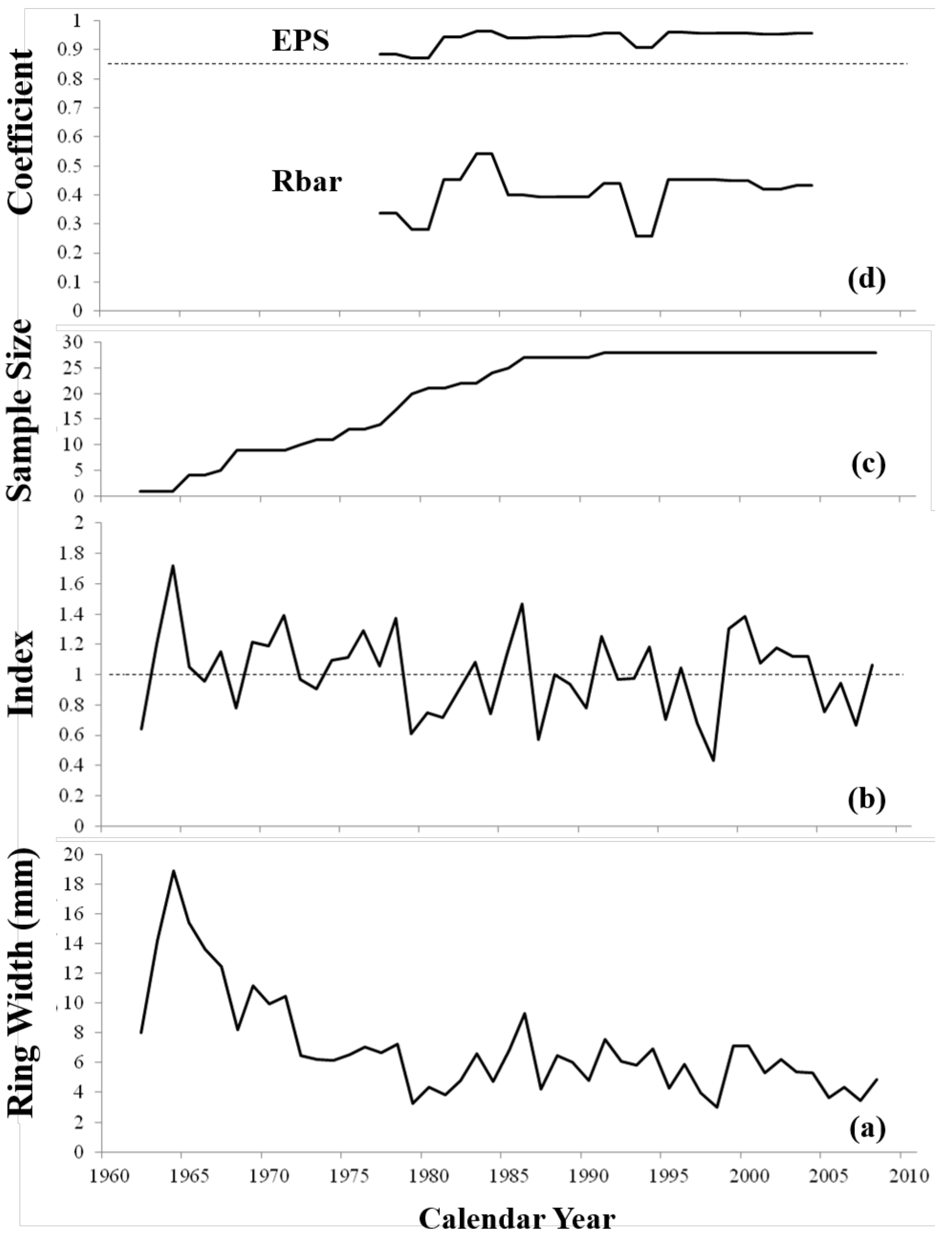

Figure 3 Teak annual ring plots: (a) mean annual ring width, (b) annual ring width index, (c) sample size, and (d) running EPS and Rbar.

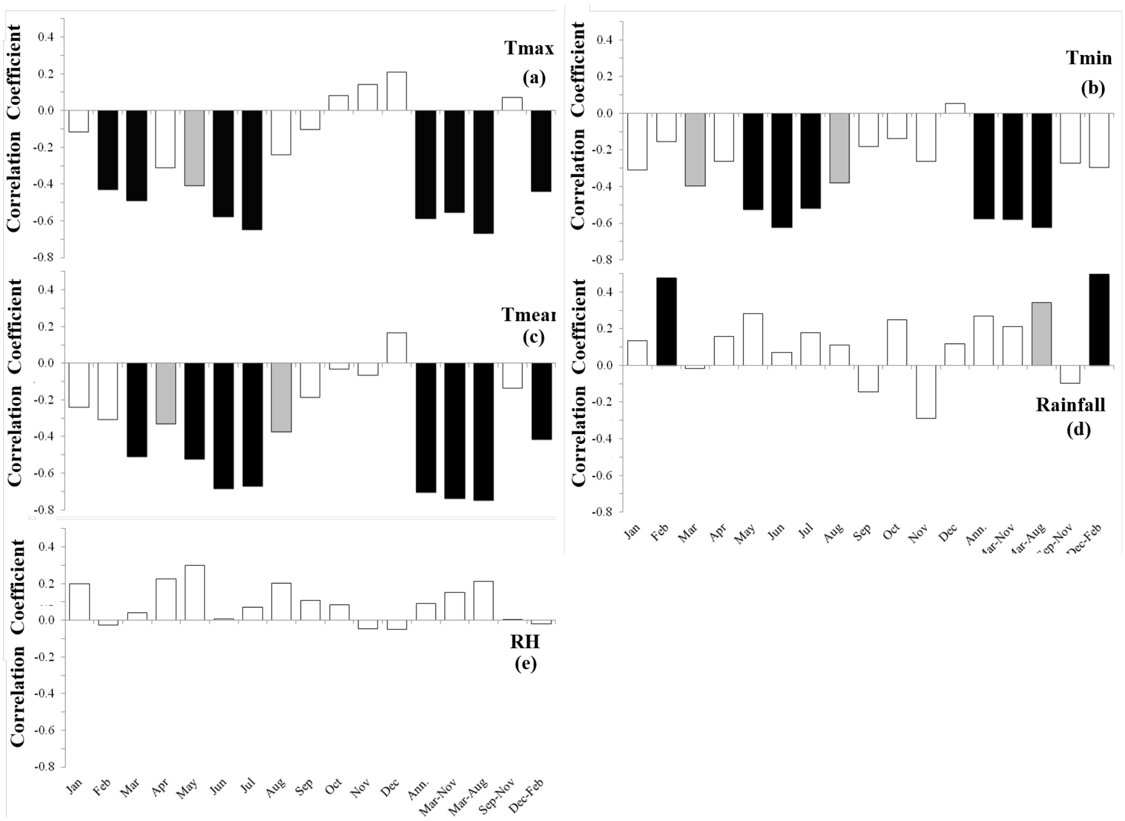

Figure 4 Plots of correlation coefficients (r) of ring width index with monthly, annual, and seasonal local climate as a function of: (a) Tmax, (b) Tmin, (c) Tmean, (d) Rainfall, and (e) Relative humidity (RH). The grey bars represent significant correlation ($p<0.05$), while black bar represent a highly significant correlation ($p<0.01$).

new growing season.

The OBD was measured monthly using a manual band dendrometer. The diameter increased for 2 months after the band installation during September - October and decreased to its lowest point of the shrinkage in February. OBD slowly increased from March until May and rapidly increased from June to August with an average cumulative OBD of 3.8 mm. OBD and the standardized values are shown in Figure 7 a & b.

Using the cambial marking technique, IBD increment, measured as the distance between the first marking and the next during the ensuing 12 months (Figure 8) was 3.58 mm. IBD increment rate decreased from September until November and the total wood increment in these three months was 0.91 mm. In December, all the trees were dormant, except WNTG05 and WNTG07, in which 0.1 and 0.5 mm wood was formed, respectively. The cessation of wood increment occurred in association with leaf abscission. All the trees were dormant in January until March, except the tree coded WNTG05, in which the initial banded parenchyma started during the period coinciding with leaf flushing in March and the total wood formed was 0.15 mm. The annual increment in teak wood was initiated in March/April and formed completely in November (Figure 7c&d), indicating a growing period of 8-9 months. From March until August, the rates of

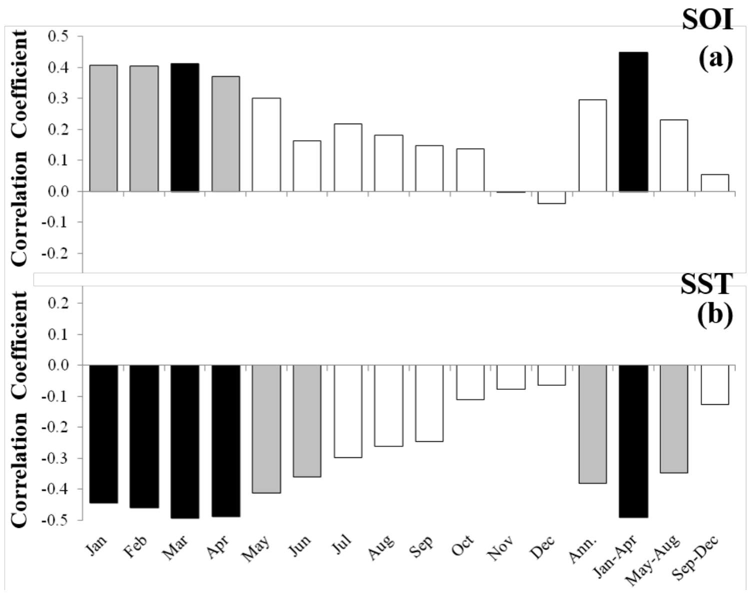

Figure 5 Plots of correlation coefficient (r) of ring width index with monthly, annual, and seasonal regional climate as a function of: (a) SOI and (b) SST. The grey bars represent a significant correlation ($p<0.05$), while black bars represent a highly significant correlation ($p<0.01$).

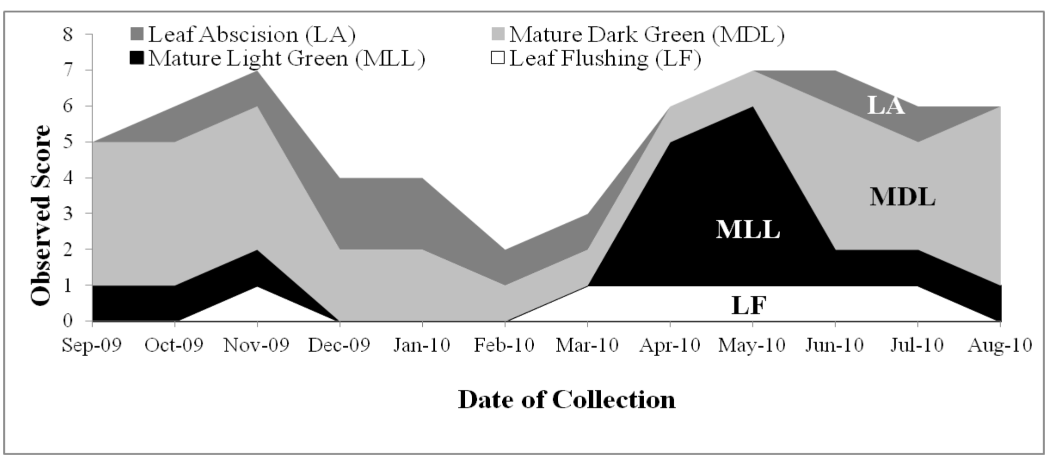

Figure 6 Leaf phenology of *Tectona grandis* during September 2009 – August 2010.

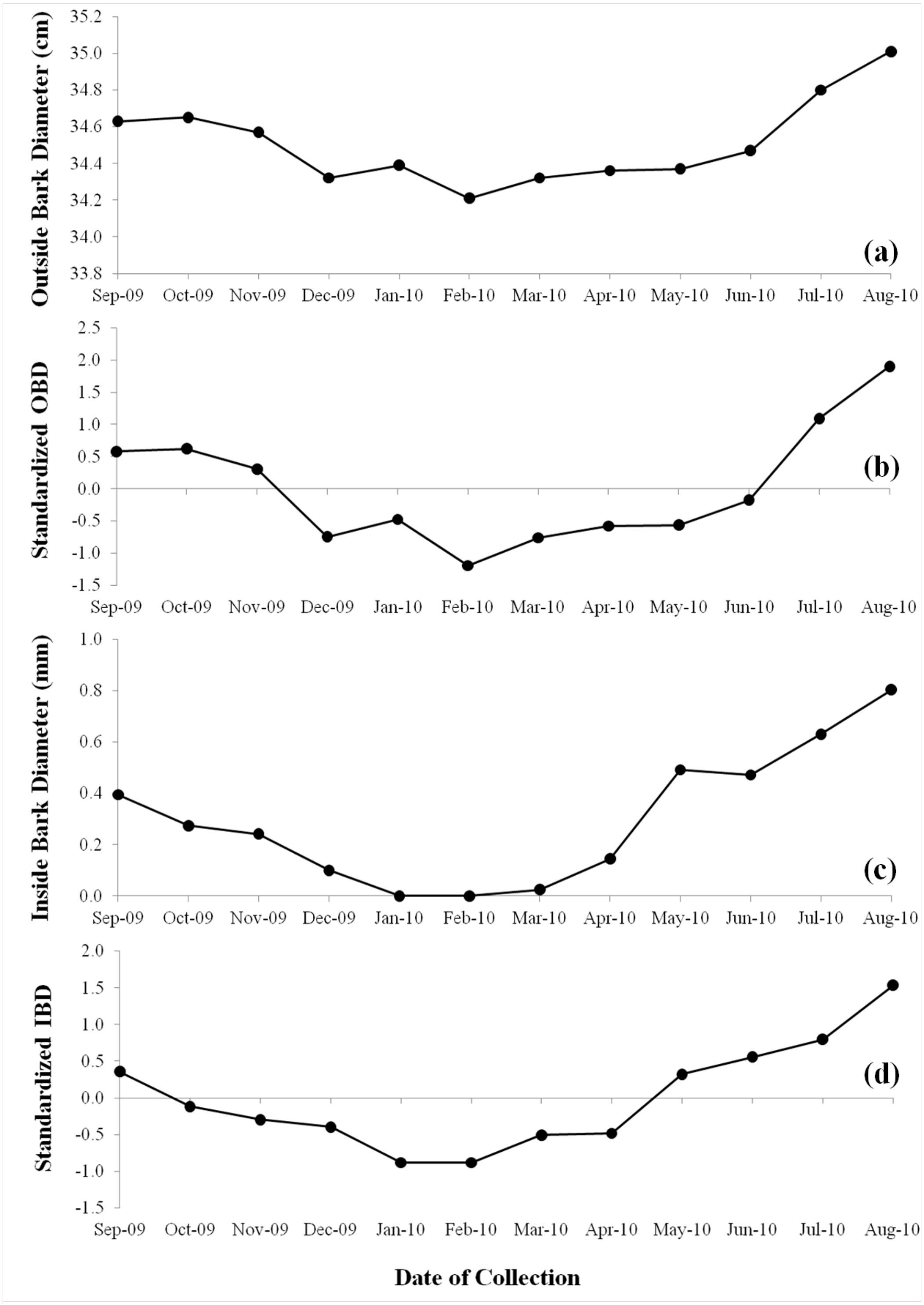

Figure 7 Monthly wood increment of teak during September 2009 – August 2010: (a) outside bark diameter (OBD), (b) standardized OBD, (c) inside bark diameter (IBD), and (d) standardized IBD.

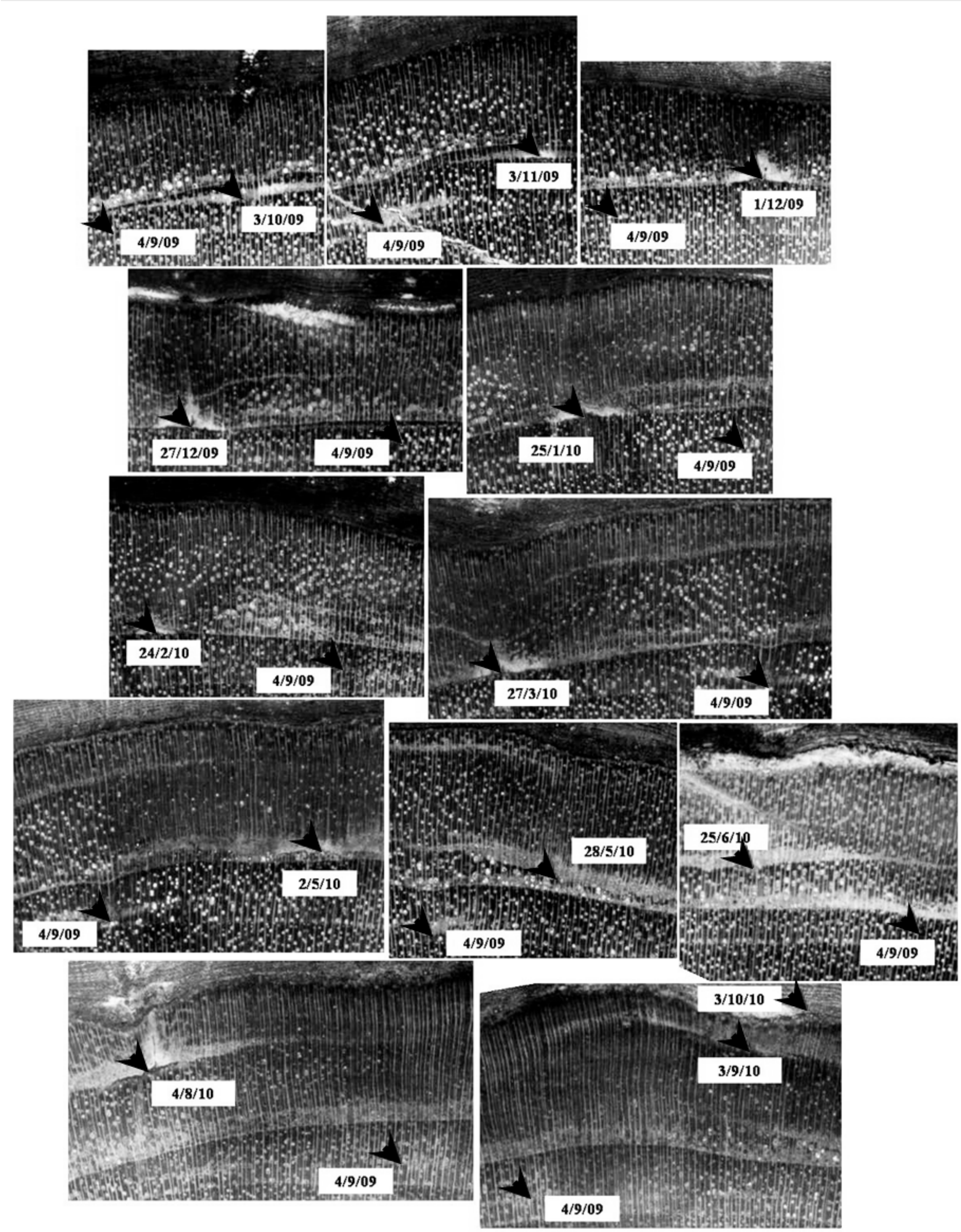

Figure 8 Scanned images of cambial markings on teak stem sections. Black arrowheads indicate the points where cambium was injured on dates defined in the text.

monthly wood increment continuously increased from 0.03 mm/month to 0.80 mm/month, as shown in Figure 7c. The z-scores fluctuations of standardized IBD during the investigated period are shown in Figure 7d.

Monthly climate data and soil moisture content could be transformed into three components of linearly uncorrelated variables using the PCA technique in order to remove the effect of multicollinearity (Figure 9). The first component was related to soil moisture content at all soil depths and was re-named as *Soil moisture*. The second component was related to the three measures of temperature, Tmax, Tmin, and Tmean, and was re-named as *Temperature*. The last component related to rainfall and RH data was re-named as *Precipitation*. The components of *Soil moisture*, *Temperature,* and *Precipitation* were not significantly correlated with the other components and could explain 53.07, 24.46, and 17.62% of the variance in all the climatic factors, respectively.

Using PA with the statistical significance at $p<0.05$, the path diagram of climate inducing leaf phenology and tree growth of teak (Figure 10) indicated that the model was a good fit and passed the overall model fit examination ($\chi2 = 4.65$, df = 6, p = 0.59; Root Mean Square Error of Approximation (RMSEA) = 0.00 and Comparative Fit Index (CFI) = 1.00). Path diagrams of teak growth predicted that *Soil Moisture*, *Precipitation,* and *Temperature* components led to the appearance of MDL, as indicated by r(11) = 0.29, 0.79 and -0.36, respectively. These 3 climatic variables could explain 84% of the variations in the occurrence of MDL.

MDL and the *Temperature* component were directly correlated with the IBD increment, with r(11) = 0.82 and 0.45, respectively. Although,

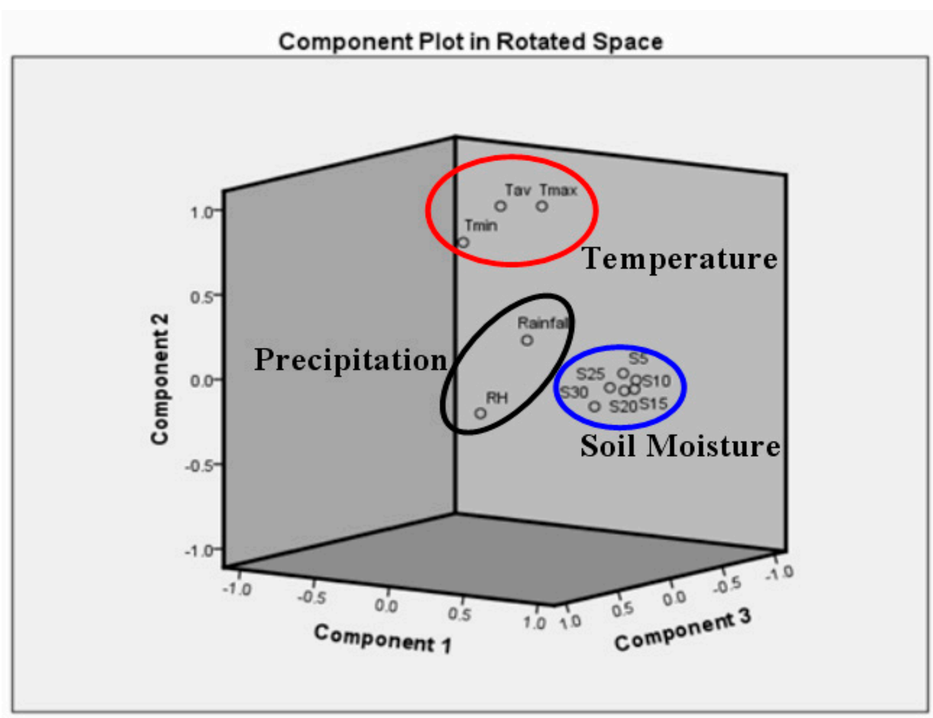

Figure 9 Grouping of climatic and soil moisture variables into 3 components of *Precipitation*, *Temperature,* and *Soil Moisture* using principle components analysis (PCA).

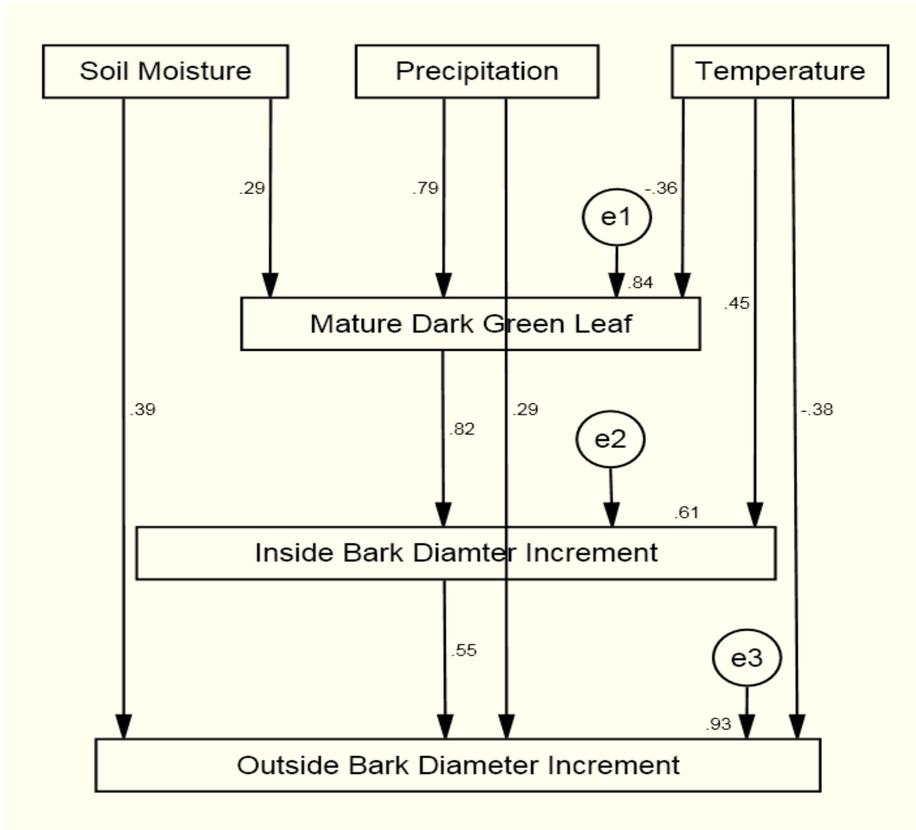

Figure 10 Path diagrams of factors affecting monthly growth of teak. The notations e1, e2, and e3 indicate errors in predicting the values of mature dark green leaf (MDL), inside bark diameter (IBD), and outside bark diameter (OBD), respectively.

Precipitation and *Soil Moisture* components were not directly correlated with IBD increment, these variables were significantly related to MDL, a potential factor which induced wood increment. *Precipitation*, *Soil Moisture,* and *Temperature* components were termed as indirect factors influencing IBD increments with r(11) = 0.65, 0.24 and 0.30, respectively. Both MDL and three climate components could be used to explain 61% of variance in the IBD increment.

The OBD increment was directly influenced by IBD and the three climate components of *Precipitation*, *Temperature,* and *Soil Moisture,* with r(11) = 0.55, 0.29, -0.38, and 0.39, respectively. The OBD increment was also indirectly influenced by *Precipitation*, *Temperature,* and *Soil moisture* components through MDL and IBD increment, with r(11) = 0.36, 0.08, and 0.13, respectively. The three climate components, MDL, and IBD increment can be used to explain 93% of the variations in OBD increment.

The total effect calculations indicated that MDL was the most important factor affecting IBD increment (r = 0.82) followed by *Precipitation* (r = 0.65), *Soil Moisture* (r = 0.24), and *Temperature* (r = 0.15), respectively. The *Precipitation* component was a major factor inducing increment in OBD (r = 0.64) followed by IBD increment (r = 0.55), *Soil Moisture* component (r = 0.53), MDL (r = 0.45), and *Temperature* component (r = -0.30), respectively.

4. Discussion

The wider teak ring widths during the juvenile stage indicates that the effect of tree age is greater than the effect of climate. Sousa et al [16] studied the growth rate and ring width variability of teak planted in an unmanaged forest in East Timor and also found that the highest growth rate ranged between 4.3-7.3 mm for the first 20 years and declined to 3.3-5.1 mm for the next 30 to 45 years. The value of mean sensitivity, a statistic measuring the mean relative change between the adjacent ring widths [8] after removing age related trend and climate signal enhancing, indicated that the influences of factors affecting teak growth at this site was 0.429 which was higher than at other sites within a naturally distributed zone in Thailand. The mean growth sensitivity of teak growing naturally in Umphang Wildlife Sanctuary and five sites in the Pai Wildlife Sanctuary in the northern part of Thailand ranged between 0.321-0.392 [7,17]. Ram et al [18] analyzed the potential of teak at 3 sites in central India, at latitudes between 16°N-22 °N. The Bori sites at a latitude of 22 °N had the highest mean sensitivity of 0.43, while the ones at Sajpur and Edugurapalli, at lower latitudes, had a lower mean sensitivity of 0.34 and 0.31, respectively. Although, teak is grown in naturally distributed zones of Myanmar, moderate slopes at elevations between 300-700 m above mean sea level, are the selected sites, with a high mean sensitivity between 0.48-0.50 [19].

To realize the limitation of teak growth and induced wider ring widths, an increased rainfall during the dry period at the beginning of the year combined with a decreased temperature throughout the year, especially during the rainy season, reduces water stress and stimulates teak growth during the growing period. Compared with other climate-growth responses of teak in Thailand and other countries, teak growing in the natural forest is generally controlled by rainfall during the monsoon season [5, 18] and during the transitional period between summer and rainy season [17]. However, our studies found the main growth response to temperature during the rainy season and the effect of rainfall on tree growth during the dry season. Priya and Bhat [20] irrigated teak trees during the pre-monsoon season and also reported that the pre-monsoon showers can break the cambial dormancy. The increase in temperature, especially in the growing period of March until November was significantly correlated with a decline in teak ring width, similar to the study of Buckley et al [5]. Fritts [8] also suggested that a lower temperature during the growing season might decrease evaporation and water stress in trees while a thicker ring width was formed following this condition.

Regional climate of the Equatorial SOI and the SST over the tropical Pacific Ocean can also influence the responses in teak growth similar to that of the local climate. An increase in SOI during the transitional period between the dry and rainy seasons (January until April) induced rapid growth, while an increased SST during the same period reduced teak growth. Although, Bijaksana et al [21] and D'Arrigo et al [6] found a significant correlation between SOI and SST and teak growth in Indonesia and Myanmar, respectively, the response period was during the monsoon period, while a significant correlation was found in the dry period in the present study.

With regards to phenological characteristics, the teak trees produced abundant leaf crowns throughout the rainy season, similar to other tropical tree species [22]. Valdez-Hernandez et al [23] explained that in deciduous and tropical species, leaf flushing was generally determined by when the rainy season began, while the leaf fall depended on the duration of dry periods.

The fluctuations in OBD increase in the rainy season and shrinkage in the dry season, which can be explained in terms of the hydrostatic force. Pelissier and Pascal [24] related the variations in OBD with the hydrostatic stem flexibility, which depended on the intensity of rainfall, soil moisture content, the degree of turgidity, and water stress in the tree. Girth flexibility of some tree species was also investigated and the cause of variation was confirmed as a deficit in rainfall and vapor pressure [25].

Most of the shrinkage and swelling in stems generally occurred within flexible tissues, such as cambial zone, phloem and bark, while turgidity in wood or xylem cells were rarely founded [26]. Approximately 40% of the variation in OBD in *Eucalyptus nitens* was due to bark and phloem shrinkage [27]. Therefore, in each year, a continuous measurement of OBD increment, using a number of dendrometers indicated that it shrunk in the dry season and swelled in the rainy season. This phenomenon was important factor for all the researchers to consider during the preparation, installation and interpretation of the OBD increment data from the dendrometer band.

IBD indicated a monthly wood increment and cessation in rainy and dry seasons, respectively. This was also confirmed by Singh and Venugopal [28], who claimed that droughts during the winter months forced a dormancy in wood increment, while an abundance of rainfall during the monsoon season induced wood increment. Cufar et al [29] found the reactivation of cambial cells immediately when beech (*Fagus sylvatica*) leaves were unfolding. They also found 75% of the annual ring width formation during the first half of the cambial activity. Sass et al [30] found continuous wood formation in evergreen tree species, *Dryobalanops sumatrensis* and *Shorea leprosula*, which was not related to the seasonality in rainfall abundance and phonological occurrence.

Furthermore, using PA, the fluctuations in leaf phenology, especially in MDL, directly affected the IBD, which was the actual wood increment. Venugopal and Liangkuwang [31] found cambial activity and annual rhythm during the xylem production in elephant apple trees (*Dillenia indica* Linn.), occurring after the sprouting of new leaves and buds for 15 days, while Askeyev et al [32] did not find any relationship between leaf phenology and wood increment in pedunculate oak (*Quercus robur*) in the central Volga region, Tatarstan, Russia. At La Selva Biological Station, Costa Rica, several deciduous trees in an old growth forest showed a significant relationship between stem increment and leaflessness, while such a relationship was absent in the evergreen trees [33].

The climate components of *Precipitation*, *Temperature,* and *Soil Moisture* had both a direct and indirect relationship with the IBD increment through the changes in MDL. However, the major factor affecting the monthly wood increments of teak was the abundances of MDL. This observation was different from a study of two evergreen species, *Aglaia odoratissima* and *Hydnocarpus illicifolius*, in which mature dark green leaves occurred in abundance throughout the year and the IBD increments were not significantly related to the leaf abundance [34]. Additionally, all the climatic data had no significant correlation with the monthly wood increment of *A. odoratissima,* but the soil moisture and rainfall were significantly related to the monthly wood increment in *H. illicifolius* [34]. Borchert [35] also confirmed that the amount of rainfall during the wet season influenced leaf phenology, cambial activity, and wood increment in the deciduous trees.

Not only did an increase in temperature during the growing period induce tree growth, but the study of *Pinus leucodermis* in a tree-line in southern Italy by Deslauriers et al [36] also suggested that the increased temperature caused an early onset of cambial activity and all differentiated phases of about 20 days resulting in an increased duration of xylogenesis. To confirm the effect of climate and phenology on tree growth, Heinrich and Banks [37] determined that under restricted growing conditions of minimum water supply and nutrients, with *Toona sinensis* and *T. ciliata* often illustrating longer leafless periods, shorter flushes of leaves, decreased vessel sizes, and diameter growth increments.

OBD increments in teak trees are positively related to the increments in xylem elements. According to the stem shrinkage and swelling, *Temperature*, *Precipitation,* and *Soil Moisture* components directly induced shrinkage or swelling of OBD. Bräuning and Burchardt [38] suggested that OBD increments during the rainy season was related to the cambial activity and the formation of xylem elements, while swelling and shrinkage of OBD during the dormant and dry periods was probably dependant on the sufficiency of bark water content rather than changes in xylem growth. Makinen et al [39] also recommended the cambial marking technique to investigate the seasonal rhythms of xylem growth or wood increment, instead of dendrometer bands, which were probably affected by bark swelling and shrinkage.

5. Conclusions

We studied the growth of teak growing at a non-native distributed site in northeastern Thailand. With a fairly high mean sensitivity, the growth was significantly related to local climate, especially temperature during the rainy season, and the regional climate of Equatorial SOI and the SST during the dry season. Leaves occurred in abundance association with wood increments during the rainy season similar to leaf abscission and wood increment cessation during the dry season. The climate components of *Precipitation*, *Temperature,* and *Soil Moisture* could explain 84% of the appearance of MDL. All the climate components with MDL could explain 61% of the variation in IBD, while the climate components with MDL and IBD could explain 93% of the variance in OBD.

Further studies will include older teak trees growing on other non-native distributed sites to explore the relationship of growth with climate and to determine the effect of local and regional climates on growth. It is important in a silviculture management plan to set up appropriate activities during the dormant and growing periods. In case of IBD and OBD increments, these measuring techniques can be applied to investigate the growth of other tree species having absent, indistinct, and distinct annual rings in all the natural forests and plantations.

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