



## THESIS APPROVAL

### GRADUATE SCHOOL, KASETSART UNIVERSITY

Doctor of Philosophy (Forestry)

DEGREE

Forestry

FIELD

Forestry

FACULTY

**TITLE:** Biology and Factors Affecting Tree-Ring Formation of Some Tree Species  
at Sakaerat Environmental Research Station

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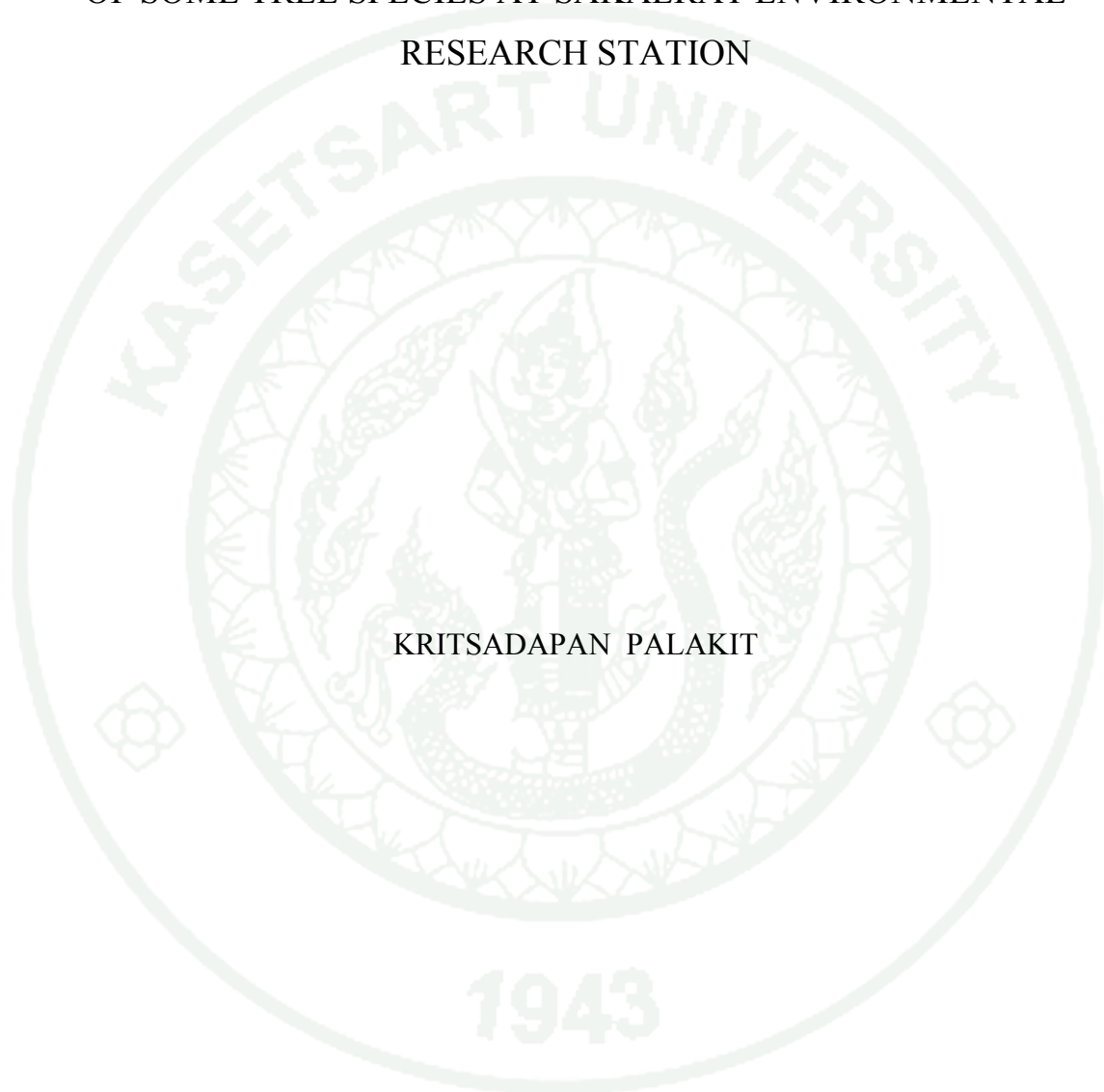
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THESIS

BIOLOGY AND FACTORS AFFECTING TREE-RING FORMATION  
OF SOME TREE SPECIES AT SAKAERAT ENVIRONMENTAL  
RESEARCH STATION



KRITSADAPAN PALAKIT

A Thesis Submitted in Partial Fulfillment of  
the Requirements for the Degree of  
Doctor of Philosophy (Forestry)  
Graduate School, Kasetsart University

2013

Kritsadapan Palakit 2013: Biology and Factors Affecting Tree-Ring Formation of Some Tree Species at Sakaerat Environmental Research Station. Doctor of Philosophy (Forestry), Major Field: Forestry, Faculty of Forestry. Thesis Advisor: Associate Professor Somkid Siripatanadilok, Ph.D. 276 pages.

The major objective of this study was to investigate biology and factors affecting tree-ring formation of the selected species at Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry (WNKFSPS). From 92 species, 6 tree species with one or both of the characteristics of presenting marginal parenchyma, showing distinct or abrupt anatomical changes at the growth ring boundary and composing of ring porous or semi-ring porous vessel arrangement were selected for the studies. The selected tree species composed of 4 deciduous species (*Tectona grandis*, *Azelia xylocarpa*, *Melia azedarach* and *Lagerstroemia duperreana*) and 2 evergreen species (*Aglaia odoratissima* and *Hydnocarpus ilicifolia*). Monthly investigations of (1) tree phenology, (2) outside bark diameter increment from band dendrometer, and (3) wood increment and wood anatomy from cambial marking samples were done and related with climate and soil moisture contents to investigate biology and factors affecting tree-ring formation. False ring and annual ring characteristics of teak (*Tectona grandis* L.f.) were also investigated to explain major factors affecting their occurrences.

Axial parenchyma and/or vessel size variation were the marked points of annual ring boundaries of *T. grandis*, *A. xylocarpa*, *L. duperreana* and *M. azedarach* while fiber cell wall thickness and flatted fiber were useful to identify the annual ring boundaries of *L. duperreana*, *A. odoratissima* and *H. ilicifolia*. Monthly wood increment of 4 deciduous trees initiated on the same periods of leaf flushing at the beginning of rainy season or a month later and cessation occurred during leaf abscission in dry and cold season at the end of the year. Wood increments of 2 evergreen trees were dormancy in dry periods at the end of the year, while leaf phenologies were abundantly found throughout the year. Outside bark diameters in all species rapidly increased in rainy season and illustrated the shrinkage in dry season.

The climatic data of monthly temperature, rainfall, relative humidity and soil moisture which were transformed to the components of moisture (rainfall, relative humidity and soil moisture content) and temperature (maximum, minimum and mean monthly temperature) illustrated both of direct and indirect relationship with wood increment of all tree species, except *A. odoratissima*. The abundances of mature dark green leaves showed the significant relationship with outside bark diameter increment of all selected deciduous species and illustrated the insignificant relationship with the selected evergreen species.

In case of teak trees, the potential species for tree-ring analysis in the tropics, vessel size variation was useful to define annual ring boundaries and identify false rings. Rainfall and temperature in pre-monsoon (January till April) and during monsoon (May till August) were important to induce both of ring width variation and false ring formation. Declined rainfall associated with increased temperature in pre-monsoon was the causation of false ring formation in earlywood zone (false ring-type I), while high temperature (especially in August) and lower rainfall during monsoon period following with heavy rainfall in post monsoon stimulated false ring formation in latewood zone (false ring-type II).

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Student's signature

Thesis Advisor's signature

## ACKNOWLEDGEMENTS

This thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study. First and foremost, my utmost gratitude to Assoc. Prof. Dr. Somkid Siripattanadilok, my thesis advisor, whose sincerity and encouragement I will never forget. Dr. Siripattanadilok gave advice and valuable suggestion for completely writing of my thesis. I would sincerely like to thank Asst. Prof. Dr. Khwanchai Duangsathaporn, my committee, for his valuable comments and suggestion.

I would like to sincerely thank Mr. Taksin Artchawakom, the director of Sakaerat Environmental Research Station (SERS), who gave me the permission for studies at SERS in 2009-2010. I also gratefully thank Assist. Prof. Dr. Wanchai Arunpraparut, the Dean of Faculty of Forestry-Kasetsart University (KUFF), who gave me the permission for studies at Wang Nam Khiao Forestry Student Practice Station (WNKFSPS).

My research couldn't be completed without very kind support from Mr. Sirisak (the ex-director of WNKFSPS) and Mr. Kusol Tungjaipitak who assisted me all steps of sample collection and wood anatomical micro-technique. Other important persons, whom I wish to express my deepest appreciation, were all proficient staffs from the Laboratory of Tropical Dendrochronology (LTD) – Bas, Pom, Ake, Kriang and Pookie – for their help in sample collection and preparation.

This research was partially funded by the Graduate School of Kasetsart University and the Center for Advanced Studies in Tropical Natural Resources, National Research University–Kasetsart University. Finally, I am especially appreciated my parents, my sister and all in my family for their continuing encouragements during my graduate study.

Kritsadapan Palakit

April 2013

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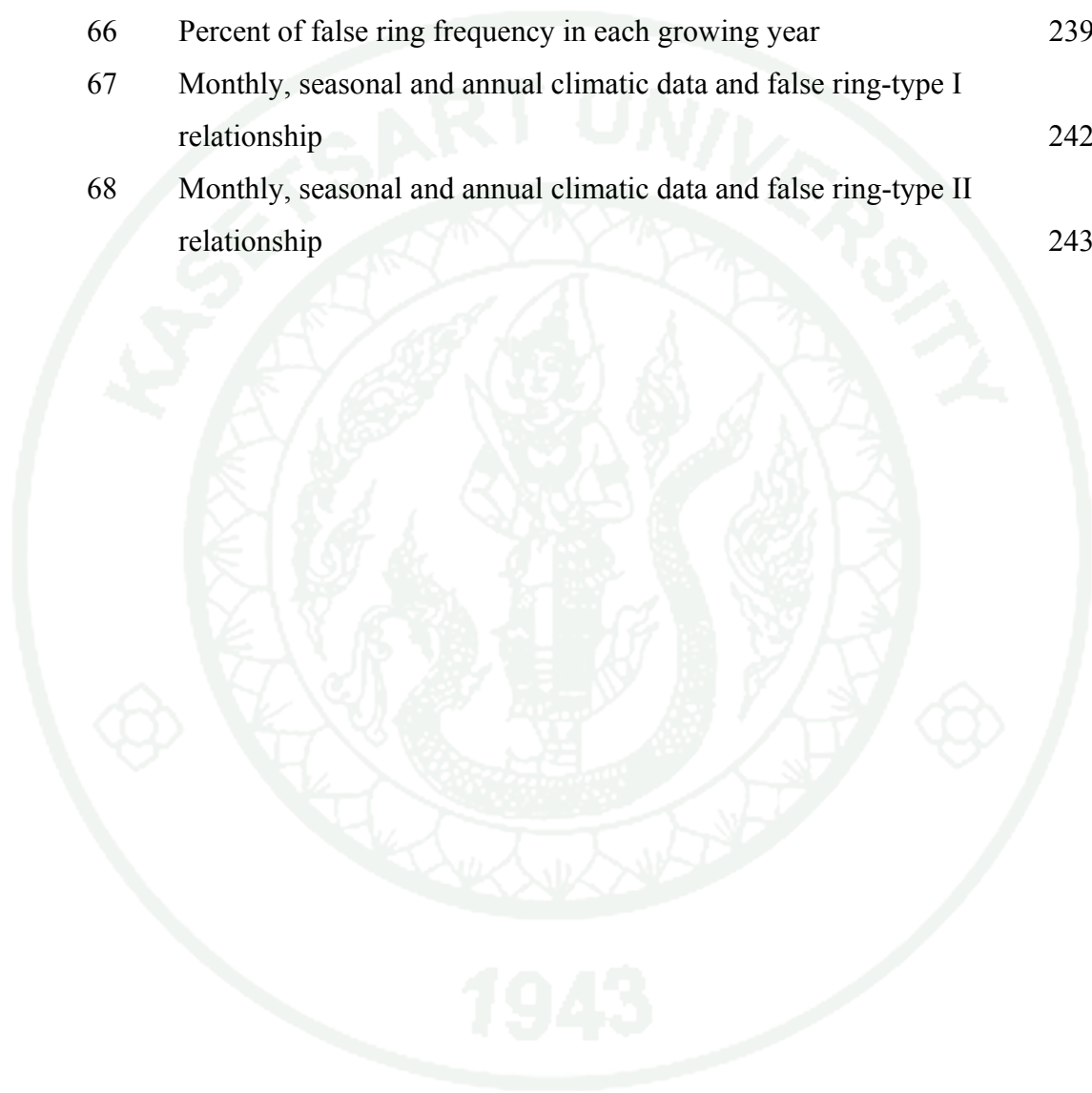
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# **BIOLOGY AND FACTORS AFFECTING TREE-RING FORMATION OF SOME TREE SPECIES AT SAKAERAT ENVIRONMENTAL RESEARCH STATION**

## **INTRODUCTION**

Tree-ring analysis (called dendrochronology) is widely and successfully used to explain long-term environmental changes especially in the temperate and boreal regions, where strong seasonality and day length force growth dormancy in the winter and release cessation in the wet season causing annual ring formation in many tree species. In tropical and subtropical regions, for a long time, tree-ring studies were believed impossible and impractical due to the extreme rarity of tree species that produce anatomically distinctive annual growth rings. However, the increasing demand for a better understanding of global climate dynamics associated with the gap of the paleoclimatic information in the tropics stimulated several dendrochronologists to extend their researches from the upper and lower zones toward the equator.

However, tree-ring analysis in the tropics is still at the beginning. Berlage (1931) explored the potential of tropical trees in tree-ring analysis when the variations of Java teak (*Tectona grandis*) annual ring widths were successfully correlated with the dynamics of climatic data. Later, a few tropical species that produce reliable annual growth rings have been identified such as *Abies religiosa* (Huante *et al.*, 1991), *Pinus merkusii* and *P. kesiya* (Buckley *et al.*, 1995), *Taxodium mucronatum* (Stahle *et al.*, 2000) *Vitex keniensis* and *Premna maxima* (Stahle *et al.*, 1995). In Thailand, tree species with annual growth rings have been reported and widely used for tree-ring researches only 3 species of *P. kesiya*, *P. merkusii* and *T. grandis* (Buckley *et al.*, 1995; D'Arrigo *et al.*, 1997; Pumijungnong, 1997; Pumijumng and Wanyaphet, 2006; Pumijumng and Eckstein, 2011), while the knowledge of annual ring formation in other tropical trees is still limited and question of which tree species form annual rings and respond to climate are not yet solved.

In order to improve the limitation of the selected tree species for tropical tree-ring studies, it is essential to explore the information which tree species is available for dendrochronological potential. Wood anatomy has to be precisely described to indicate annual ring boundaries and prove the periodic growth relating with environmental factors. Focused on this study, some tropical tree species generally found in the dry evergreen forest of Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry, Kasetsart University (WNKFSPS) were monthly investigated phenology and wood formation in order to indicate annual ring boundaries and the potential of climate-growth responses.

Another problem of the existing tropical tree-ring species is the occurrences of false rings, which often misleads the task of age and growth rate determination. To make a clear understanding on false ring characteristics and factors affecting false ring formation, seven natural *T. grandis*, located at WNKFSPS, were defined annual ring boundaries and identified false rings by using the technique of vessel size varied measurement. In addition, cell types forming false ring will be described by using wood anatomical technique and monthly climatic variability were also used to explain the occurrences of these false rings.

## OBJECTIVES

The objectives of this study were shown as follows:

1. To identify annual rings and annual ring types in some tree species standing at Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry (WKNFSPS).
2. To investigate some biological factors (phenology) and some physical factors (environment) which periodically affect growth and wood formation.
3. To investigate periodic wood formation and annual ring boundary characteristics by monthly wounding with the marking knife.
4. To distinguish teak false ring from normal annual ring and describe its anatomical characteristics.
5. To relate biological factors, environmental factors and both factors to periodic wood formation, annual ring formation and teak false ring formation.

## LITERATURE REVIEW

### 1. Dendrochronology

#### 1.1 Definition

During the first half of the 20th century, tree-ring studies, called dendrochronology, have been established and integrated worldwide into research on global change by the astronomer, namely A. E. Douglass (Fritts, 1976). The prefix dendro is from the Greek word for tree, dendron, and the word “chronology” is the name of the science that deals with the time and the assignment of dates to particular events. Dendrochronological research is in a state of rapid development, which is being used across the globe by a vast number of researchers from diverse scientific fields. The science of reconstructing past climate by use of tree rings is known as dendroclimatology, which is a branch of the more general discipline of dendrochronology.

#### 1.2 Applications of dendrochronology

Dendrochronology was specifically divided according to its application as dendroclimatology, dendroecology, dendrogeomorphology and dendrohydrology (Alestalo, 1971). Recently, new subfields were presented including dendroglaciology, dendrochemistry, dendropyrochronology and dendroarchaeology (Mager and Fitzsimons, 2002).

Focused on dendroclimatology, which was closed to this study, Briffa (1995) stated that the beginning of the general approach taken in dendroclimatic studies work is to collect samples from a set of trees, which climate should be the major growth-limiting factors. The next important thing is to assemble the data from individual trees into a composite site chronology by crossdating and averaging the individual series after the removal of age effects, called standardization. The next step is to build up a network of site chronologies for a region, and then is to identify

statistical relationship between the chronology time series and instrumental climate data for the recent period (the calibration period). Finally, all of these relationships are used to reconstruct climate information from an earlier period covered by the tree-ring proxy data.

### 1.3 Tropical dendrochronology

In the tropics, including Thailand, forests are complex and contain a large number of tree species. Many trees appear to form more or less pronounced layers similar to annual rings. These layers do not always represent one year's growth (Eckstein *et al.*, 1981). However, in Indonesia, annual rings of tropical trees have been reported in 1927 by Coster. It was followed in more than 20 different countries and in many different tree species throughout the tropic (Worbes, 2002).

Formation of annual tree rings in tropical tree species caused by annual flooding (Schongart *et al.*, 2002; Dezzeo *et al.*, 2003), seasonal variation in day length (Borchert and Rivera, 2001), seasonal variation in rainfall (Worbes, 1999; Borchert, 1999) and possibly by unidentified internal rhythms (Alvim and Alvim, 1978). In most non-flooded forest areas, the formation of tree rings is probably induced by the occurrence of an annual dry season of several months (Coster, 1927; Worbes, 1999; Dunisch *et al.*, 2002). Due to a water deficit, tree species often show a reduced diameter growth or cambial dormancy during the dry season, resulting in the formation of a distinct boundary (Worbes, 1999). Many ring-forming species are deciduous or change all their leaves during the dry period (Worbes, 1999; Borchert, 1999). The connection between the formation of annual tree rings and seasonal precipitation was well illustrated by Coster (1927). He found that trees of the same species might form clear annual rings under monsoon climates, while the same species form less distinct or irregular rings under almost ever wet condition. Worbes (1999) suggested that a dry period of at least 2 months with less than 50 mm of rain would be required to expect annual rings in tropical tree species, but recently, by Fichtler *et al.* (2003), annual rings have been proven for tree species in ever wet

climate (all months > 100 mm). Even small annual variation in rainfall occurring under ever wet conditions may trigger ring formation.

Several tree-ring researches in tropic were completely succeeded (D'Arrigo *et al.*, 1994; Borchert and Rivera, 2001; Schongart *et al.*, 2002; Worbes, 2002; Dezzeo *et al.*, 2003). D'Arrigo *et al.* (1994) stated that, from the study of Berlage in 1931, Java teak ring widths could be correlated with wet season precipitation. These teak samples were reanalyzed by DeBoer (1951) and the tree-ring index was updated by D'Arrigo *et al.* (1994). In India, Pant (1979; 1983) found the potential of Himalayan trees for climatic responsive studies. It was confirmed by Borgaonkar *et al.* (1999), who successfully evaluated the climate-growth relationship of Himalayan conifers with pre-monsoon climate. In addition, Borgaonkar *et al.* (1994) also successfully studied the climatic response of *Abies pindrow* and *Picea smithiana* growth. To confirm the possibility of teak, Jacoby and D'Arrigo (1990) analyzed Indian teak and compared with Java teak. They found that teak growths from these areas were similarly responded to climatic data in wet season. As equally to the study of Wood (1996), she found that teak growth from central India related particularly well to the climate in the transitional stage between summer monsoon and the wet season.

#### 1.4 Dendrochronology in Thailand

In Thailand, dendroclimatic researches were successfully done by using 2 species of pines, *P. kesiya* and *P. merkusii*, and teak (*T. grandis*). Buckley *et al.* (1995), Buckley *et al.* (1995), Boonchirdchoo (1996), D'Arrigo *et al.* (1997), Sukkosol (1998), and Pumijumnong, and Wanyaphet (2006) correlated pine ring width indices from the north of Thailand with climatic variables. Additionally, for teak chronologies, Pumijungnong (1995, 1997), Phanijskul (1999), and Buckley *et al.* (2007) studied dendrochronology of teak in the north of Thailand, and found the significantly positive correlation of teak growth with the amount of wet season rainfall.

## 1.5 Problems in tropical dendrochronology

Most tropical trees are impossible to measure successive annual growth rings because these trees do not clearly show annual rings and/or because equatorial climate has no annual season, which induces dormancy and stops the growth of trees (Mariaux, 1981). Therefore, it has been largely believed impossible or impractical to study tropical dendrochronology and dendroclimatology due to climatic, genetic or phenological factors that conspire to inhibit the formation of clear annual growth rings (Bass and Vetter, 1989; Jacoby, 1989; and Worbes, 1995). However, the increasing demand for palaeoclimatic information from this area had stimulated renewed interest with increasing numbers of successful studies being published over the past decade (Buckley *et al.*, 1995; 2001; 2005; Pumijumnong *et al.*, 1995; Pumijumnong, and Wanyaphet, 2006; D'Arrigo *et al.*, 1994; 1997; 2008).

The diminutive information referred to tropical tree species forming the annual ring is rareness and it is the main obstacle for dendrochronological studies in tropical region. Many researchers attempted to study annual ring in tropical woods based on their training and professional specialization (Coster, 1927; Hummel, 1946; Rodriguez, 1962; Tshinkel, 1966; Bryant, 1968; McKenzie, 1972; Amobi, 1973; and Mucha, 1979), which will be described in the next section.

## 2. Wood Formation, wood structure and annual ring identification

### 2.1 Wood formation

There are numerous opinions as to what constitutes wood. Webster and McKechnie (1980) described the meaning of wood as the hard fibrous substance beneath the bark in the stems and branches of tree and shrubs, while Larson (1969) gave the definition of wood as the xylem of the tree, which is a product of cambium and consists of cells or wood elements that have passed through various stages of development.

Wood formation in trees is a periodic process regulated by genetic and environmental factors (Lauchaud *et al.*, 1999). Wood is mainly composed of two types of cell with secondary cell wall. Fiber is one kind of woody cell, which mechanically support the plant bodies and another is tracheary elements. These elements compose of vessels in angiosperm woods and tracheids found in both angiosperm and gymnosperm woods in order to transport water and solutes (Demura and Fukuda, 2007). In general, these cells are initiated by cell division in the vascular cambium, followed by differentiation of cambial derivatives. The successful differentiation or formation of these cells involves five major steps including cell division, cell expansion (elongation and radial enlargement), cell wall thickening (involving cellulose, hemicellulose, cell wall proteins, and lignin biosynthesis and deposition), programmed cell death, and heartwood formation (Larson, 1994; Higuchi, 1997; Roberts and McCann, 2000; Jones, 2001; Plomion *et al.*, 2001).

For vascular cambium which is the origin of cell division and wood formation, IAWA (1964) and Little and Jones (1980) described the definition of the vascular cambium as the lateral meristem in vascular plants which produces secondary xylem, secondary phloem, and ray parenchyma usually in radial rows, consisting of one layer of initials and their undifferentiated derivatives. The structure and activity of the vascular cambium is not uniform, but shows great variation according to the differing genetic constitutions of plants and differences in internal conditions and the external environment (Philipson *et al.*, 1971).

Philipson *et al.* (1971) also stated that the dormant cambium consists of a narrow zone of radially flattened cell with relatively thickened cell wall followed by the onset of periclinal division and the production of new secondary xylem and phloem cells. Wilson (1966) found that the rate of cell division at the beginning of the season is faster than cell differentiation, resulting in a widening of the cambial zone. Until the rate of differentiation is faster than division, the cambium is shown a narrow zone. Therefore, the remaining cambial zone could not be confirmed the totally cambial division.

Many researchers also suggested that several environmental factors affecting cambial activities i.e. rainfall, temperature, soil moisture, light intensity, photoperiod, competition, crown size, oxygen and carbon dioxide levels, wind, defoliation, topography, latitude, and altitude, but rainfall and temperature have been widely studied in cambial growth relationship (Fritts, 1958; Wareing, 1958; Fraser, 1962; Kozłowski *et al.*, 1962; Philipson *et al.*, 1971).

Cambial growth can be readily identified by using a few methods, which have been used to label partial growth increments (Kozłowski, 1971). Kennedy and Farrar (1965) described a method of producing an internal mark in the xylem by tilting seedlings for short periods, namely tilting method, to produce an arc of reaction wood. Waisel and Fahn (1965) developed radiological method, which only the most recently deposited cell-wall materials were labeled with radioactive carbon. Therefore, the newly divided and differentiated cells could be readily identified. Wolter (1968) inserted an insect mounting needle horizontally through the bark in order to injure the cambium. The injury caused by the mechanical stimulation to the dividing and differentiating cells resulted in formation of abnormal parenchymatous cells. Wood formation could be identified microscopically in stem or branch located above or below the point of needle insertion.

## 2.2 Wood structure

Due to the different kinds of elements in porous and nonporous woods, the details described in this section will only focus on wood anatomy of hardwoods, which relate to the studies. The types of cells found in porous woods are divided as longitudinal and transverse elements.

### 2.2.1 The longitudinal Cells

The longitudinal cells as vessel elements, fibers, and tracheids are elongated longitudinally, equipped with a variety of pits, and perform primary conductive and/or mechanical functions. These elements are characterized by the loss

of their protoplast as or shortly after cell developments are completely finished. In contrast, the parenchyma cells, equipped only with simple pits, retain their protoplasts for sometime and mainly perform a storage function.

*Vessel elements*, tube-like structures separating hardwoods from softwoods, are the specialized conducting cells, which range from drum-shaped and barrel-shaped to oblong and linear with or without broadly tapering or tail-like extensions at one or both ends (Wiedenhoef and Miller, 2005). In the same ring, particularly in the ring-porous woods, the length of the elements may be varied because the vessel members in the latewood remain about the same length as the cambial initials, while those in the earlywood become shorten appreciably as the increasing in diameter and turn into annular or barrel shaped (Panshin and Zeeuw, 1980).

Vessel elements in transverse aspect appear as pores, which can be divided into three groups on the basis of the variation in pores size within growth rings. If the pores formed in the spring are much larger than those occurred later in the season, the wood is called ring-porous. On the other hand, if the pores are fairly uniform in size and quite evenly distributed throughout the ring, the wood is said to be diffuse-porous. Certain woods intermediated in this respect are classed as semi-ring-porous or semi-diffuse-porous. Additionally, pores may be solitary or grouped in various ways such as pore multiple, and pore chains (Panshin and Zeeuw, 1980).

Leal *et al.* (2007) studied vessel size and distribution of *Quercus suber* by continuously measuring along the radial direction in the transverse section of approximately 40 years old wood discs. The results showed that the vessel size increased with age while the vessel density remained approximately constant. A year prior, Aguilar-Rodriguez *et al.* (2006) stated that environmental factors such as location, soils, and climate induced the wood variability of *Buddleja cordata*. Individuals of *B. cordata* collected from the most northern provenances were shrubs which possessed ring porous wood and in the late wood vessels tended to showed

longer and more abundant radial groups. In contrast, *B cordata* collected in most southern provenances commonly possessed diffuse porosity and shorter vessel groups.

*Hardwood tracheids* are other longitudinal elements recognized as vascular tracheids and vasicentric tracheids. Panshin and Zeeuw (1980) informed that vascular tracheids are cells very similar in size, shape, and position to small late wood vessel elements, except that they are imperforate at the ends. In contrast, vasicentric tracheids are short, irregularly shaped cells with tapering or rounded closed ends, which abound in the proximity of the large early wood vessels of such ring porous woods. Rathgeber *et al.* (2006) linked intra-tree ring wood density variations and tracheid anatomical characteristics in Douglas fir (*Pseudotsuga menziesii*) and found that radial and tangential tracheid diameters declined from earlywood to latewood by 50% and 15%, respectively.

*Fibers* in hardwoods are the long and narrow cells with closed ends that function solely as support and also recognized as fiber tracheids and libriform fibers. Both types of fibers may have moderately to very thick wall, while the nature of the pitting between the two is difference. Fiber tracheids have distinctly bordered pits, with lenticular to slitlike apertures, but libriform fibers possess simple pits or too narrow border pits. However, both types of fibers exhibit a number of modifications such as inner surface smooth, spiral thickening, thin transverse walls (septa), or gelatinous fibers (Panshin and Zeeuw, 1980; Wiedenhoef and Miller, 2005).

*Longitudinal (axial) parenchyma* is a tissue composed of comparatively short, brick-shaped, or isodiametric cells equipped in most cases with simple pits only. These cells are involved primarily in storage and to a lesser extent in the conduction of carbohydrates. Panshin and Zeeuw (1980) mentioned that there are three kinds of longitudinal parenchyma including strand parenchyma, fusiform parenchyma and epithelial parenchyma.

Strand parenchyma is the most common type of longitudinal parenchyma in hardwoods, which is often visible lighter or darker than the

surrounding tissue on transverse surfaces at low magnification. The strand parenchyma is also defined to four types based on the visibility in transverse sections. The longitudinal parenchyma arranging independently of the pores is called *apotracheal parenchyma*, while the parenchyma associating with the vessels or vascular tracheids is defined as *paratracheal parenchyma*. Additionally, *banded parenchyma* and *marginal parenchyma* form concentric lines or bands of parenchyma and form a more or less continuous layer of one to more cells in width at the margin of a growth ring, respectively (Panshin and Zeeuw, 1980).

Panshin and Zeeuw (1980) also mentioned to fusiform parenchyma and epithelial parenchyma. Fusiform parenchyma, derived from a fusiform cambial initial without subdivision, is the characteristic of the more highly developed hardwoods, while epithelial parenchyma is consisted of parenchyma cells encircling the cavities of longitudinal canals, which may consist of gums or resins.

### 2.2.2 The transverse cells

The transverse elements in hardwoods are confined to the rays, which have a greater variety of cell shapes, more variation in cell arrangement, and more variety in the cell inclusions. The rays in hardwoods, consisting entirely of parenchyma cells, are also more variable in width and height than those of softwoods. When ray cells are all of approximately the same size and shape, the rays are termed homocellular. In contrast, the rays are said to be heterocellular, if containing more than one type of ray parenchyma cells. Additionally, the rays occurring in softwoods are frequently being uniseriate, tail-like projections of the rays, while most hardwoods possess rays ranging from two to multiseriate (Panshin and Zeeuw, 1980).

### 2.3 Annual ring identification

Worbes (1995) introduced methods to investigate annual rings of tropical trees based on wood anatomy and radiocarbon dating.

### 2.3.1 Ring counting in trees of known age

The comparison of the number of rings with the known age of the tree readily proves the periodical nature of tree rings, however, is usually only available from plantations, botanical gardens, and sometimes from natural grown trees if local people give reliable information.

### 2.3.2 Cambial wounding (Windows of Mariaux)

The cambial wounding developed by Mariaux (1981) provides exact information on the growth rhythm. The cambium is injured in a small window of some square centimeters either mechanically by incision or chemically by injection. The optimal advantages of different cambial marking methods are discussed by Sass *et al.* (1995). The wounds are covered by callus tissue in the consecutive years and remain as an artificial and exactly datable scar in the wood. One year or several years later, the trees can be cut and the number of rings on the stem disc can be compared with the time of cambium marks. Moreover, incisions made in different seasons throughout the year can give information on the formation of different tissues which depend on corresponding seasonal climatic conditions (Sass *et al.*, 1995)

### 2.3.3 Radiocarbon dating

Another artificial marker is the content of radiocarbon in individual growth zones. Due to atomic bomb explosions, atmospheric  $^{14}\text{C}$  concentration almost doubled between 1950 and 1965 and subsequently decreased until the present time. Radiocarbon concentration in each growth ring with unknown age is analyzed and the radiocarbon concentrations of all growth rings are compared with the curve of the radiocarbon level. The pointer years of peak atmospheric  $^{14}\text{C}$  concentration allow the dating of the samples and provide the proof that rings are annual in nature. Although the method is more complicated, it is one of the safest tools for the dating of growth zones if the use of cambial wounding is impossible.

#### 2.3.4 Pointer year from fire scar

Natural scars in the wood are the result of cambial injuries caused by fire. Some trees can react by the formation of traumatic parenchyma bands, probably induced crown damage. Together with the existing reports of the fire, the scars serve to date the number of years and growth rings after scar formation.

### 3. Factors affecting tree growth

In this section, the important factors related to tree growth will be discussed. The increment of tree stem is basically influenced by biotic and abiotic factors. Biotic factors are defined as genetic and ageing, while abiotic factors are defined as temperature, precipitation, humidity and other environmental factors (Schweingruber, 1996). The shape of a woody plant is dictated by its genetic makeup, while a combination of influencing environmental factors plays a key role by eliminating some species not suited to these factors. Aging is shown in different ways within a tree. According to Lassig (1991), growth culminations appear earlier higher in the tree than at breast height.

In addition to biotic factor, hormones play an important role in the initialization and maintenance of growth and cell differentiation processes (Schweingruber, 1996). Auxin and gibberellic acid (GA) is involved in the differentiation of cambial derivatives (Morey, 1976). Schweingruber (1996) explained that auxin, formed in young leaves, involve in the differentiation of cambial derivatives while GA, formed in adult leaves, stimulates cell division leading to the production of the cambial derivatives. Both hormones are applied together a wide increment of xylem resembling normal wood develops. A natural inhibitor produced in leaves in short days has been identified as abscisic acid (ABA) which is involved in the onset of dormancy in many angiosperms and gymnosperms (Morey, 1976).

Therefore, the study of tree phenology which is the science of monitoring periodically recurring biological events and reflects growth periodicity of trees is

importance. The emphasis lies on the physical appearance (Greek: *phanestai*, to appear) (Meier, 2007) and relies on visual observation (biomonitoring). Data is based on observations and records covering various scales. Its sources comprehend historical records, specifically designed networks to collect phenological data and phenological records by individuals. Data is also collected using remote sensing methods. Although, there are defined criteria for biomonitoring, record quality is still depending on the observer's skills (Rutishauser, 2003). Phenological research includes monitoring, modeling and reconstructing of phenological changes, the use of phenological records as a climate reconstruction proxy (Meier, 2007; Rutishauser, 2003; 2007) and goes further to analyze the socio-economic impact of phenological changes such as prolongation of growth periods (Rutishauser *et al.*, 2004). Climate impacts on phenology and influences of environmental conditions on the phenological phases of a plant are also part of it.

Abiotic factors can influence the radial increment of a stem at any time. Kirchner *et al.* (1906) observed the light response on two mountain pines of the same age and found that solitary trees grow faster than trees under canopy. Mitscherlich (1975) explained the slower growth rates of trees under canopy involved to the decline of light intensity and photosynthesis.

Temperature is a major limiting factor of tree growth, especially in stands along northern timberlines. Most influential and damaging are extreme temperature changes and late frosts and winter frosts (Krasowki *et al.*, 1993). As similar as temperature, the water supply has a great impact on plants (Kahle, 1994). Precipitation is absorbed by plants in the form of rain, clouds, dew, snow, sleet and hail. The intensity of the precipitation is a very close physical relationship to humidity and can be used to determine growth. Air movement or winds have a considerable influence on the growth and shape of trees. Strong and constant winds reduce the growth in height and the radial increment. Compression and tension woods are formed on the pressure spots, while heavy wind can break crowns or uproot stems (Mitscherlich, 1975). The nutrient supply, mostly determined by the chemical constitution of the bedrock, does not usually have an extremely limiting impact on

growth in natural forest (Schweingruber, 1996). In addition, other mechanical disturbances including anthropogenic air and soil pollution will damage crown, roots and stems, but trees can self develop some survival mechanism, such as shoot and crown regenerating, by forming new sprouts, compartmentalization taking place around the wounds or developing a tolerance to anthropogenic pollution (Mattheck and Kubler, 1995).

#### **4. Tree growth measurement**

Worbes (1995) also suggested methods to investigate growth rhythms in tropical trees included the observation of cambial activity and phenological events. Methods were divided to 2 groups of non-destructive and destructive methods as followed:

##### 4.1 Non-destructive methods

###### 4.1.1 Phenological investigation

As described above, phenological observations give a first indication of the growth rhythm of a tree. The observation of tree phenology over a period of several years shows that leaf fall behavior in the tropics is correlated with the occurrence of dry season, even if periods of low precipitation may appear unpredictably throughout the year (Medway, 1972).

###### 4.1.2 Band dendrometer

Band dendrometer enable the continuous measurement of diameter growth and thus of the cambial activity of a tree. The comparison of these results with climatic data provides information on growth rhythms dependent on climate events (Katsch *et al.*, 1992).

#### 4.1.3 Measuring cambial activity with a Shigometer

Measurements of the electrical resistance of the cambial zone with a Shigometer (Shigo and Shortle, 1985) have occasionally been used to describe cambial activity. Higher electrical resistance means less cambial activity, while lower electrical resistance possibly reflects the mobilization of carbohydrates from the storage tissue in the wood (wood increment).

#### 4.2 Destructive methods

In case of destructive methods, ring counting in trees of known age, cambial wounding, radiocarbon dating and pointer year from fire scare in the topic of annual ring identification can be used for periodic growth measurement in term of wood increment. Additionally, other methods are described as followed:

##### 4.2.1 Ring width analysis

Ring width measurements can be manually made with a hand lens or with tree-ring measuring system. From several trees, successful crossdated ring width series, the comparison of different tree-ring curves in order to recognize unique patterns of wide and narrow rings (Pilcher, 1990), can be summarized and transformed to a mean curve of growth fluctuation in each year, called tree-ring index.

##### 4.2.2 X-ray densitometry

X-ray densitometry was originally applied to tropical species to identify ring boundaries due to differences in density between earlywood and latewood, if they are hardly visible macroscopically. Annual time series of minimum, maximum, mean, earlywood and latewood densities are derived from the results of density measurement. Worbes *et al.* (1995) suggested that the time series of maximum density showed the best correlation with the time series of the length of the flood-free period.

#### 4.2.3 Stable isotopes

The variation of stable isotope concentrations in tree rings of the temperate zones was significantly related to variations in climate (Long, 1982; White, 1983). However, a weak or no correlations was found in Amazonian trees. More basic research on the influence of climate on the uptake of isotope in the tropical plants is necessary before the technique can be efficiently used due to the expensive cost and time consuming (Worbes, 1995).

#### 5. The statistic of path analysis (PA)

Path Analysis is the statistical technique used to examine causal relationships between two or more variables. It is based upon a linear equation system which was adopted by the social sciences in the 1960s and has been used with increasing frequency in the ecological literature since the 1970s. In ecological studies, path analysis is used mainly in the attempt to understand comparative strengths of direct and indirect relationships among a set of variables (Stoelting, 2002).

Traditional statistical methods normally utilize one statistical test to determine the significance of the analysis, R square for regression analysis. Path analysis, however, relies on several statistical tests to determine the adequacy of model fit to the data. The chi-square test indicates the amount of difference between expected and observed covariance matrices. A chi-square value close to zero indicates little difference between the expected and observed covariance matrices. In addition, the probability level must be greater than 0.05 when chi-square is close to zero.

The Comparative Fit Index (CFI) is equal to the discrepancy function adjusted for sample size. CFI ranges from 0 to 1 with a larger value indicating better model fit. Acceptable model fit is indicated by a CFI value of 0.90 or greater (Hu and Bentler, 1999). Root Mean Square Error of Approximation (RMSEA) is related to residual in the model. RMSEA values range from 0 to 1 with a smaller RMSEA value indicating

better model fit. Acceptable model fit is indicated by an RMSEA value of 0.06 or less (Hu and Bentler, 1999).

## 6. Related research

Most tropical trees are impossible to measure successive annual growth rings, because these trees do not clearly show annual rings and/or because equatorial climate has no annual season, which induces dormancy and stops the growth of trees (Mariaux, 1981). Due to climatic, genetic or phenological factors conspiring to inhibit the formation of clear annual growth rings, it has been largely believed that is impossible or impractical to study tropical dendrochronology and dendroclimatology (Worbes, 1995). However, the increasing demand of palaeoclimatic information from this area had stimulated renewed interest, with increasing numbers of successful studies being published over the past decade (D' Arrigo *et al.*, 1997; Buckley *et al.*, 2005).

The diminutive information referred to tropical tree species forming the annual ring is still rareness and is the main obstacle for dendroclimatic studies in tropical region. Many researchers attempted to study annual ring in tropical woods based on their training and professional specialization (Brienen and Zuidema, 2005; León-Gómez and Monroy-Ata, 2005; Marcati *et al.*, 2006).

For dendrochronological studies of teak (*Tectona grandis* Linn.), a valuable and suitable species for tropical dendrochronology, D'Arrigo *et al.*, (1994) stated that Berlage firstly applied to study dendrochronology of *T. grandis* in Central Java in 1931. The ring width index was covered 416 years, A.D. 1514-1929, and could be correlated with wet season local rainfall. Later, DeBoer (1951) and D'Arrigo *et al.* (1994) reanalyzed and extended the original Berlage's index to A.D. 1991.

Teak also familiarized for other tropical dendrochronologists, Jacoby and D'Arrigo (1990) studied the climate-growth response of India teak and the result was similar to the study of Java teak. In 1996, Wood correlated India teak index with

climatic data and presented the equivalent result with Jacoby and D'Arrigo (1990). Shah *et al.* (2007) also studied on the dendroclimatic potentiality of Indian teak and demonstrated the reconstructed monsoon precipitation back to A.D. 1835.

In Thailand, Pumijumnong (1995), and Pumijumnong *et al.* (1996) commenced to construct the past climate from the 312 years living teak in northern Thailand. Later, in 2004, Palakit extended teak chronology back to AD 1591 by using stump remnants in northern Thailand. Three years later, Buckley *et al.* (2007) reanalyzed and extended Palakit's index. They also highlighted the response on teak growth to rainfall and PDSI data.

It is necessary to understand cambial activity and wood formation in order to classify annual ring and/or tree-ring formation. This section will focus on the cambial analysis and wood formation of *T. grandis* and other tree species. Venugopal and Krishnamurthy (1987) investigated cambial dynamic in Indian teak branches and recognized the activity during the wet periods, which was similar to the study of seasonal behavior of vascular cambium in moist deciduous and dry deciduous forest in western India (Rao and Rajput, 1999). Tomazello and Cardoso (1999) also studied the cambial activities of teak in relation to seasonality in Brazil. They found the fusiform initial cells presented thicker radial than tangential walls during the cambial dormancy period. Teak cambial activity also analyzed in northern Thailand by Pumijumnong (1995; 1997). The result indicated the occurrence of cambial initiation in the beginning of rainy season and continuous grow until the end of this season. These teak cambial analyses, in Brazil and Thailand, showed the comparable results. Based on dendrometer band technique, Buckley *et al.* (2001) studied the phenology of teak trees in the north of Thailand and also completely agreed with the studies of Pumijumnong (1995; 1997)

The technique of pinning method was used to investigate seasonal characteristics of wood formation of *Eucalyptus camaldulensis*, *Hopea odorata*, *Shorea henryana*, *Chamaecyparis obtusa*, *Picea abies*, and *Pinus sylvestris* (Nobuchi *et al.*; 1995; Kuroda and Kiyono; 1997; Veenin *et al.*; 2006; Makinen *et al.*; 2008).

The authors did not focus on the anatomical marker that could be used as the references of the annual ring boundaries, but all of these researches agreed with the radial growth increasing in wet/rainy season and decreasing in dry season.

To confirm the response of tropical trees to climatic data, Nobushi *et al.* (1995) investigated the seasonality of wood formation in tropical trees. Cambial initials and the cells of the initiation of S<sub>1</sub> layer formation at the time of pinning were estimated. The results showed that wood formation of *Hopea odorata* and *Shorea henryana* actively progressed in rainy season and decreased in dry season. In Central Amazon, Dunisch *et al.* (2002) investigated the cambial growth dynamics of *Swietenia macrophylla*, *Carapa guianensis*, and *Cedrela odorata* by using dendrometer measurements, and pin markers. Distinct growth increments were found in these species. The formation of parenchyma bands in *Swietenia*, and *Cedrela* were induced by dry periods before a cambial dormancy, while parenchyma bands in *Carapa* was induced by extremely dry and extremely wet periods before a cambial dormancy.

In addition, cambial growth dynamics and the formation of increment zones were affected by the insect attack and the water supply of the soil. *Rhizophora mucronata*, which had previously been reported to lack annual growth rings, was marked for 2-5 years and was conducted to determine the periodic nature of the visible growth layers. The onset of the formation of the low vessel density wood coincided with the onset of the long rainy season and continues until the end of the short rainy season (Verheyden *et al.*, 2004). Moreover, Menezes *et al.* (2003) also studied the relation between mangrove tree growth, *R. mangle*, and rainfall amount on a peninsula in north Brazil, they classified the mean radial increments from a pattern of three distinct groups (fast, medium, and slow growth). For the trees belonging to the medium growth group, the cambial growth correlated significantly with the precipitation in the transition months between the dry and the rainy season, while the slowest growing trees showed a close relationship between the ring width and the number of months with rainfall < 50 mm. Therefore, the presence of annual growth

rings in these mangrove species offers further potential for dendrochronological applications.

Worbes (1999) attempted to demonstrate the seasonality of cambium growth and the connection between precipitation patterns and tree growth from semi-deciduous forest in Venezuela by using dendrometer band and cambium marking techniques. His studies confirmed the distinct ring formation of *C. odorata* and *S. macrophylla* and also investigated other species that formed distinct ring such as *Terminalia guianensis*, *Pterocarpus vernalis*, and *Pinus caribaea*. He also found the similar growth rhythms in different individuals of a species that was generally high during the rainy season and decreased to zero toward the end of rainy season or soon after the beginning of dry season.

Bullock (1997) disagreed with the assumption, which tropical trees do not form annual rings and have been described as fast and continuously growing plants for their entire life span. The studied showed that the deciduous trees *Cochlospermum vitifolium* and *Cnidocolus spinosus* in southwestern México showed radial growth to be highly correlated only with precipitation during an interval of less than 2 months in the mid-wet season. Rao and Rajput (2001) found the different climate-growth responses of *Azadirachta indica*, semi-evergreen trees, in moist deciduous (MDF), dry deciduous (DDF), and scrub land forest (SF). Therefore, the local climatic conditions were important and related to seasonal behavior and phenological occurrence of *A. indica* vascular cambium. In a lowland tropical rainforest of Mexico, León-Gómez, and Monroy-Ata (2005) determined cambial activities of *Machaerium cobanense*, *M. floribundum*, *Gouania lupuloides* and *Trichostigma octandrum* by counting the number of layers of cells in the cambial zone. All species, the cambium was active throughout the year and in three of the species (all but *T. octandrum*) cambial activity was significantly higher in the rainy period than the dry period, while *T. octandrum* was not significantly associated with the wet or dry season.

Not only cambial activity, but another technique could be applied to investigate new tree species for climate–growth response. Brien and Zuidema

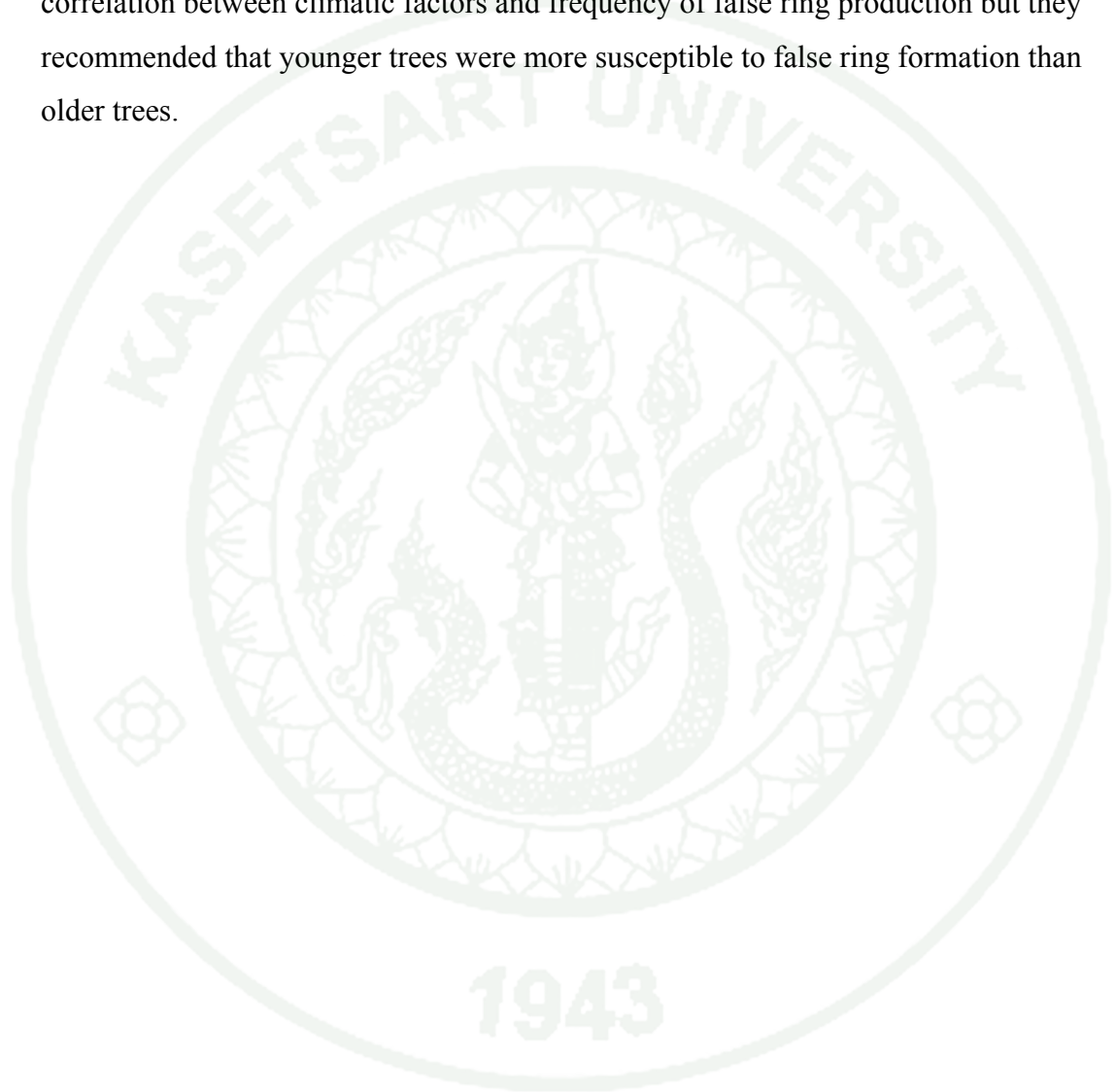
(2005) selected six tree species, based on the visibility of growth rings and the feasibility of obtaining sufficient samples for each species, from Bolivian Amazon to correlate with local rainfall. Relations between their growths and rainfall are generally positive, indicating that growth was limited by the amount of rainfall. Additionally, some researchers presented the existence of clear growth rings, which were opportunistically explored in a salvage dendrochronological study.

Roig *et al.* (2005) and Marcati *et al.* (2006) characterized growth ring occurrences of 52 and 48 tree species from the semi-tropical forests of the Yucatan Peninsula and the state of São Paulo, Brazil, respectively. The existence of clear growth rings in these trees is a key prerequisite for further studies, and a convincing demonstration of the dendrochronological potential of tropical tree species will allow the development of future research programs concerning the ecology of the species and inferences about past environmental changes detected from tree rings.

However, in some tropical trees, seasonal climatic variation did not related to their growth pattern. Sass *et al.* (1995) wounded the cambium of *Dryobalanops sumatrensis* in West Malaysia every two months during a four-year period, but there was no evident relationship between the dynamics of radial growth and seasonality in rainfall.

The occurrence of false rings often misleads the task of age and growth rate determination. False ring formation is triggered by drought during the growing season (Fritts, 1976; Ewel and Parendes, 1984; Yamaguchi; 1991). Younger trees and trees with faster growth rates are also more prone to false ring formation (Vogel *et al.*, 2001). False rings occurred in teak trees were first observed by Chowdhury as early as 1939, but no adequate information is available on tree-ring responses to changes in the environmental conditions, particularly in the false ring formation. Until AD 1998, Priya and Bhat determined that the factor mainly causing false ring occurrences in teak was drought stress in mid-growing season. Droughts were also induced false ring formation in several tree species such as *Nothofagus pumilio* in Patagonia, *Pinus nigra* in Vienna, *Larix sibirica* in Mongolia, and *Picea abies* in France (Wimmer *et*

*al.*, 2000; Treter *et al.*, 2002; Masiokas and Villalba, 2004; Bouriaud *et al.*, 2005). Other Stresses had been attributed to the formation of false rings such as unusually high levels of air pollution, and insect defoliation (Kurczynska *et al.*, 1997; Priya and Bhat, 1998). In *Pinus banksiana*, Copenheaver *et al.* (2006) found no significant correlation between climatic factors and frequency of false ring production but they recommended that younger trees were more susceptible to false ring formation than older trees.



## MATERIALS AND METHODS

In order to investigate biology and factors affecting tree-ring formation of some tree species, wood formative periodicity and phenology of the selected tree species were studied once a month for a year. Later, annual ring boundaries were defined and their formations were explained. According to the investigations of annual ring and wood formative periodicity, there were exhibited the potential of annual ring formative species for dendrochronological studies. Hence, causations and characteristics of false ring occurring in teaks (*Tectona grandis* L.f.) were analyzed to improve the accuracy of tree-ring dating and offered the opportunity to trace anomalous climate in the past. Materials and methodology used in this study were shown as followed:

### Materials

1. Global Positioning System (GPS)
2. Modified knife for cambial marking
3. Binocular
4. Increment borer
5. Sliding microtome
6. Epson Perfection 1270 scanner
7. Belt and rotary sanders
8. TA unislide tree ring measurement system
9. Compound photomicroscope
10. Stereomicroscope
11. Hot air oven
12. Analytical balance

## Methods

The studies were hierarchically processed as shown in Figure 1. Wood macroscopic investigation was the first step for suitable tree species selection. Six species with distinct and/or indistinct growth ring occurrences were selected from this step. These selected trees were investigated phenology and recorded once a month for one year. Not only phenology, but outside bark diameter and wood increment were also investigated in the third and the fourth steps of outside bark diameter investigation and cambial marking for the investigation of periodic wood annual ring formation, respectively. These 2 steps were also done once a month as similar as phenological investigation. The fifth and the sixth steps were focused on the teak (*Tectona grandis*) which was the valuable tropical tree species in tree-ring analysis. These steps were false ring investigation and formation and tree-ring analysis of teak. The last step was the statistical analysis of all records and measurements together with climatic and soil moisture data using simple correlation and path analysis (PA) to obtain the relationship of biology and factors affecting tree-ring formation in some tree species.

### 1. Wood macroscopic investigation and tree ring identification

Several dominant and co-dominant tree species in the dry evergreen forest of Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry, Kasetsart University, Nakhon Ratchasima province (WNKFSPS), were observed. Wood samples of these tree species were collected by using a handsaw and an increment borer. The samples were latterly polished by using several grades of abrasive papers ranged between 100 to 800 grits to obtain a clean and smooth transverse surface. Growth ring boundaries were observed with the naked eyes and 4X to 40X magnified stereo microscope as wood porosity (WP) and marginal parenchyma (MP). Wood porosity was divided to 3 groups of ring-porous (RP), semi-ring porous (SP) and diffuse porous (DP). Marginal parenchyma including marginal bands and marginal lines of axial parenchyma was divided to 3 groups of continuous (CMP), discontinuous (DMP) and without marginal

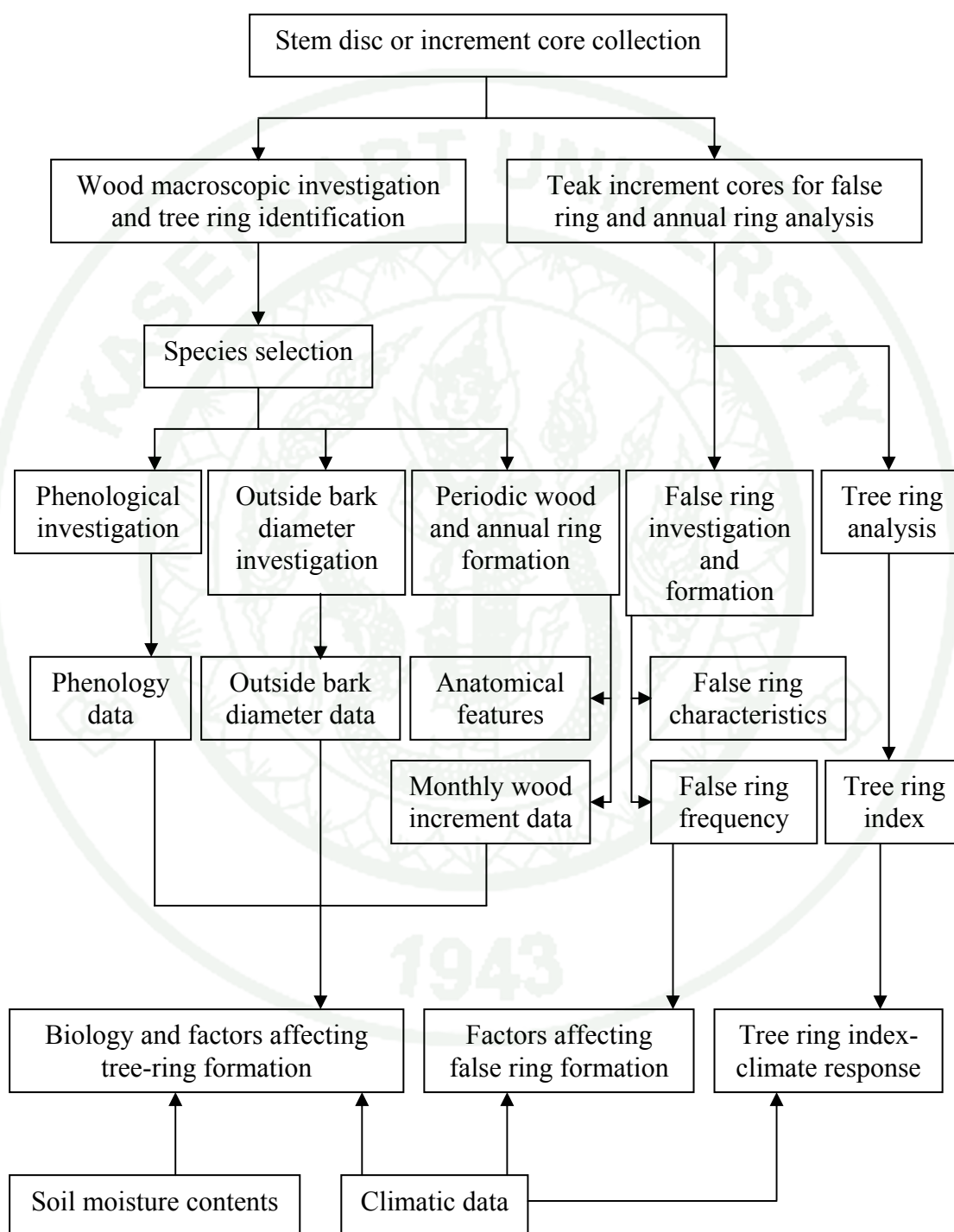
parenchyma (WMP). Using the criteria of wood porosity and marginal parenchyma, growth ring was divided into 3 types as distinct ring (DR), indistinct ring (IDR) and non-distinct ring (NDR). Distinctness of growth rings in these 3 types were referred to any of the concentric rings of the cross-section of a tree trunk with little uncertainty, with high degree of uncertainty identifying ring boundaries and unidentifying ring boundaries, respectively. Scanned images of wood transverse surfaces at 2400 dot per inch (dpi) were taken by using an ordinary scanner (Epson Perfection 1270) and macroscopic characteristics were explained. The species showing distinct and indistinct rings were potentially selected for annual ring formative studies.

## **2. Phenological investigation**

From the first section of wood macroscopic investigation and tree ring identification, six tree species which were classified as distinct and/or indistinct tree ring species were selected at least five trees each species. Each selected tree must be dominant, located on good drained area and had symmetrical crown and straight trunk. Each tree location was marked by using Global Positioning System (GPS). Pheno-phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF) were routinely investigated once a months for a year in September 2009 till September 2010 as similar as the studies of outside bark diameter changes and periodic wood and annual ring formations. In order to record the quantities of tree pheno-phases, the definitions of some phases were explained as followed:

LF was defined as the first green bud visibility, while leaf pushing themselves completely out of the bud or leaf bract and completely unfolding was defined as MLL. The dark green leaf with mature form and size was recorded as the phase of MDL. Yellowish and/or brownish leaves indicated the times of leaf fallen off and were noted as LA. FB was referred to the first small flower occurrences, while ultimate size and the fading of flowers were recorded as FM and FF, respectively. It

was similar to the pheno-phases of fruits, the small fruit was defined as YF, while ultimate size with green and yellow/brown were defined as MF and RF, respectively.



**Figure 1** Research procedure.

Visual estimates with binoculars had been successfully used in several phenological surveys in the temperate and tropical zones (O'Brien *et al.*, 2008; Vitasse *et al.*, 2009). Following these researches, tree pheno-phases were monitored by using a binocular. The proportion of each phenological feature on crown canopy was visually estimated and the observed scores were varied from 0-100%. For all phenological categories, followed O'Brien *et al.* (2008), the observer assigned an index from 0 to 5 based on the percentages of the full crown potential occupied by each category. The observer scored 0 for a bare crown, 1 for >0–20 percent, 2 for >20–40 percent, 3 for >40-60 percent, 4 for >60-80 percent and 5 for > 80 percent cover of the crown occupied by each class.

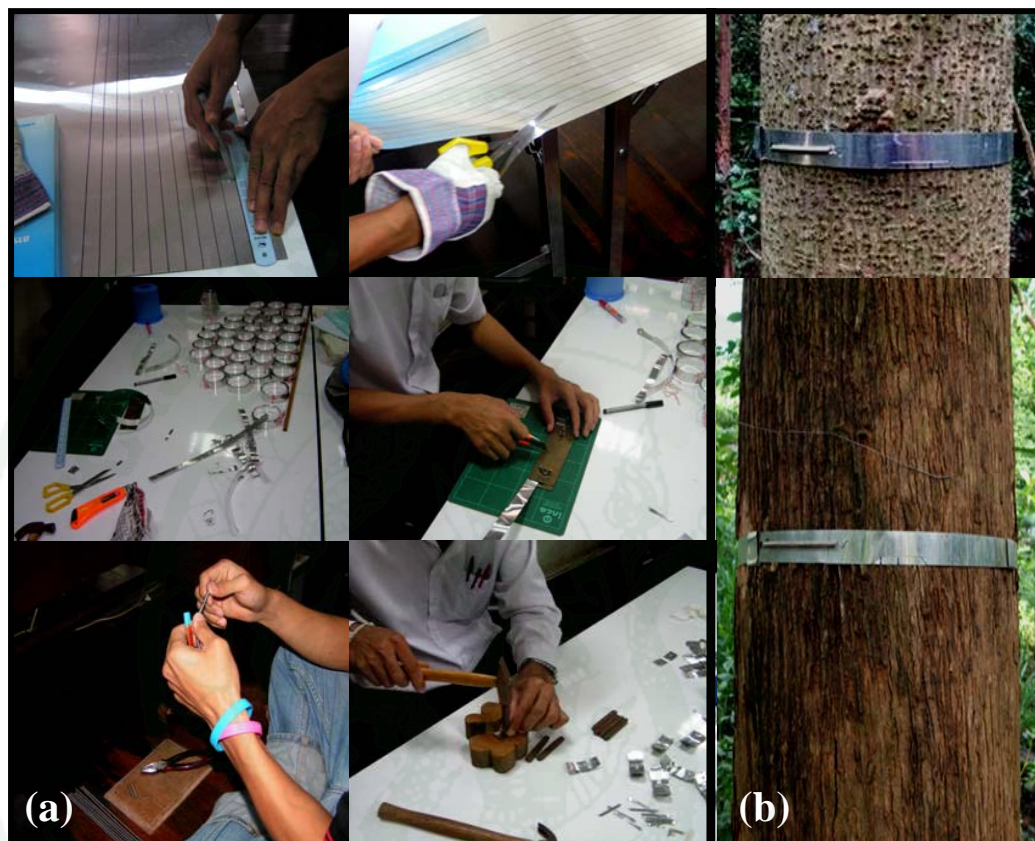
### **3. Outside bark diameter investigation**

Outside bark diameter increment was another periodic growth investigation. It was recorded by using a modified manual band dendrometer (Figure 2). The band consisted of a thin strap of aluminum (2 cm wide) placed around the selected tree. One end of the band was passed through a collar and then connected back to itself with a spring and a 0.1 mm accurate vernier scale. As the tree growth, the spring allowed the band to move with the circumference of the tree and the moved vernier scale on the band could be manually read and recorded. The measurements of monthly diameters were taken for one year; coincided with the studies of wood formation and tree phenology. Finally, monthly data of tree phenology, wood increment, and changed diameter provided from manual band dendrometer were correlated with monthly climatic data and soil moisture contents in order to identify factors mainly controlling tree growth in term of outside bark diameter increments.

### **4. Periodic wood and annual ring formations**

All selected trees from section 1 were also selected for phenological studies. The periodicity of monthly wood increments and annual ring boundaries were studied by using the techniques of cambial wounded marking. Once a month, cambial zones

of the selected trees were injured in order to mark and investigate the boundaries of monthly growth zone and cell differentiation.

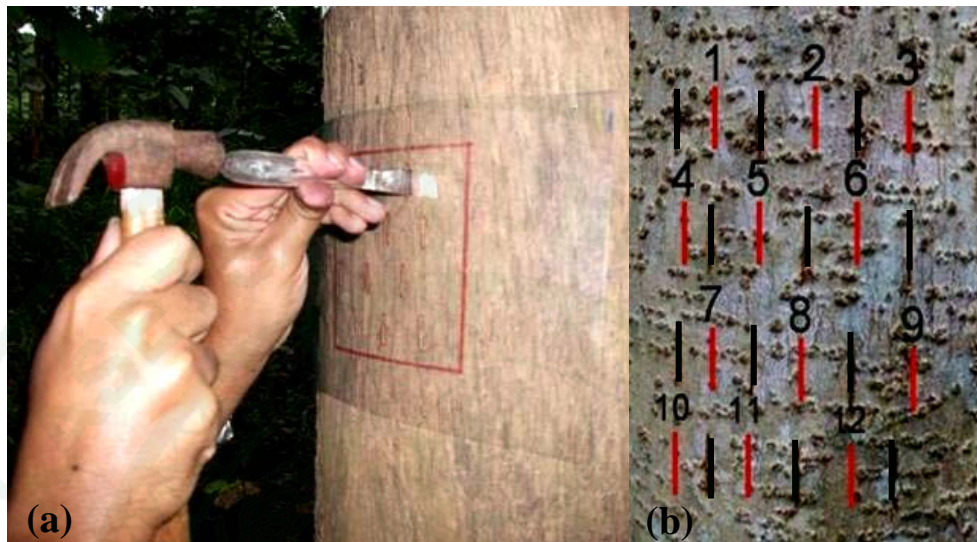


**Figure 2** Modified manual band dendrometers: (a) band dendrometer making; (b) installed band dendrometer on selected trees.

#### 4.1 Cambial marking and sample collection

The modified pinning method, called knife-cutting method, was used for cambial wounded marking once a month on each selected tree. The marking was applied at 130 cm above ground level by using a modified knife of 1 mm thickness and 5 mm width. In each selected trees, cambial cells were marked as the baseline of measurement in 4 September 2009. Cambial cells were repeatedly marked over the continuous observed periods for 12 months (Figure 3). A year later when the markings finished, all marked points were extracted as a block by using a handsaw, a chisel and a mallet (Figure 4). The large block of cambial wounds was cut into

smaller blocks which contained six marking for each block (Figure 5). These blocks were preserved in 50% ethyl alcohol in order to avoid the effects of fungi.



**Figure 3** Cambial marked points on the selected tree: (a) cambial marking on *T. grandis*; (b) cambial marked points on *A. xylocarpa*. Black and red lines indicated the baseline of measurement in 4 September 2009 and monthly marked points during October 2009 till September 2010, respectively.



**Figure 4** Extraction of wood block containing marked points on *A. odoratissima*.



**Figure 5** Blocks of cambial wounds containing six marked points in each block. Markings on *A. xylocarpa*, tree no. 603.

#### 4.2 Sample preparation

In the laboratory at the Department of Forest Biology, Faculty of Forestry, Kasetsart University, wounded blocks contained two marked points of baseline and monthly marked points were put into boiled water for 5-10 minutes in order to make their fibers softness and were suddenly sectioned in transverse and radial planes to study cell structure by using a sliding microtome at a thickness between 10-15 micrometers ( $\mu\text{m}$ ). Thin sections were stained, and mounted on microscopic glass slides using permount in order to permanently preserve the specimens in a sufficient transparent condition for microscopic investigation.

For monthly wood increment and vessel size investigation using a stereo microscope, wounded blocks were carefully polished by using several grades of

abrasive papers to obtain clean and smooth wood surfaces and ring boundaries and marked wounds were prominently visible.

#### 4.3 Sample investigation

Thin sections of all cambial wounded specimens were used to study the anatomical features of wood increment during investigated periods. Wood anatomical characteristics of each transverse section including vessel sizes, vessel types, and parenchyma types were examined to obtain the anatomical variations and markers of annual ring boundaries. Polished samples were used to study the overall variation of cell sizes and cell types from the wounded marking of the first month (baseline of measurement) in 4 September 2009 to the last month in 3 October 2010. The distances from the baseline and monthly marked point to the cambial line of each specimen was measured and calculated for monthly and total wood increments (Siripatanadilok, 1983). Actual monthly wood increments and relative monthly wood increments which were also calculated by ratios of monthly and total wood increment were illustrated and explained. Vessel diameters forming each season were also averaged and calculated the variation of seasonal vessel sizes. These data were then correlated with climatic and phenological data in order to indicate factors affecting tree growth.

### 5. False ring investigation and formation

False ring investigation and formation were only carried on mature teak trees (*Tectona grandis*) which were already confirmed as annual ring formative species.

#### 5.1 Sample collection and preparation

An increment borer with drilling size of 40 cm long and 0.5 cm diameter was cored on 7 healthy teak trees in cardinal (north, east, west, south) directions at breast height (1.3 m) and avoided the effect of buttress. Wood cores were kept in plastic straws with the purpose of sample fragile avoidance. In the Laboratory of

Tropical Dendrochronology (LTD) at the Department of Forest Management, Faculty of Forestry, Kasetsart University, wood cores were air dried at room temperature and fixed in supported woods followed the standard method of dendrochronology (Stokes and Smiley, 1995). These samples were glued on wooden core sample supporters then carefully halved by using several grades of abrasive papers to obtain clean and smooth wood surfaces until the ring boundaries were readily visible and quite prominent. Polished wood cores were then coated with blackboard chalk so as to fill teak vessels with chalk powder. Filling teak vessels with chalk powder enhanced the visibility of vessel boundaries and made it easier to measure vessel diameters using image analysis. Then, these wood cores were ready for examination under the stereo microscope.

### 5.2 Visual matching

All specimens were macroscopically analyzed by visual matching as to roughly distinguish false rings and true annual rings. The gradual change of vessel sizes at the ring boundary from the beginning to the end of the abnormal growing season was the main characteristic for false ring recognition, while the abrupt change of vessel sizes was the common characteristic of actual annual ring boundary in ring porous to semi-ring porous species as teak. Later, cross-dating which was the useful technique of growing year identification was used to match the pattern of tree growth from the interested increment core to each others. If all false rings were identified and eliminated, the variation of all annual ring width series should be resemblance and the correlation coefficients among ring width series must be higher than the significant at the 0.05 level.

### 5.3 Image analysis for vessel size measurement

To identify annual rings and false rings, image analysis was applied to study the variation of vessel diameters from pith to bark. The boundaries of annual rings were identified as the abrupt change of the vessel diameter sizes at transition zone of adjacent annual ring combined with the appearance of paratracheal banded

parenchyma, while false rings only showed a small increase in vessel sizes and/or the occurrence of the paratracheal parenchyma with flatted fibers in cross section. Fixed teak cores, coated with blackboard chalk, were scanned along transverse surfaces at 2400 dots per inch (dpi) resolution using an ordinary scanner (Epson Perfection 1270). The scanned images were converted to negative color and saved as TIFF (Tag Image File Format) digital image file format. The image was divided to several segments. In each segment, it was the rectangular box, which was overlaid in each 50 pixel widths (530  $\mu\text{m}$ ) of the scanned images. All vessels in each rectangle were numbered and five vessels selected by using the technique of generated random number were measured diameters by using a free standing program, namely, ImageJ (Rasband, 1997). Vessel diameters in each quadrilateral segment were averaged and plotted to examine the variations of vessel diameter sizes from pith to bark. Trends of vessel size variation due to the age effect were then standardized or removed by using the proportion of the average vessel diameters of current and prior quadrilateral segments. Standardized vessel diameters were also plotted to examine the variation of vessel diameters from pith to bark and to indicate annual ring boundaries and false rings. In each annual ring, semi-ring porous characteristic illustrated the gradually declined vessel diameters from earlywood to latewood and the proportion of the average vessel diameters of current and prior rectangular segments seem to be equal and were commonly close to 1 while abrupt changes of vessel diameters at the transition zones of adjacent annual rings indicated the high proportion of the average vessel diameters equal or greater than 2 indicating the edge of each annual ring.

#### 5.4 Anatomy of teak cell forming false ring

Three each of annual and false rings from increment cores were chosen and separated from the wooden supports using chisel and razor blade in order to study anatomical features of teak cells. Ring samples were prepared for paraplast embedding and transverse sectioning. Microsections, each 15  $\mu\text{m}$  thick, were cut using a sliding microtome in transverse and radial planes. The wood sections were stained and mounted on microscopic glass slides using permount. Cell types forming

annual and false rings were studied and their photographs were taken under a compound photomicroscope.

For the topic of false ring investigation and formation, the variations of vessel diameters were used for true annual ring and false ring identifications. In each calendar year, false ring frequencies were calculated as the number of trees forming false rings divided by all trees and convert into percentages of false ring frequencies by multiplication with 100. Finally, these data were related to climatic data to describe the factors affecting false ring formation.

## **6. Tree-ring analysis of teak**

As described in section 5, tree-ring analysis and false ring investigation and formation were focused on *T. grandis* which was already confirmed as annual ring formative species. Tree-ring analysis was done following the standard method of dendrochronology (Stokes and Smiley, 1995).

### **6.1 Ring width measurement**

The patterns of annual ring width variations, collected and prepared in section 5.1, were cross-matching among wood cores in order to define the exact year in which each annual ring formed. Anomalous intra-annual rings were re-checked for this step. Each wood core was investigated on a TA Unislide Tree Ring Measurement System (Velmex Inc.) interfacing with a microcomputer, a 4x to 40x magnified stereo microscope, encoder and digital readout units. During the measurement, it was necessary to keep the line of the sample movement parallel to wood rays. Ring width values were read to the nearest 0.001 mm accuracy and recorded on a microcomputer through a ring width measurement program, called MeasureJ2X. However, the accuracy still depended on the operator. Annual ring width data was transformed to international tree-ring format and kept in microcomputer.

## 6.2 Data processing

The data processing was divided to 2 steps. The first step was the exact growth year identification which was verified by using software COFECHA (Holmes, 1983). The software performed data quality control on a set of tree-ring measurements, and indicated possible dating or measurement problems. The second step was ring width index development which constructed an individual site index, maximized the climatic response, and minimized or removed the unwanted factors from this index. To make ease, the software ARSTAN (Cook and Peter, 1981) was applied for this step to remove non-climatic age trend from the ring width series and average the standardized values of individual series into a mean-value. ARSTAN performed a suitable model of negative exponential curve or a straight line of negative slope, which was fitted to each ring width series. Tree ring index was constructed according to the proportion of actual ring width and suitable fitted curve in each year. All standardized series were combined to obtain a master chronology by using the arithmetic mean. The expressed population signals (EPS), which was a function of the average correlation between tree-ring series ( $R_{bar}$ ) and sample depth, was calculated to indicate the acceptable number of the sample sizes and common variance (Borgaonkar *et al.*, 2009; Cook *et al.*, 1990; Wigley *et al.*, 1984). Wigley *et al.* (1984) also suggested the acceptable values of  $EPS \geq 0.85$  as the reliable chronology for dendroclimatic research. The ring width index was latterly correlated with climatic data in order to describe climate-growth response.

## 7. Factors affecting periodic wood and annual ring formation

### 7.1 Climatic data and soil moisture at the growing site

Climatic data including total monthly rainfall (Rain), mean monthly relative humidity (RH), mean monthly maximum temperature (Tmax), mean monthly mean temperature (Tmean) and mean monthly minimum (Tmin) obtained from the nearest meteorological station of SERS. Soil moisture contents (SM) were directly

measured once a month over the investigated periods and were selected for the analysis of climate-growth response.

Soil samples from 3 points of each location were collected to obtain the best representative sample of the site. At the depth of 5, 10, 15, 20, 25, 30, 50, 70 and >70 cm, soil samples were cored by using a soil auger and kept as quickly as in tightened containers to prevent moisture loss from evaporation. Soil wet weights were immediately measured to the nearest 0.01 g and note. Soil samples were dried in an oven at 105 °C for 24 hours, and re-weighted again to obtain the oven dry weight of soil. Soil moisture content in each depth was calculated as the percentage of the different weights between wet and oven dry soils as shown in the following formula:

$$\theta_d = \frac{[wt_w + tare] - [wt_d + tare]}{[wt_d + tare] - [tare]} \times 100 \dots\dots\dots(1)$$

where  $\theta_d$  was the percent of soil moisture content,  $wt_w$  was the soil wet weight (g),  $wt_d$  was the soil dry weight (g) and  $tare$  was the container weight (g).

All of these climatic data were defined as independent factors inducing monthly tree growths which were derived from tree phenology, monthly wood and outside bark diameter increments and false ring occurrences by using simple correlation and multiple regression analysis. Apart from monthly climatic data, average climatic data during the drought period in January till April, the first half of wet season in May till August, and the second half of wet season in September till December were also correlated with the percentages of false ring frequencies in order to estimate the major climatic factors inducing false ring and annual ring formations in teak trees.

## 7.2 The description of phenology and wood formation relating to climate

Tree pheno-phases and the periodic wood formation including monthly wood increments and vessel size variations were described association with the variation of monthly climatic data and soil moisture contents. This topic demonstrated monthly development and the relationship of all factors by using the descriptive technique, while the next topic pointed to the correlation among these factors by using the statistical techniques of simple correlation and path analysis.

## 7.3 Intercorrelation among climatic factors, phenology and wood increment

### 7.3.1 The relationship of tree phenology with climate

All quantitative phenological data of each selected species were correlated with climatic data by using the statistics of simple correlation analysis. For linear correlation, it reflected the degree of linear relationship between two variables ranging from +1 to -1. This statistical analysis was able to reveal which climatic factors mainly influenced on phenological characteristics.

### 7.3.2 The relationship of wood increment with climate and phenology

Due to wood formation reflected both of climate and phenology, all climatic data, as described above, were defined as exogenous variables, and phenological variations affected from climate were defined as endogenous variables. These variables were related to monthly wood increment, and outside bark diameter to analyze factors affecting wood formation using both of ordinary linear regression and the application of multiple linear regression technique, namely path analysis. This is an effective tool for direct and indirect effect explanation among significant factors affecting tree growth.

Multicollinearity, a statistical characteristic in which two or more independent variables in a multiple regression model were highly correlated, was

firstly calculated because it might not give valid results about any individual predictor, or about which predictors were redundant with respect to others. Climatic data of Tmax, Tmin, Tmean, Rainfall, RH and all soil moisture content in all soil depths were detected multicollinearity using the calculation of “the tolerance” and “the variance inflation factor (VIF)”. Some authors have suggested a formal detection-tolerance or the variance inflation factor (VIF) for multicollinearity as:

$$\text{Tolerance} = 1 - R_j^2 \dots\dots\dots(2)$$

$$\text{VIF} = 1/\text{Tolerance} \dots\dots\dots(3)$$

where  $R_j^2$  was the coefficient of determination of a regression of variable j on all the other variables. A tolerance of less than 0.20 and/or a VIF of 5 and above indicated a multicollinearity problem (O'Brien, 2007).

If independent variables showed the multicollinearity problem, principle component analysis (PCA) was then applied to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables. These variables combined with phenological data, monthly wood increment and outside bark diameter increment were described the directed dependencies among a set of variables using the path analysis (PA). PA was easier to understanding due to rely very heavily on pictures called path diagrams to visualize the hierarchy of correlation. All of the variables were represented by rectangles and each path was represented by a straight line with an arrow head at one end. The straight arrows were the paths representing the correlations among the variables. The circle with an arrow pointing to the dependent variable is the error term, called the disturbance term. However, models which were constructed should always be based on theory, knowledge, or even hunches.

To see how well the model fitted the data, the absolute fit of the model was firstly tested using the goodness of fit chi-square ( $\chi_{GOF}^2$ ). A chi-square value closed to zero indicates little difference between the expected and observed

covariance matrices. In addition, the probability level must be greater than 0.05 when chi-square was close to zero. The Comparative Fit Index (CFI) is equal to the discrepancy function adjusted for sample size. CFI ranged from 0 to 1 with a larger value indicating better model fit. Acceptable model fit was indicated by a CFI value of 0.90 or greater (Hu and Bentler, 1999). Root Mean Square Error of Approximation (RMSEA) was related to residual in the model. RMSEA values ranged from 0 to 1 with a smaller RMSEA value indicating better model fit. Acceptable model fit was indicated by an RMSEA value of 0.06 or less (Hu & Bentler, 1999).

### 7.3.3 The relationship of false ring formation with climate

Growing periods, when teak trees illustrated false rings, were analyzed to identify synchrony in false ring formation. Defined climatic factors were correlated with frequencies of false ring production as to identify factors affecting false ring formation by using the statistics of linear correlation and multiple regression analysis. Frequencies of false ring production were recognized as the dependent variable, while defined climatic factors were defined as independent variables.

### 7.3.4 The relationship of ring width index with climate

Based on the principle of dendrochronology, the increments of ring widths were fluctuated and limited due to dynamics of environmental factors. The variation in ring to ring growth was referred as sensitivity and the lack of ring variability was called complacency. The sensitivity could be calculated by using the following equation:

$$\text{Mean Sensitivity (MS)} = \sum_{i=1}^n \frac{X_i - X_{i-1}}{(X_i + X_{i-1})/2} \dots \dots \dots (4)$$

where  $X_i$  was the most recent years growth,  $X_{i-1}$  was the previous years growth, and  $n$  was the number of year in calculation.

Mean sensitivity varied among species and regional climate from around 0.650 for very drought-sensitive trees to 0.150 for the most complacent trees. However, mean sensitivity was not a measurement of the chronology's utility for climate reconstruction but it was a good measurement of the relative ease of cross-dating.

The constructed ring width index was correlated with the variations of climatic factors. The statistics of linear regression was used to analyze the correlation between monthly climatic data and growths of selected species. Ring width index was recognized as the dependent variable, while climatic data were defined as independent variables. These statistical analyses were able to reveal the factors affecting tree growth and how the selected factors influenced ring width variation.

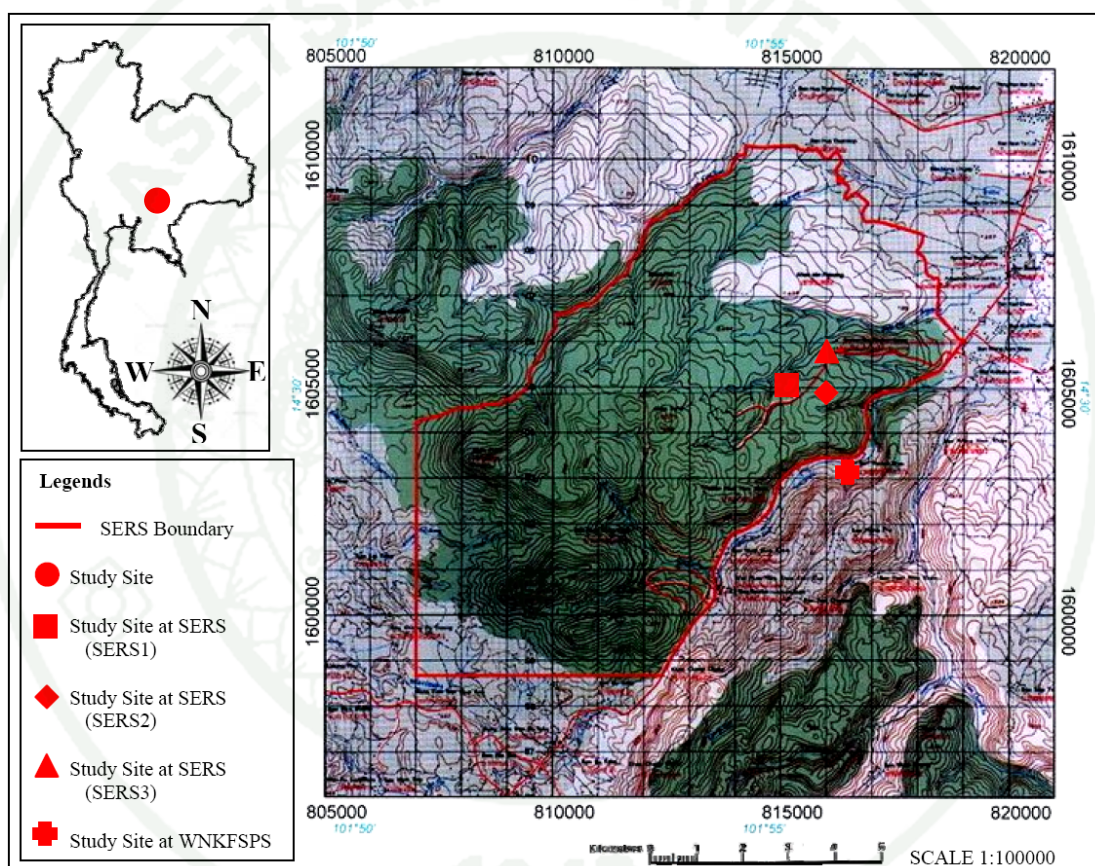
## 8. Study sites

The study sites were included 2 nearby areas at Udomsap Sub-district, Wang Nam Khiao District, Nakhon Ratchasima Province. The first area was the dry evergreen forest of Sakaerat Environmental Research Station (SERS) and the second one was Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry, Kasetsart University (WNKFSPS) (Figure 6).

SERS occupies an area of 80 km<sup>2</sup> on the edge of the Khorat Plateau, at longitude 101° 51 E and latitude 14° 30 N. It rises from 250 m above mean sea level to 762 m at the top of its highest mountain. Mountains dominate the southwest region, with the slopes easing to smaller hills in the northeast. The entire area appears to be underlain with sandstone.

SERS is a primary forest that has two major natural forest types. The majority is dense dry evergreen forest, except for the north and northeast sections of the SERS where an open dry dipterocarp forest occurs. The dry evergreen forest has a dense, four-storey canopy, and dominates the southwest section of the station, extending north-east to cover 60% of the station. It includes species such as *Hopea ferrea* and

*Hydnocarpus ilicifolia*. The dry dipterocarp forest occupies the rolling hills, which sandstone boulders and laterite are common. It covers 18% in the northeast of the station area. Vegetation in this forest is more seasonal, but common trees are *Shorea obtusa*, *S. siamensis*, *Dipterocarpus intricatus*, and *Gardenia sootepensis*. The remaining area is composed of reforested land (18%), grassland (1%), bamboo (1%), and the office and operational buildings (2%).

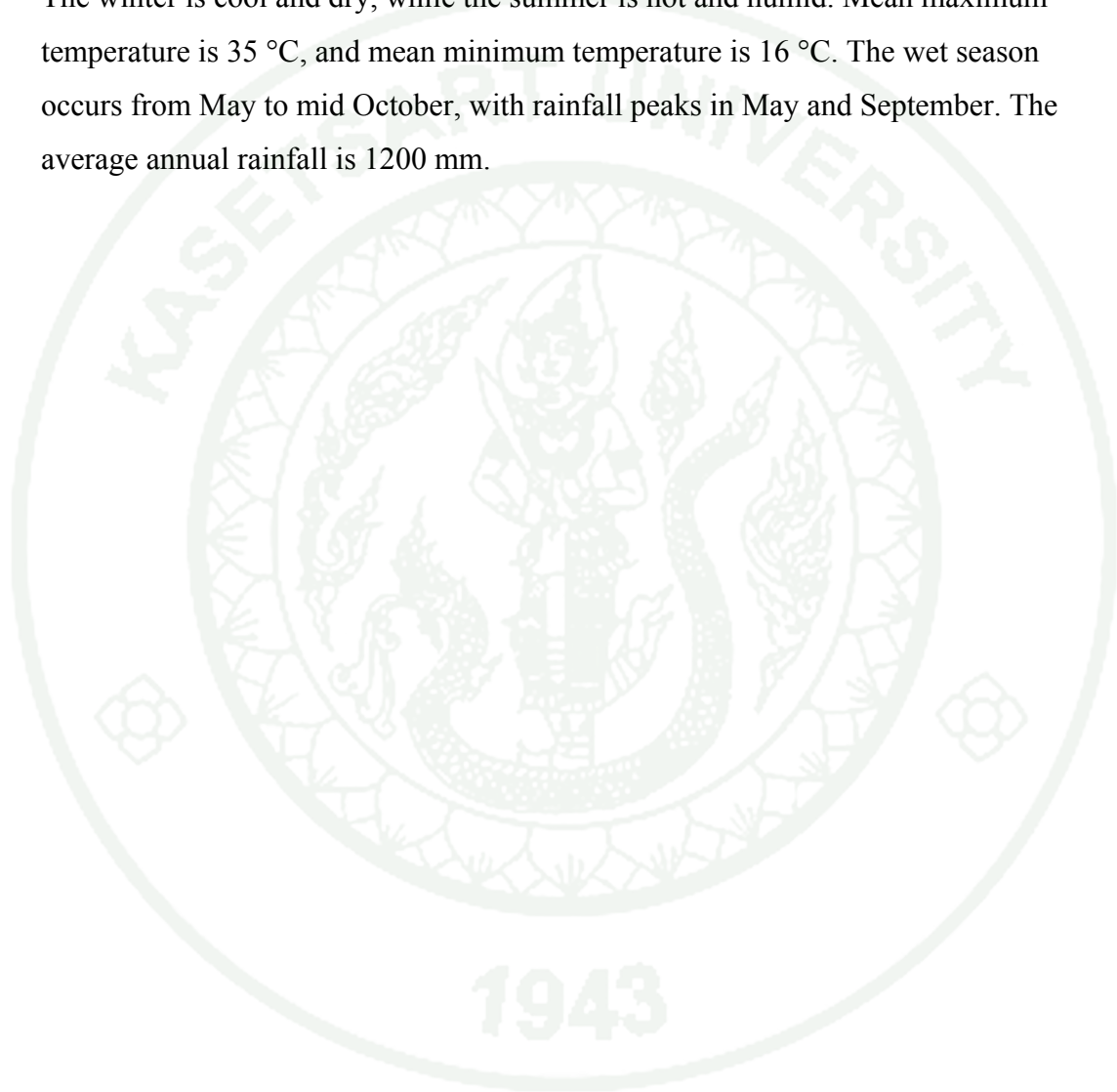


**Figure 6** Locations of WNKFSPS and 3 sub-areas at SERS (SERS1, SERS2 and SERS3) in the northeastern Thailand. Red marked points indicated the study sites.

Another selected site nearby SERS is WNKFSPS. Based on the personal contact with thesis committee and preliminary studies of teak increment cores from this site, unusual occurrences of false rings seem to be occurred to all trees. Therefore,

it was necessary to identify the cause of false ring formation which was the common source of error in tree-ring research.

The climatic condition at these sites was tropical with no occurrence of frost. The winter is cool and dry, while the summer is hot and humid. Mean maximum temperature is 35 °C, and mean minimum temperature is 16 °C. The wet season occurs from May to mid October, with rainfall peaks in May and September. The average annual rainfall is 1200 mm.



## RESULTS AND DISCUSSION

### 1. Wood macroscopic investigation and tree ring identification

This section was the pre-observation of many tree species for the selection of six appropriate species in the studies. In the following sections, based on tree species lists of SERS and WNKFSPS (Eiadthong, 2000), wood samples of 92 tree species from 38 families were collected by using increment borers and handsaws. General anatomical characteristics of tree growth zones for various species were described (Table 1) and illustrated with figures of scanned wood transverse sections as shown in Table 2 to Table 4 in which the location of ring boundaries was indicated by arrows. Growth ring (GR) characteristics which were investigated on transverse surfaces using a stereomicroscope were divided into 3 groups of distinct (DR), indistinct (IDR) and non-distinct (NDR) rings. For the species of distinct ring could be classified into three groups: 1) presenting marginal parenchyma; 2) showing distinct or abrupt anatomical changes at the growth ring boundary and 3) composing of ring porous or semi-ring porous vessel arrangement. However, in several cases, the limitations of macroscopic investigations, collected specimens (stem disc and/or increment core) and sample preparation indicated uncertainty in growth ring boundaries and grouping of growth ring types.

Distinct ring species were defined for 32 species (35%), while indistinct and non-distinct ring species were 48 species (52%) and 12 species (13%), respectively. A list of the collected species sorted by botanical family illustrated growth ring characteristics of all 92 species was shown in Table 1. Scanned images on transverse surfaces of all collected species in three groups of distinct, indistinct and non-distinct rings were respectively shown in Table 2 to Table 4.

To support the general trend of tropical woods using their wood porosity (WP), diffuse-porous (DP) was the major characteristic which was found for 88 species (96%) as similar as other tropical tree studies (Metcalf and Chalk, 1983;

Alves and Angyalossy-Alfonso, 2000; Roig *et al.*, 2005) while the rest of 4 species were ring porous (RP) and semi-ring porous (SP). Marginal parenchyma (MP) was the most common characteristics to identify growth ring boundaries of these diffuse-porous species and for 50 species (54%). In these MP occurred species, there were divided as continuous marginal parenchyma (CMP) and discontinuous marginal parenchyma (DMP) for 49 and 1 species, respectively, while the rest of 43 species (46%) were found without marginal parenchyma (WMP).

Not only the occurrences of marginal parenchyma (MP), but distinct growth ring boundaries could also be identified by other structural changes especially dynamics of cell numbers and sizes. As shown in Table 1, abundances of vessel elements (V) for 7 species (8%), changes of fiber wall thickness or fiber radial size (F) for 15 species (16%) and changes in distances between adjacent apotracheal banded parenchyma (P) for 7 species (8%) were used to identify growth ring boundaries. Trees with the absents of MP and other structural changes as described above, called non-distinct growth ring species, were absolutely found in Fagaceae, Lauraceae, Malvaceae, and Sterculiaceae. In Dipterocarpaceae and Meliaceae, the non-distinct growth ring characteristic was found for one species from each family. Figure 7 illustrated the percentage of above macroscopic features showing in 92 collected tree species.

Tree families of all selected species as shown in Table 1 seem to be a genetic grouping for growth ring formation. The occurrences of distinct and indistinct growth rings caused from the formations of marginal parenchyma and the variations of vessel sizes and their distribution. Although vessel arrangements were diffused, the formation of continuous marginal parenchyma (CMP) could increase the visibility of growth ring boundaries. CMP mostly occurring in Bignoniaceae, Burseraceae, Caesalpiniaceae, Chrysobalanaceae, Combretaceae, Connaraceae, Dilleniaceae, Dipterocarpaceae, Lamiaceae, Lythraceae, Magnoliaceae, Meliaceae, Mimosaceae, Moraceae, Myristicaceae, Oleaceae, Papilionaceae, Rutaceae and Sapindaceae. In case of ring porous or semi-ring porous associated with continuous marginal parenchyma in Lamiaceae (*Tectona grandis*) and Meliaceae (*Melia azedarach* and *Toona ciliata*),

these characteristics enhanced the visibility of distinct growth ring clearer than the investigation using the individual characteristic of wood porosity (WP) or marginal parenchyma (MP). Without marginal parenchyma, diffuse porous species were difficulty to identify growth ring boundaries by using the macroscopic investigation and were generally defined as the non-distinct ring (NDR) species. NDR species were found in Fagaceae, Lauraceae, Malvaceae and Sterculiaceae. Diffuse porous species in some families explored the characteristics of indistinct growth ring instead of non-distinct growth ring due to the occurrences of cell size dynamics (SD) such as fiber wall thickness or fiber radial size (F), distance between adjacent apotracheal banded parenchyma (P) and vessel abundances (V). The changing in fiber wall thickness or fiber radial size (F) illustrated the characteristic of indistinct growth ring in Anacardiaceae, Apocynaceae, Bombacaceae, Datisceae, Euphorbiaceae, Lecythidaceae and Rubiaceae. Annonaceae illustrated the characteristic of indistinct ring due to the changing in distance between adjacent apotracheal banded parenchyma (P), while Memecylaceae formed indistinct ring due to the changing in vessel abundances (V).

**Table 1** Growth ring characteristics of 92 collected tree species from SERS and WNKFPS.

Species	GR	WP	MP	SD
<b>ANACARDIACEAE</b>				
<i>Buchanania lanzan</i> Spreng.	IDR	DP	WMP	F
<b>ANNONACEAE</b>				
<i>Cananga latifolia</i> (Hook.f. & Thomson) Finet & Gagnep.	IDR	DP	WMP	P
<i>Polyalthia obtusa</i> Craib	IDR	DP	WMP	P
<i>Mitrephora vandaeflora</i> Kurz	IDR	DP	WMP	P
<i>Orophea polycarpa</i> A. DC.	IDR	DP	WMP	F
<b>APOCYNACEAE</b>				
<i>Wrightia arborea</i> (Dennst.) Mabb.	IDR	DP	WMP	F

**Table 1** (Continued)

<b>Species</b>	<b>GR</b>	<b>WP</b>	<b>MP</b>	<b>SD</b>
<b>BIGNONIACEAE</b>				
<i>Oroxylum indicum</i> (L.) Kurz	DR	DP	CMP	
<i>Fernandoa adenophylla</i> (Wall. ex G. Don) Steenis	DR	DP	CMP	
<i>Markhamia stipulata</i> (Wall.) Seem. ex K. Schum. var <i>stipulata</i>	DR	DP	CMP	
<b>BOMBACACEAE</b>				
<i>Bombax</i> sp	IDR	DP	WMP	F
<b>BURSERACEAE</b>				
<i>Garuga pinnata</i> Roxb.	DR	DP	CMP	V
<i>Protium serratum</i> (Wall.) Engl	IDR	DP	CMP	
<b>CAESALPINIACEAE</b>				
<i>Dialium cochinchinense</i> Pierre	IDR	DP	WMP	P
<i>Bauhinia</i> sp	DR	DP	CMP	
<i>Cassia garrettiana</i> Craib	DR	DP	CMP	
<i>Azelia xylocarpa</i> (Kurz) Craib	DR	DP	CMP	
<i>Cassia fistula</i> L.	DR	DP	CMP	
<i>Sindora siamensis</i> Teijsm. ex Miq.	DR	DP	CMP	
<b>CHRYSOBALANACEAE</b>				
<i>Parinai anamensis</i> Hance	IDR	DP	CMP	
<b>COMBRETACEAE</b>				
<i>Terminalia catappa</i> L.	IDR	DP	WMP	F
<i>Terminalia triptera</i> Stapf	IDR	DP	WMP	V
<i>Terminalia calamansanai</i> (Blanco) Rolfe	IDR	DP	CMP	
<i>Terminalia chebula</i> Retz.	IDR	DP	CMP	
<b>CONNARACEAE</b>				
<i>Ellipanthus tomentosus</i> Kurz var. <i>tomentosus</i> .	IDR	DP	CMP	
<b>DATISCAEAE</b>				
<i>Tetrameles nudiflora</i> R.Br.	IDR	DP	WMP	F

**Table 1** (Continued)

<b>Species</b>	<b>GR</b>	<b>WP</b>	<b>MP</b>	<b>SD</b>
<b>DILLENACEAE</b>				
<i>Dillenia obovata</i> Hoogl.	DR	DP	CMP	
<b>DIPTEROCARPACEAE</b>				
<i>Shorea siamensis</i> Miq.	DR	DP	CMP	
<i>Shorea obtusa</i> Wall.	IDR	DP	CMP	
<i>Shorea roxberghii</i> G.Don	IDR	DP	CMP	
<i>Hopea ferrea</i> Pierre	DR	DP	CMP	
<i>Hopea odorata</i> Roxb.	IDR	DP	DMP	
<i>Dipterocarpus alatus</i> Roxb.	NDR	DP	WMP	
<i>Dipterocarpus tuberculatus</i> Roxb.	IDR	DP	CMP	
<b>EBENACEAE</b>				
<i>Diospyros curranii</i> Merr.	IDR	DP	WMP	P
<i>Diospyros mollis</i> Griff.	IDR	DP	WMP	F
<i>Diospyros montana</i> Roxb.	DR	DP	CMP	
<i>Diospyros rhodocalyx</i> Kurz	IDR	DP	WMP	
<b>ELAEOCARPACEAE</b>				
<i>Elaeocarpus lanceaefolius</i> Roxb.	IDR	DP	WMP	V
<b>EUPHORBIACEAE</b>				
<i>Croton oblongifolius</i> Roxb.	IDR	DP	WMP	F
<i>Phyllanthus emblica</i> L.	IDR	DP	WMP	F
<i>Suregada multiflorum</i> (A.Juss.) Baill.	IDR	DP	WMP	F
<i>Mallotus philippensis</i> Muell. Arg.	DR	DP	CMP	
<i>Bridelia vetusa</i> Spreng.	DR	DP	CMP	
<b>FAGACEAE</b>				
<i>Lithocarpus thomsonii</i> (Miq.) Rehder	NDR	DP	WMP	
<i>Quercus kerrii</i> Craib.	NDR	DP	WMP	
<b>FLACOURTIACEAE</b>				
<i>Hydnocarpus ilicifolia</i> King	IDR	DP	WMP	

**Table 1** (Continued)

<b>Species</b>	<b>GR</b>	<b>WP</b>	<b>MP</b>	<b>SD</b>
<i>Flacourtia indica</i> (Burm.f.) Merr.	IDR	DP	CMP	
<b>GENTIANACEAE</b>				
<i>Fagraea racemosa</i> Jack ex Wall.	IDR	DP	CMP	
<b>GUTTIFERAE</b>				
<i>Garcinia cowa</i> Roxb. Ex DC.	IDR	DP	WMP	P
<i>Mammea harmandii</i> Kosterm	IDR	DP	WMP	V
<b>IRVINGIACEAE</b>				
<i>Irvingia malayana</i> Oliv. ex A.W. Benn.	IDR	DP	WMP	P
<b>LAMIACEAE</b>				
<i>Tectona grandis</i> L.f.	DR	RP	CMP	
<i>Vitex canescens</i> Kurz	DR	DP	CMP	
<i>Vitex peduncularis</i> Wall. ex Schauer	DR	DP	CMP	
<b>LAURACEAE</b>				
<i>Litsea elliptica</i> Blume	NDR	DP	WMP	
<i>Dehaasia candolleana</i> (Meisn.) Kosterm.	NDR	DP	WMP	
<b>LECYTHIDACEAE</b>				
<i>Careya sphaerica</i> Roxb.	IDR	DP	WMP	F
<b>LYTHRACEAE</b>				
<i>Lagerstroemia calyculata</i> Kurz	IDR	DP	CMP	
<i>Lagerstroemia duperreana</i> Pierre	DR	DP	CMP	
<i>Lagerstroemia macrocarpa</i> Wall.	DR	DP	CMP	
<b>MAGNOLIACEAE</b>				
<i>Michelia alba</i> DC.	DR	DP	CMP	
<b>MALVACEAE</b>				
<i>Talipariti macrophyllum</i> (Roxb. Ex Hornem.) Fryxell	NDR	DP	WMP	
<b>MELIACEAE</b>				
<i>Aglaia edulis</i> (Roxb.) Wall.	IDR	DP	WMP	V

**Table 1** (Continued)

<b>Species</b>	<b>GR</b>	<b>WP</b>	<b>MP</b>	<b>SD</b>
<i>Aphanamixis polystachya</i> Parker	NDR	DP	WMP	
<i>Walsura trichostemon</i> Miq.	DR	DP	CMP	
<i>Melia azedarach</i> L.	DR	SP	CMP	
<i>Toona cilliata</i> R. Br.	DR	SP	CMP	
<i>Aglia odoratissima</i> Blume	IDR	DP	CMP	
<b>MEMECYLACEAE</b>				
<i>Memecylon caeruleum</i> Jack	IDR	SP	WMP	V
<i>Memecylon ovatum</i> J.E. Smith	IDR	DP	WMP	V
<b>MIMOSACEAE</b>				
<i>Parkia sumatrana</i> Miq.	IDR	DP	CMP	
<i>Parkia timoriana</i> Merr.	IDR	DP	CMP	
<i>Xylia xylocarpa</i> (Roxb.) Taub.	DR	DP	CMP	
<i>Albizia odoratissima</i> (Linn.f.) Benth.	DR	DP	CMP	
<b>MORACEAE</b>				
<i>Sterblus ilicifolius</i> (Vidal) Corner	DR	DP	CMP	
<b>MYRISTICACEAE</b>				
<i>Knema globularia</i> (Lam.) Warb.	IDR	DP	CMP	
<b>OLEACEAE</b>				
<i>Linociera microstigma</i> Gagnep.	DR	DP	CMP	
<b>PAPILIONACEAE</b>				
<i>Millettia leucantha</i> Kurz	DR	DP	CMP	
<i>Pterocarpus macrocarpus</i> Kurz	IDR	DP	CMP	
<b>RUBIACEAE</b>				
<i>Hymenodictyon orixense</i> (Roxb.) Mabb.	IDR	DP	WMP	F
<i>Mitragyna brunonis</i> Craib	DR	DP	WMP	F
<i>Haldina cordifolia</i> Ridsd.	IDR	DP	WMP	F
<i>Morinda coreia</i> Ham.	IDR	DP	WMP	F
<i>Mitragyna rotundifolia</i> (Roxb.) Kuntze	IDR	DP	CMP	

**Table 1** (Continued)

<b>Species</b>	<b>GR</b>	<b>WP</b>	<b>MP</b>	<b>SD</b>
<b>RUTACEAE</b>				
<i>Murraya paniculata</i> Jack	DR	DP	CMP	
<b>SAPINDACEAE</b>				
<i>Xerospermum noronhianum</i> (Blume) Blume	IDR	DP	CMP	
<i>Schleichera oleosa</i> (Lour.) Oken	DR	DP	CMP	
<b>STERCULIACEAE</b>				
<i>Sterculia pexa</i> Pierre	NDR	DP	WMP	
<i>Pterocymbium tinctorium</i> (Blanco) Merr.	NDR	DP	WMP	
<i>Macaranga siamensis</i> S.J. Davies	NDR	DP	WMP	
<i>Pterospermum grandiflorum</i> Craib	NDR	DP	WMP	
<i>Pterospermum acerifolium</i> (L.) Willd.	NDR	DP	WMP	

**Remarks:** Growth Ring (GR): DR= distinct; IDR = indistinct; NDR = non-distinct. Wood Porosity (WP): RP = ring-porous; SP = semi-ring porous; DP = diffuse-porous. Marginal Parenchyma (MP): CMP = continuous; DMP = discontinuous; WMP = without. Size Dynamic (SD): F = change in fiber wall thickness or fiber radial size; P = change in distance between adjacent apotracheal parenchyma; V = change in vessel number and diameter.

**Table 2** List of scanned transverse surface images of 32 distinct growth ring species from SERS and WNKFSPS. Arrowheads indicated growth ring boundaries.

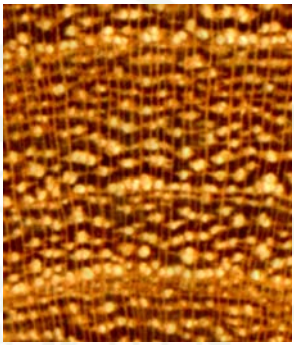
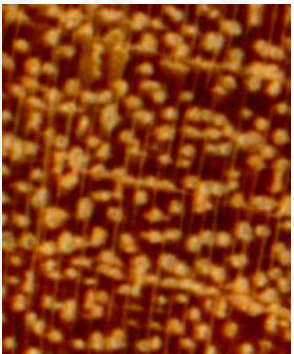

Species	Scanned image
<b>BIGNONIACEAE</b>	
<i>Oroxylum indicum</i> (L.) Kurz	
<i>Fernandoa adenophylla</i> (Wall. ex G. Don) Steenis	
<i>Markhamia stipulata</i> (Wall.) Seem. ex K. Schum. var <i>stipulata</i>	

Table 2 (Continued)

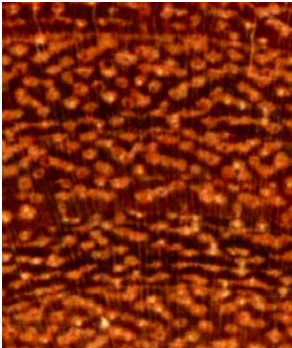
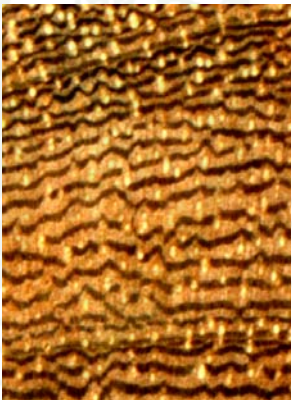

Species	Scanned image
<b>BURSERACEAE</b>	
<i>Garuga pinnata</i> Roxb.	 Two black arrows point left from the right side of the image, and one black arrow points right from the left side of the image.
<b>CAESALPINIACEAE</b>	
<i>Bauhinia</i> sp	 One black arrow points right from the left side of the image, and one black arrow points left from the right side of the image.
<i>Cassia garrettiana</i> Craib	 One black arrow points right from the left side of the image, and two black arrows point left from the right side of the image.

Table 2 (Continued)

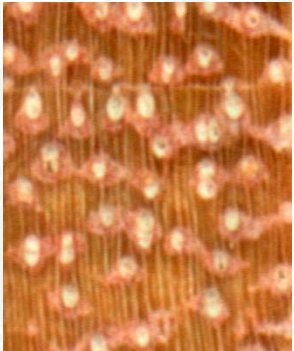
Species	Scanned image
<i>Azelia xylocarpa</i> (Kurz) Craib	
<i>Cassia fistula</i> L.	
<i>Sindora siamensis</i> Teijsm. ex Miq.	

Table 2 (Continued)

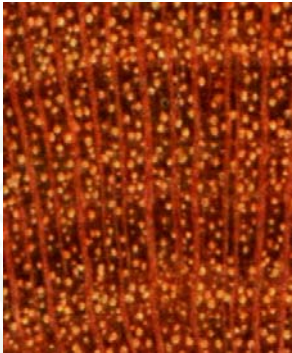

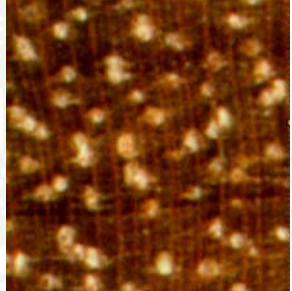

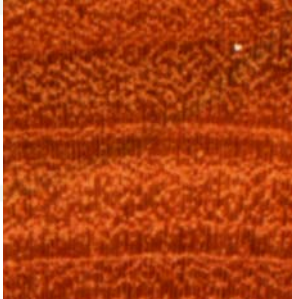

Species	Scanned image
<b>DILLENiaceae</b>	
<i>Dillenia obovata</i> Hoogl.	 
<b>DIPTEROCARPACEAE</b>	
<i>Shorea siamensis</i> Miq.	 
<i>Hopea ferrea</i> Pierre	 

Table 2 (Continued)

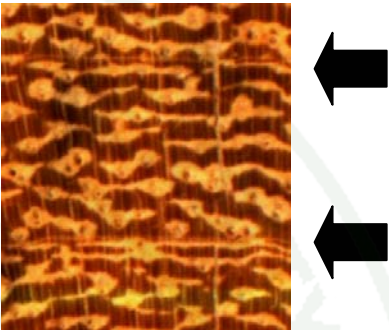
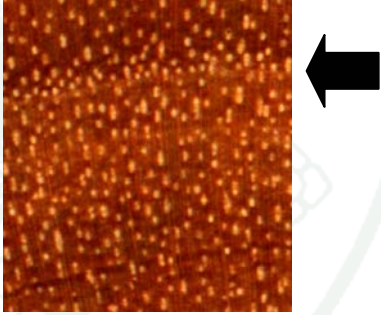
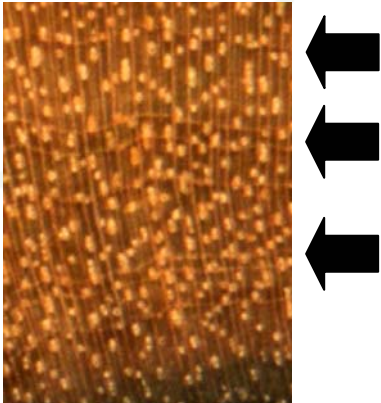
Species	Scanned image
<b>EBENACEAE</b>	
<i>Diospyros montana</i> Roxb.	
<b>EUPHORBIACEAE</b>	
<i>Mallotus philippensis</i> Muell. Arg.	
<i>Bridelia vetusa</i> Spreng.	

Table 2 (Continued)

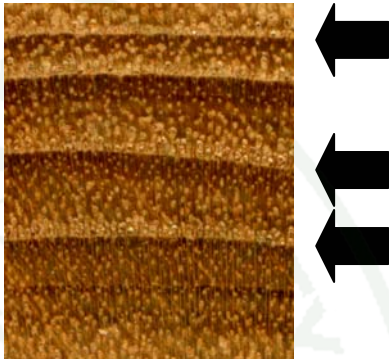
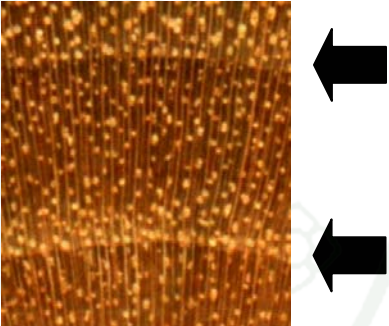
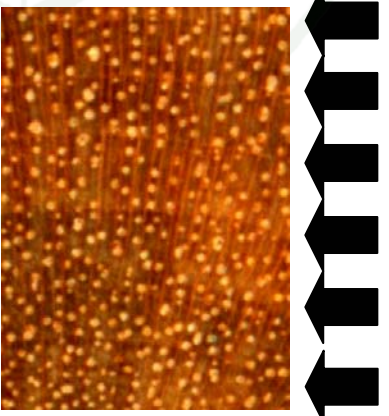
Species	Scanned image
<b>LAMIACEAE</b>	
<i>Tectona grandis</i> L.f.	
<i>Vitex canescens</i> Kurz	
<i>Vitex peduncularis</i> Wall. ex Schauer	

Table 2 (Continued)

Species	Scanned image
<b>LYTHRACEAE</b>	
<i>Lagerstroemia duperreana</i> Pierre	 Two black arrows point to the right towards the image.
<i>Lagerstroemia macrocarpa</i> Wall.	 Two black arrows point to the right towards the image.
<b>MAGNOLIACEAE</b>	
<i>Michelia alba</i> DC.	 One black arrow points to the right towards the image.

Table 2 (Continued)

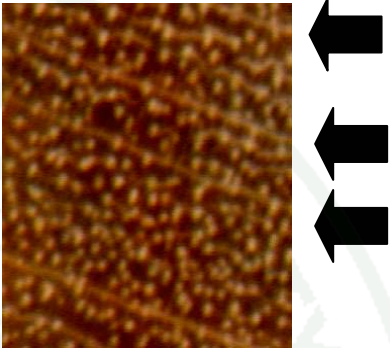
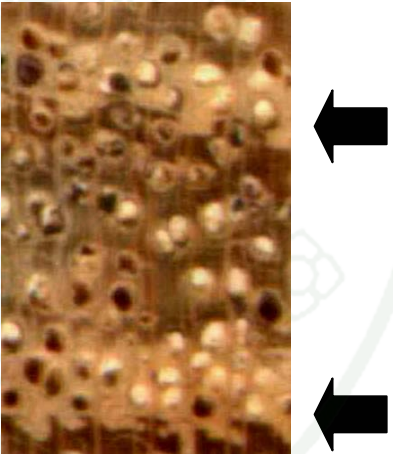
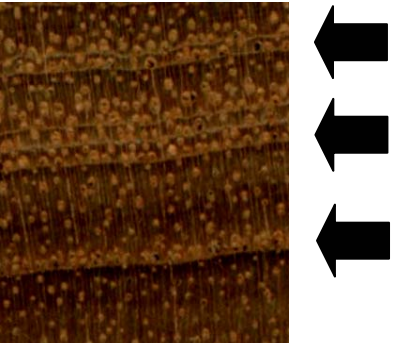
Species	Scanned image
<b>MELIACEAE</b>	
<i>Walsura trichostemon</i> Miq.	
<i>Melia azedarach</i> L.	
<i>Toona ciliata</i> R. Br.	

Table 2 (Continued)

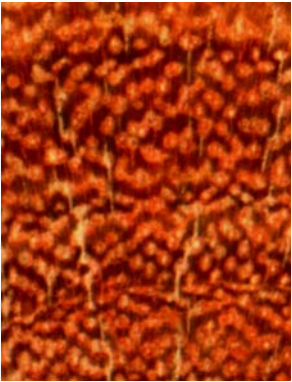

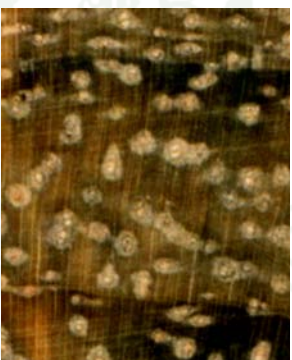




Species	Scanned image
<b>MIMOSACEAE</b>	
<i>Xylia xylocarpa</i> (Roxb.) Taub.	 
<i>Albizia odoratissima</i> (Linn.f.) Benth.	 
<b>MORACEAE</b>	
<i>Sterblus ilicifolius</i> (Vidal) Corner	  

Table 2 (Continued)

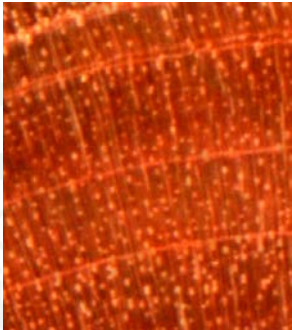
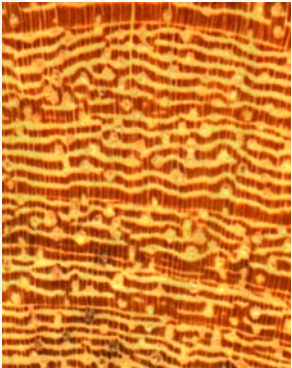
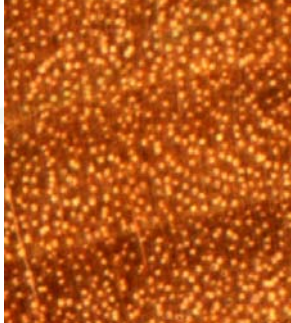
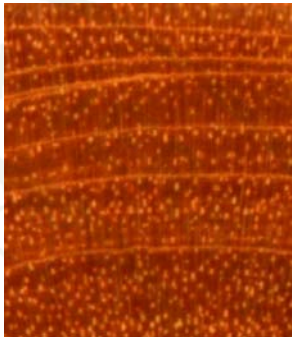
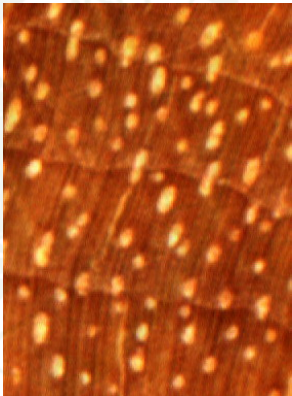
Species	Scanned image
<b>OLEACEAE</b>	
<i>Linociera microstigma</i> Gagnep.	
<b>PAPILIONACEAE</b>	
<i>Millettia leucantha</i> Kurz	
<b>RUBIACEAE</b>	
<i>Mitragyna brunonis</i> Craib	

Table 2 (Continued)

Species	Scanned image
<b>RUTACEAE</b>	
<i>Murraya paniculata</i> Jack	
<b>SAPINDACEAE</b>	
<i>Schleichera oleosa</i> (Lour.) Oken	

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**Table 3** List of scanned transverse surface images of 48 indistinct growth ring species from SERS and WNKFSPS. Arrowheads indicated growth ring boundaries.

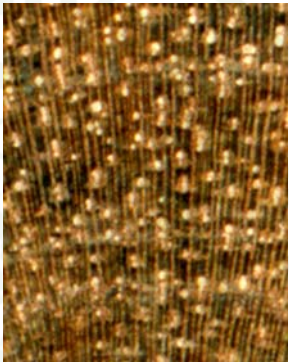

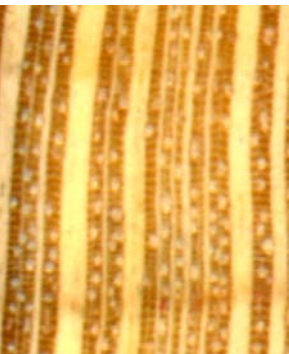
Species	Scanned Image
<b>ANACARDIACEAE</b>	
<i>Buchanania lanzan</i> Spreng.	
<b>ANNONACEAE</b>	
<i>Cananga latifolia</i> (Hook.f. & Thomson) Finet & Gagnep.	
<i>Polyalthia obtusa</i> Craib	

Table 3 (Continued)

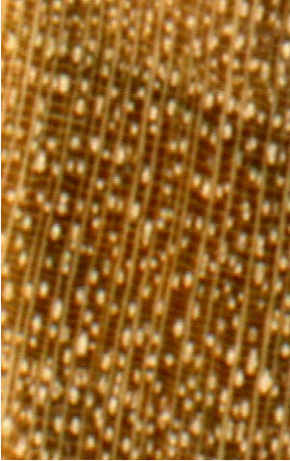

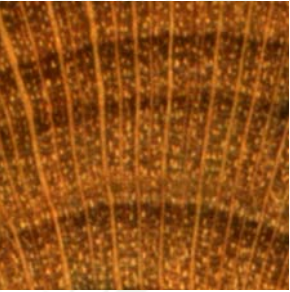

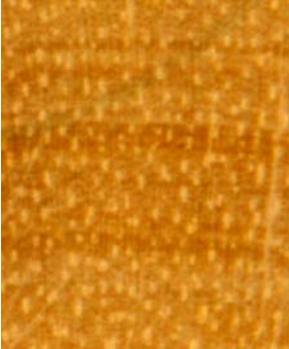
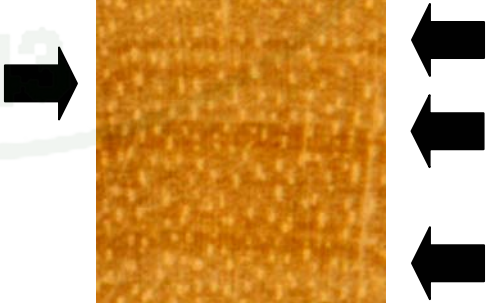
Species	Scanned image
<i>Mitrephora vandaeflora</i> Kurz	 
<i>Orophea polycarpa</i>	 
<b>APOCYNACEAE</b>	
<i>Wrightia arborea</i> (Dennst.) Mabb.	 

Table 3 (Continued)

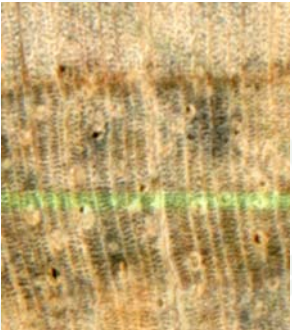
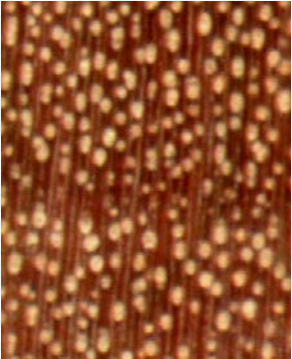

Species	Scanned image
<b>BOMBACACEAE</b>	
<i>Bombax sp</i>	
<b>BURSERACEAE</b>	
<i>Protium serratum</i> (Wall.) Engl	
<b>CAESALPINIACEAE</b>	
<i>Dialium cochinchinense</i> Pierre	

Table 3 (Continued)

Species	Scanned image
<b>CHRYSOBALANACEAE</b>	
<i>Parinari anamensis</i> Hance	  
<b>COMBRETACEAE</b>	
<i>Terminalia catappa</i> L.	  
<i>Terminalia triptera</i> Stapf	  

Table 3 (Continued)



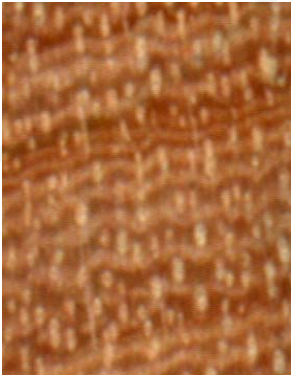
Species	Scanned image
<i>Terminalia calamansanai</i> (Blanco) Rolfe	
<i>Terminalia chebula</i> Retz.	
<b>CONNARACEAE</b>	
<i>Ellipanthus tomentosus</i> Kurz var. <i>tomentosus</i> .	

Table 3 (Continued)

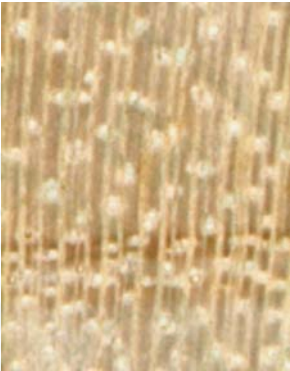

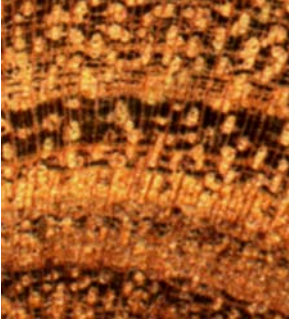
Species	Scanned image
<b>DATISCACEAE</b>	
<i>Tetrameles nudiflora</i> R.Br.	
<b>DIPTEROCARPACEAE</b>	
<i>Shorea obtusa</i> Wall.	
<i>Shorea roxberghii</i> G.Don	

Table 3 (Continued)

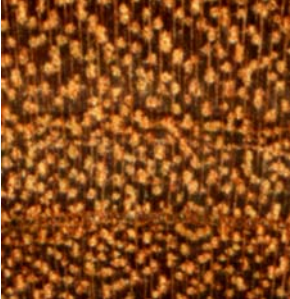

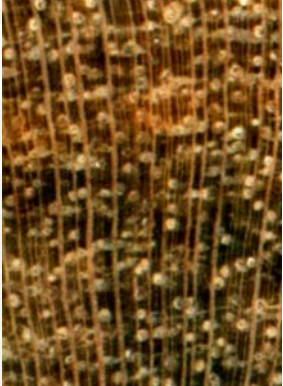


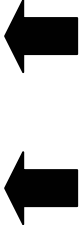
Species	Scanned image
<i>Hopea odorata</i> Roxb.	 
<i>Dipterocarpus tuberculatus</i> Roxb.	 
<b>EBENACEAE</b> <i>Diospyros curranii</i> Merr.	 

Table 3 (Continued)

Species	Scanned image
<i>Diospyros mollis</i> Griff.	
<i>Diospyros rhodocalyx</i> Kurz	
<b>ELAEOPARPACEAE</b>	
<i>Elaeocarpus lanceaefolius</i> Roxb.	

Table 3 (Continued)

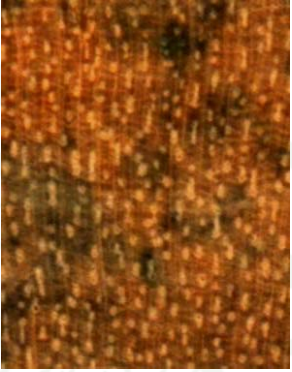

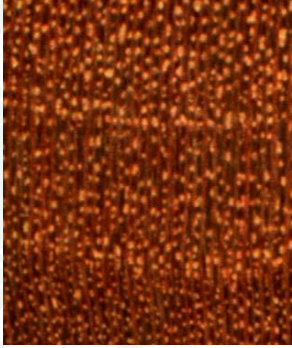
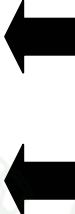



Species	Scanned image
<b>EUPHORBIACEAE</b>	
<i>Croton oblongifolius</i> Roxb.	 
<i>Phyllanthus emblica</i> L.	 
<i>Suregada multiflorum</i> (A.Juss.) Baill.	  

Table 3 (Continued)

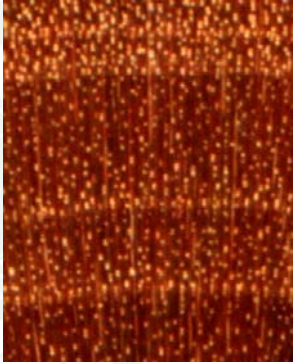

Species	Scanned image
<b>FLACOURTIACEAE</b>	
<i>Hydnocarpus ilicifolia</i> King	
<i>Flacourtia indica</i> (Burm.f.) Merr.	
<b>GENTIANACEAE</b>	
<i>Fagraea racemosa</i> Jack ex Wall.	

Table 3 (Continued)


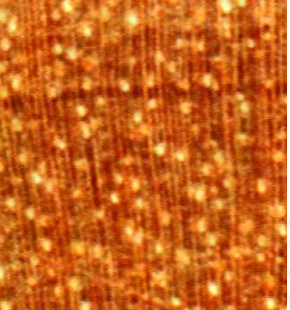
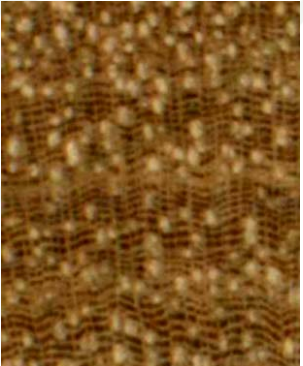
Species	Scanned image
<b>GUTTIFERAE</b>	
<i>Garcinia cowa</i> Roxb. Ex DC.	
<i>Mammea harmandii</i> Kosterm	
<b>IRVENGIACEAE</b>	
<i>Irvingia malayana</i> Oliv. ex A.W. Benn.	

Table 3 (Continued)

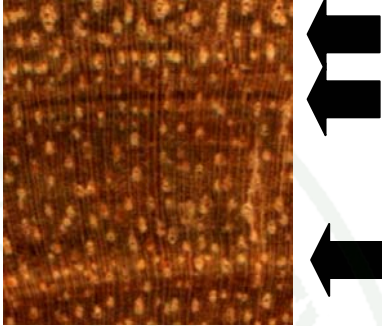
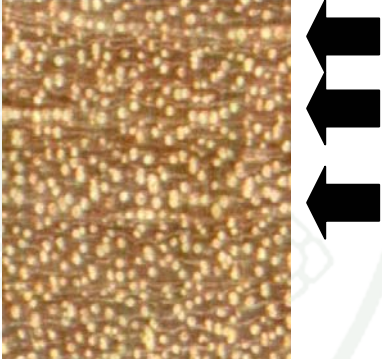
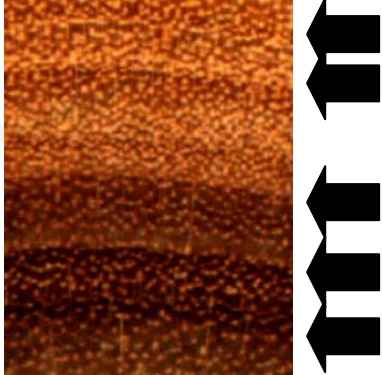
Species	Scanned image
<b>LECYTHIDACEAE</b>	
<i>Careya sphaerica</i> Roxb.	
<b>LYTHRACEAE</b>	
<i>Lagerstroemia calyculata</i> Kurz	
<b>MELIACEAE</b>	
<i>Aglaia edulis</i> (Roxb.) Wall.	

Table 3 (Continued)

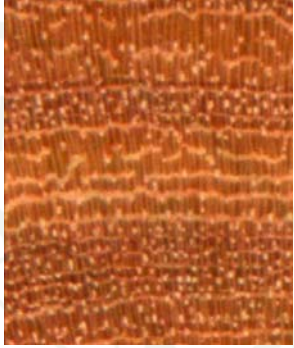
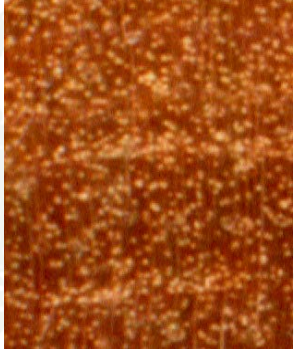

Species	Scanned image
<i>Aglia odoratissima</i> Blume	 ← ←
<b>MEMECYLACEAE</b>	
<i>Memecylon caeruleum</i> Jack	 ← ← ←
<i>Memecylon ovatum</i> J.E. Smith	 ← ← ←

Table 3 (Continued)

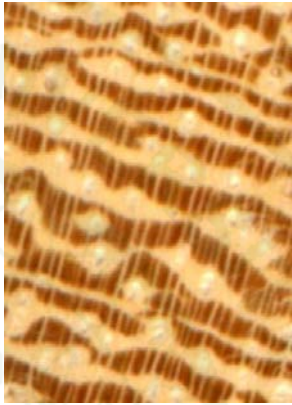
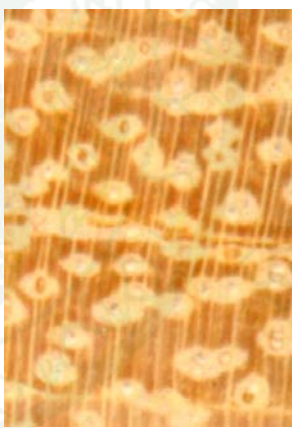
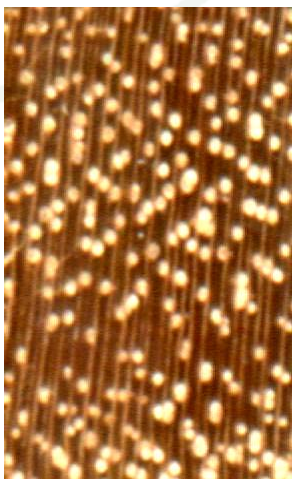
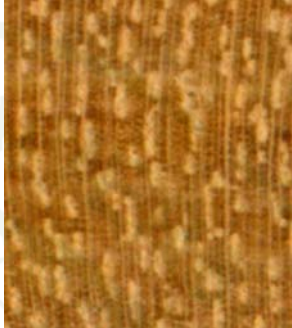
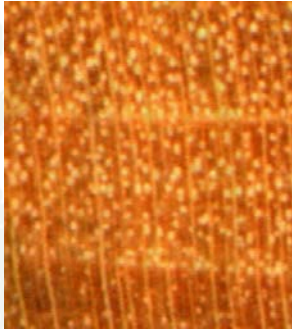
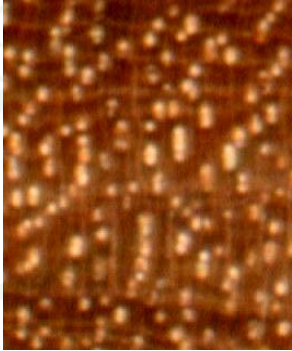
Species	Scanned image
<b>MIMOSACEAE</b>	
<i>Parkia sumatrana</i> Miq	 ← ←
<i>Parkia timoriana</i> Merr.	 ← ← ←
<b>MYRISTICACEAE</b>	
<i>Knema globularia</i> (Lam.) Warb.	 ← ←

Table 3 (Continued)

Species	Scanned image
<p><i>Pterocarpus macrocarpus</i> Kurz</p> <p><b>RUBIACEAE</b></p>	 
<p><i>Hymenodictyon orixense</i> (Roxb.) Mabb.</p>	 
<p><i>Haldina cordifolia</i> Ridsd.</p>	 

Table 3 (Continued)

Species	Scanned image
<i>Morinda coreia</i> Ham.	
<i>Mitragyna rotundifolia</i> (Roxb.) Kuntze	
<b>SAPINDACEAE</b>	
<i>Xerospermum noronhianum</i> (Blume) Blume	

**Table 4** List of scanned transverse surface images of 12 non-distinct growth ring species from SERS and WNKFSPS.

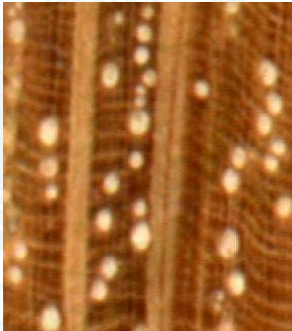

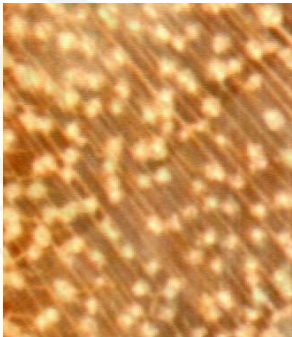
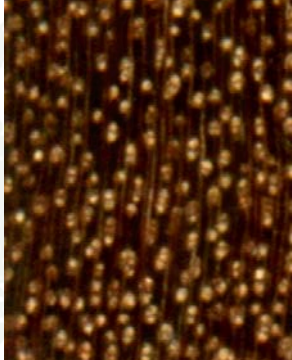
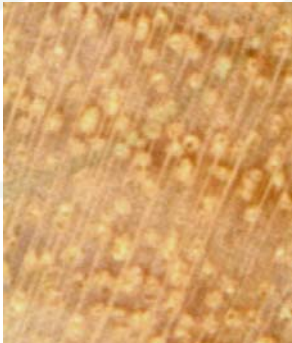


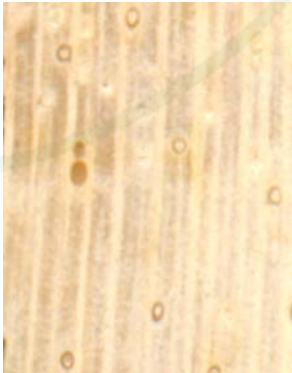
Species	Scanned Image
<b>DIPTEROCARPACEAE</b>	
<i>Dipterocarpus alatus</i> Roxb.	
<b>FAGACEAE</b>	
<i>Lithocarpus thomsonii</i> (Miq.) Rehder	
<i>Quercus kerii</i> Craib var. <i>kerii</i>	

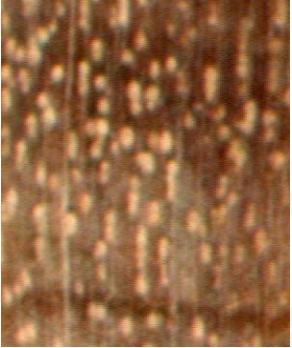
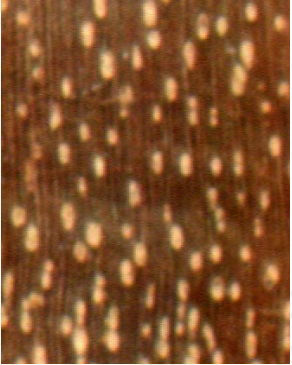
Table 4 (Continued)

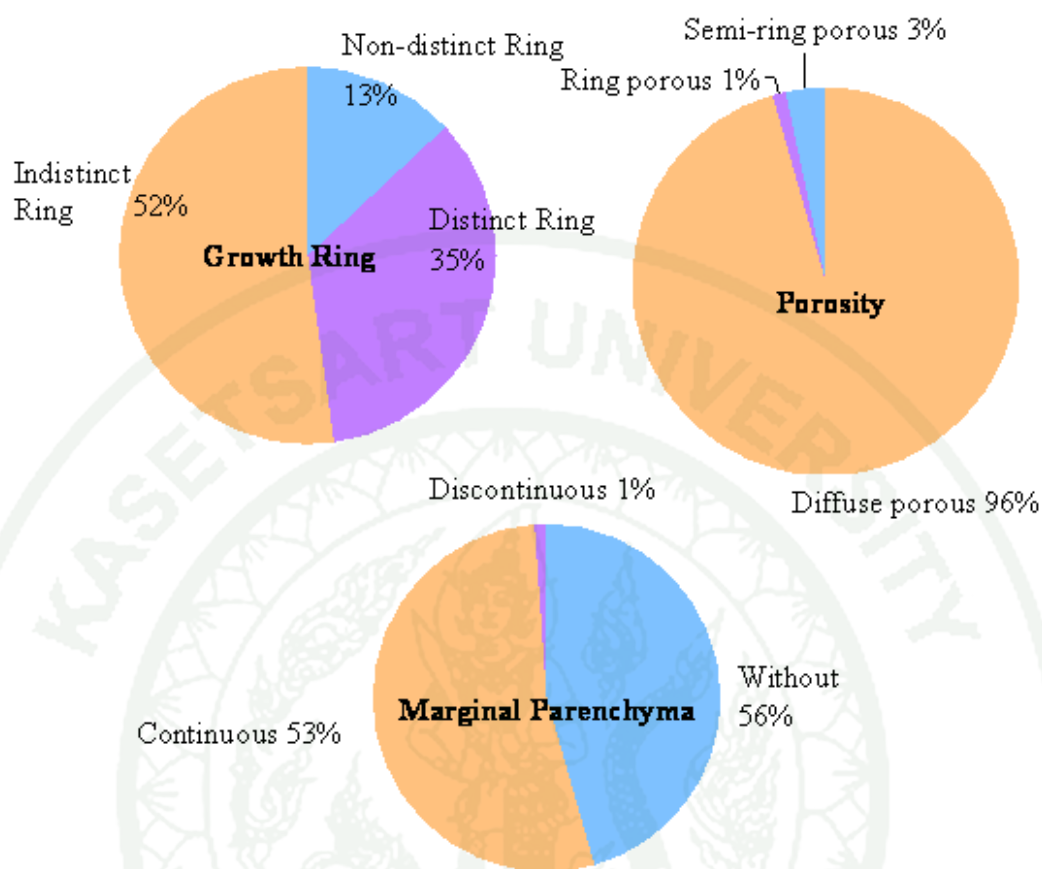
Species	Scanned image
<b>LAURACEAE</b>	
<i>Litsea elliptica</i> Blume	
<i>Dehaasia candolleana</i> (Meisn.) Kosterm.	
<b>MALVACEAE</b>	
<i>Talipariti macrophyllum</i> (Roxb. Ex Hornem.) Fryxell	

**Table 4** (Continued)

Species	Scanned image
<b>MELIACEAE</b>	
<i>Aphanamixis polystachya</i> Parker	
<b>STERCULIACEAE</b>	
<i>Sterculia pexa</i> Pierre	
<i>Pterocymbium tinctorium</i> (Blanco) Merr.	

**Table 4** (Continued)

Species	Scanned image
<i>Pterospermum grandiflorum</i> Craib	
<i>Pterospermum acerifolium</i> (L.) Willd.	



**Figure 7** Percentage of some macroscopic features illustrating in all 92 collected tree species.

Mean sensitivity (MS), a measurement of the relative change in ring-width from one year to the next in a given series, was tried to calculate using growth ring width series of 32 distinct ring species studied here and was shown in Table 5. MS values in the study did not clarify or confirm that these 32 tree species illustrated annual rings. It was the preliminary study on the assumption that growth rings were formed once a year. The high MS only indicated the potential of these trees in dendrochronological studies when annual ring formation was approved. Trees with high values of mean sensitivity ( $\geq 0.5$ ) were 12 species and the highest mean sensitivity was 0.822 in *Murraya paniculata*, while the rest of 18 species illustrated the moderate mean sensitivity in range of 0.25-0.50. *Garuga pinnata* and *Sterblus ilicifolius* illustrated low mean sensitivity for 0.242 and 0.180, respectively.

**Table 5** Mean sensitivity (MS) of distinct growth ring species.

<b>Species</b>	<b>MS</b>
<b>BIGNONIACEAE</b>	
<i>Oroxylum indicum</i> (L.) Kurz	0.562
<i>Fernandoa adenophylla</i> (Wall. ex G. Don) Steenis	0.531
<i>Markhamia stipulata</i> (Wall.) Seem. ex K. Schum. var stipulata	0.662
<b>BURSERACEAE</b>	
<i>Garuga pinnata</i> Roxb.	0.242
<b>CAESALPINIACEAE</b>	
<i>Bauhinia</i> sp	0.289
<i>Cassia garrettiana</i> Craib	0.672
<i>Azelia xylocarpa</i> (Kurz) Craib	0.425
<i>Cassia fistula</i> L.	0.311
<i>Sindora siamensis</i> Teijsm. ex Miq.	0.631
<b>DILLENACEAE</b>	
<i>Dillenia obovata</i> Hoogl.	0.404
<b>DIPTEROCARPACEAE</b>	
<i>Shorea siamensis</i> Miq.	0.496
<i>Hopea ferrea</i> Pierre	0.397
<b>EBENACEAE</b>	
<i>Diospyros montana</i> Roxb.	0.256

**Table 5** (Continued)

<b>Species</b>	<b>MS</b>
<b>EUPHORBIACEAE</b>	
<i>Mallotus philippensis</i> Muell. Arg.	0.310
<i>Bridelia vetusa</i> Spreng.	0.680
<b>LAMIACEAE</b>	
<i>Tectona grandis</i> L.f.	0.426
<i>Vitex canescens</i> Kurz	0.436
<i>Vitex peduncularis</i> Wall. ex Schauer	0.758
<b>LYTHRACEAE</b>	
<i>Lagerstroemia duperreana</i> Pierre	0.287
<i>Lagerstroemia macrocarpa</i> Wall.	0.677
<b>MAGNOLIACEAE</b>	
<i>Michelia alba</i> DC.	0.360
<b>MELIACEAE</b>	
<i>Walsura trichostemon</i> Miq.	0.361
<i>Melia azedarach</i> L.	0.268
<i>Toona ciliata</i> R. Br.	0.578
<b>MIMOSACEAE</b>	
<i>Xylia xylocarpa</i> (Roxb.) Taub.	0.374
<i>Albizia odoratissima</i> (Linn.f.) Benth.	0.592
<b>MORACEAE</b>	
<i>Sterblus ilicifolius</i> (Vidal) Corner	0.180

**Table 5** (Continued)

<b>Species</b>	<b>MS</b>
<b>OLEACEAE</b>	
<i>Linociera microstigma</i> Gagnep.	0.747
<b>PAPILIONACEAE</b>	
<i>Millettia leucantha</i> Kurz	0.437
<b>RUBIACEAE</b>	
<i>Mitragyna brunonis</i> Craib	0.408
<b>RUTACEAE</b>	
<i>Murraya paniculata</i> Jack	0.822
<b>SAPINDACEAE</b>	
<i>Schleichera oleosa</i> (Lour.) Oken	0.429

At the selected sites of Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forest Student Practice Station of the Faculty of Forestry (WKNFSPS), all distinct ring species of this study in Bignoniaceae, Oleaceae and Rutaceae and some species in Caesalpiniaceae, Euphorbiaceae, Lamiaceae, Lythraceae, Meliaceae and Mimosaceae illustrated high values of mean sensitivity greater than 0.5. Leaf phenology might not relate to the occurrences of sensitive growth rings. Tree species in Bignoniaceae and Lamiaceae were deciduous trees which bare leaf occurred in some periods, while Oleaceae and Rutaceae were evergreen species, but these tree families being in different forest types also exhibited high mean sensitivity. Although all tree species forming distinct growth rings in Caesalpiniaceae, Euphorbiaceae, Lamiaceae, Lythraceae, Meliaceae and Mimosaceae were deciduous species, mean sensitivity were fluctuated in both of low and high

values. Fritts (1976) explained factor affecting the occurrences of sensitive growth rings upon the specific characteristic of each individual site. Based on the limiting factors of tree growth which were different in each species, although tree species was similar, growing sites with more limiting generally induced trees forming sensitive growth ring greater than growing sites with no limiting. It means that the identical tree species with high mean sensitivity in specific site might exhibit low mean sensitivity in other sites. However, tree species in Bignoniaceae, Lamiaceae, Oleaceae and Rutaceae illustrated high potential for environment-growth analysis at SERS and WNKFSPS.

From the pre-observation of many tree species as described above, six tree species showing distinct and indistinct growth rings were selected to study wood and annual ring formation association with phenology and climatic data (Table 6). In order to understand the annual ring formation and causation and characteristic of false ring formation, teak (*Tectona grandis* L.f.) was the first priority of the selected species. *Afzelia xylocarpa* (Kurz) Craib, *Lagerstroemia duperreana* Pierre ex Gagnep, and *Melia azedarach* L. were the representation of the tree habit with dominant crown and were distinct growth ring species, while 2 species of *Aglaia odoratissima* Blume and *Hydnocarpus ilicifolia* King were respectively selected as the suppressed and co-dominant crown habitable representations and were indistinct growth ring species.

**Table 6** Six selected species with their crown habits, DBH, and number of trees.

Species	Crown habit	DBH (cm)	No. of trees
<i>Afzelia xylocarpa</i>	Dominant	22.4 – 35.7	5
<i>Aglaia odoratissima</i>	Suppressed	12.2 – 16.4	5
<i>Hydnocarpus ilicifolia</i>	Co-dominant	11.7 – 18.1	6
<i>Lagerstroemia duperreana</i>	Dominant	11.6 – 48.7	6
<i>Melia azedarach</i>	Dominant	21.6 – 40.3	6
<i>Tectona grandis</i>	Dominant	32.7 - 40.0	6

## 2. Phenological investigation

In order to investigate the variation of leaf, flower and fruit phenology of all selected tree species, the phenology of 6 selected tree species were described below. In each pheno-phase, the observed scores were 0 for bare crown, 1 for >0-20 percent, 2 for >20-40 percent, 3 for >40-60 percent, 4 for >60-80 percent and 5 for >80 percent of the selected phenology retaining in the crown. As similar to the section of wood formation and annual ring investigations, *T. grandis* was firstly explained followed by *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.

### 2.1 *Tectona grandis* L.f.

Six mature teak trees (*Tectona grandis*), coded TG04-TG09, were selected for phenological investigation. Teak trees, coded TG01-TG03, were rejected due to the lack of monthly wood formation and outside bark diameter increment data. The observation was made once a month for one year in August 2009 till August 2010. The timing of leaf flushing (LF) was founded in March-August and November. Mature light green leaves (MLL) developed from LF were commonly found in April-November and were abundantly found for 2 months in April and May. In June, most of MLL developed to mature stage (mature dark green leaves: MDL) and plentifully appeared until November. The quantities of MDL continuously decreased from December to March. Leaves had started to abscise (LA) as indicated by a change in their coloration to yellowish and/or brown during June-March. LA was rarely found in June-November and equalized to MDL in December to January. All phases of teak leaves were rarely found in February and March indicating dormancy and transition to new growing periods. Leaf phenology of teak was shown in Table 7 and Figure 8a.

All flower pheno-phases (flower bud burst: FB, flower maturation: FM, and flower fading: FF) were found in April to October associated with the abundances of MLL and MDL and absented in November till March (Table 7 and Figure 8b). Teak fruits were found a month later after flower bud burst (FB) firstly occurred in

June and seem to be abundantly found in August and September. Mature fruits (MF) were found from July to November and abundantly found in August and September, while ripe fruits (RF) were continuously found in August to April (Table 7 and Figure 8c).

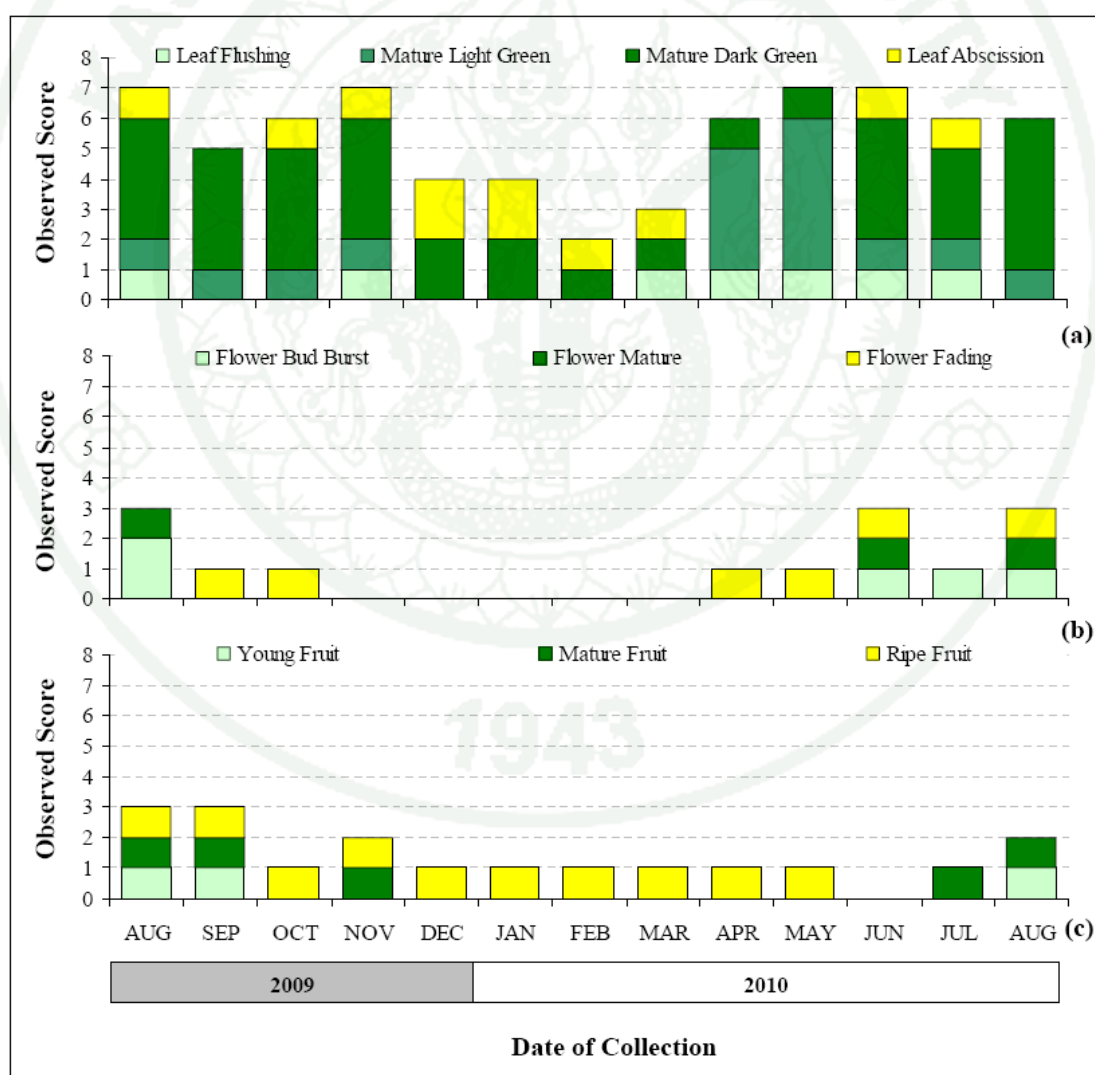
**Table 7** Phenological data of *Tectona grandis*.

Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	1	1	4	1	2	1	0	1	1	1
Sep 09	0	1	4	0	0	0	1	1	1	1
Oct 09	0	1	4	1	0	0	1	0	0	1
Nov 09	1	1	4	1	0	0	0	0	1	1
Dec 09	0	0	2	2	0	0	0	0	0	1
Jan 10	0	0	2	2	0	0	0	0	0	1
Feb 10	0	0	1	1	0	0	0	0	0	1
Mar 10	1	0	1	1	0	0	0	0	0	1
Apr 10	1	4	1	0	0	0	1	0	0	1
May 10	1	5	1	0	0	0	1	0	0	1
Jun 10	1	1	4	1	1	1	1	0	0	0
Jul 10	1	1	3	1	1	0	0	0	1	0
Aug 10	0	1	5	0	1	1	1	1	1	0

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).

## 2.2 *Azelia xylocarpa* (Kurz) Craib.

Five *Azelia xylocarpa*, common name is black rosewood (coded AF02 to AF06), were selected. The pheno-phase of leaf flushing (LF) in *A. xylocarpa* abundantly found in January after the short period of bare leaves occurred in December. Mature light green leaves (MLL) developed and could be continuously found in January till August. Mature dark green leaves (MDL) commonly found in February till November, while yellowish leaves, the indicator of leaf abscission (LA), were rarely found in June till December (Table 8 and Figure 9a).



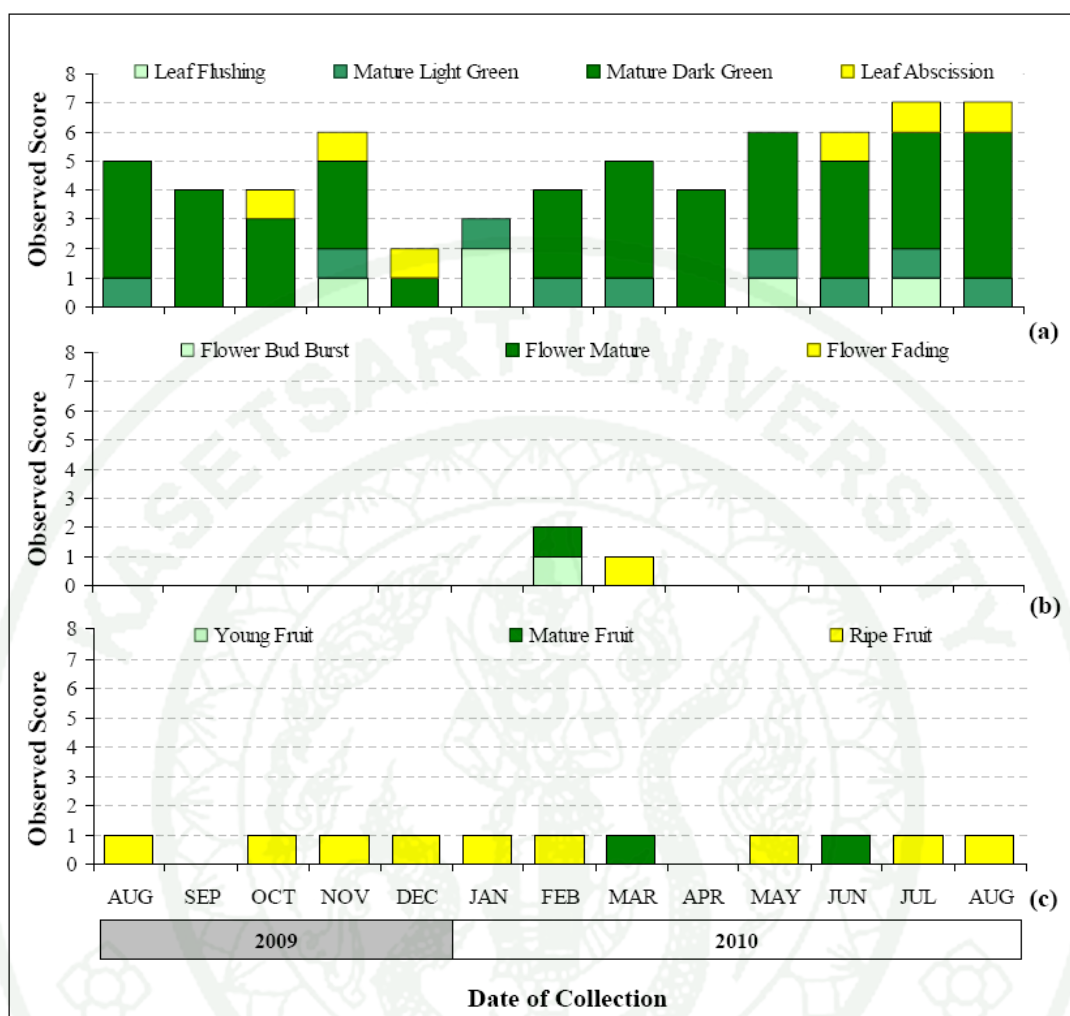
**Figure 8** Phenological investigation of *Tectona grandis*: (a) Leaf phenology; (b) Flower phenology; (c) Fruit phenology.

**Table 8** Phenological data of *Azelia xylocarpa*.

Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	0	1	4	0	0	0	0	0	0	1
Sep 09	0	0	4	0	0	0	0	0	0	0
Oct 09	0	0	3	1	0	0	0	0	0	1
Nov 09	1	1	3	1	0	0	0	0	0	1
Dec 09	0	0	1	1	0	0	0	0	0	1
Jan 10	2	1	0	0	0	0	0	0	0	1
Feb 10	0	1	3	0	1	1	0	0	0	1
Mar 10	0	1	4	0	0	0	1	0	1	0
Apr 10	0	0	4	0	0	0	0	0	0	0
May 10	1	1	4	0	0	0	0	0	0	1
Jun 10	0	1	4	1	0	0	0	0	1	0
Jul 10	1	1	4	1	0	0	0	0	0	1
Aug 10	0	1	5	1	0	0	0	0	0	1

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).

Flower bud burst (FB) and flower maturation (FM) of *A. xylocarpa* were recorded in February after LF emerged in January, while flower fading (FF) was found in March (Table 8 and Figure 9b). Small amounts of mature fruit (MF) were only found in March and June and ripe fruit (RF) could be rarely found in several months, except the drought periods in March and April (Table 8 and Figure 9c).



**Figure 9** Phenological investigation of *Afzelia xylocarpa*: (a) Leaf phenology; (b) Flower phenology; (c) Fruit phenology.

### 2.3 *Melia azedarach* L.

Bastard Cedar trees (*Melia azedarach* – coded MA01 to MA06) were selected for phenological investigation. From Table 9 and Figure 10a, leaf flushing (LF) of *M. azedarach* emerged in January to July. Small amounts of mature light green leaves (MLL) could be found in several months and could abundantly found in June. Mature dark green leaves (MDL) were firstly found in February after leaf flushing in January and was abundantly found in April and May. In June, MDL and MLL seem to equalize due to the decreased MDL and increased MLL. MDL re-

abundantly found in August to October. Leaf amounts of MDL phase declined since November and almost completely fell in December. Leaf abscission (LA) rarely found in May to December and all mature leaves extremely felled in December.

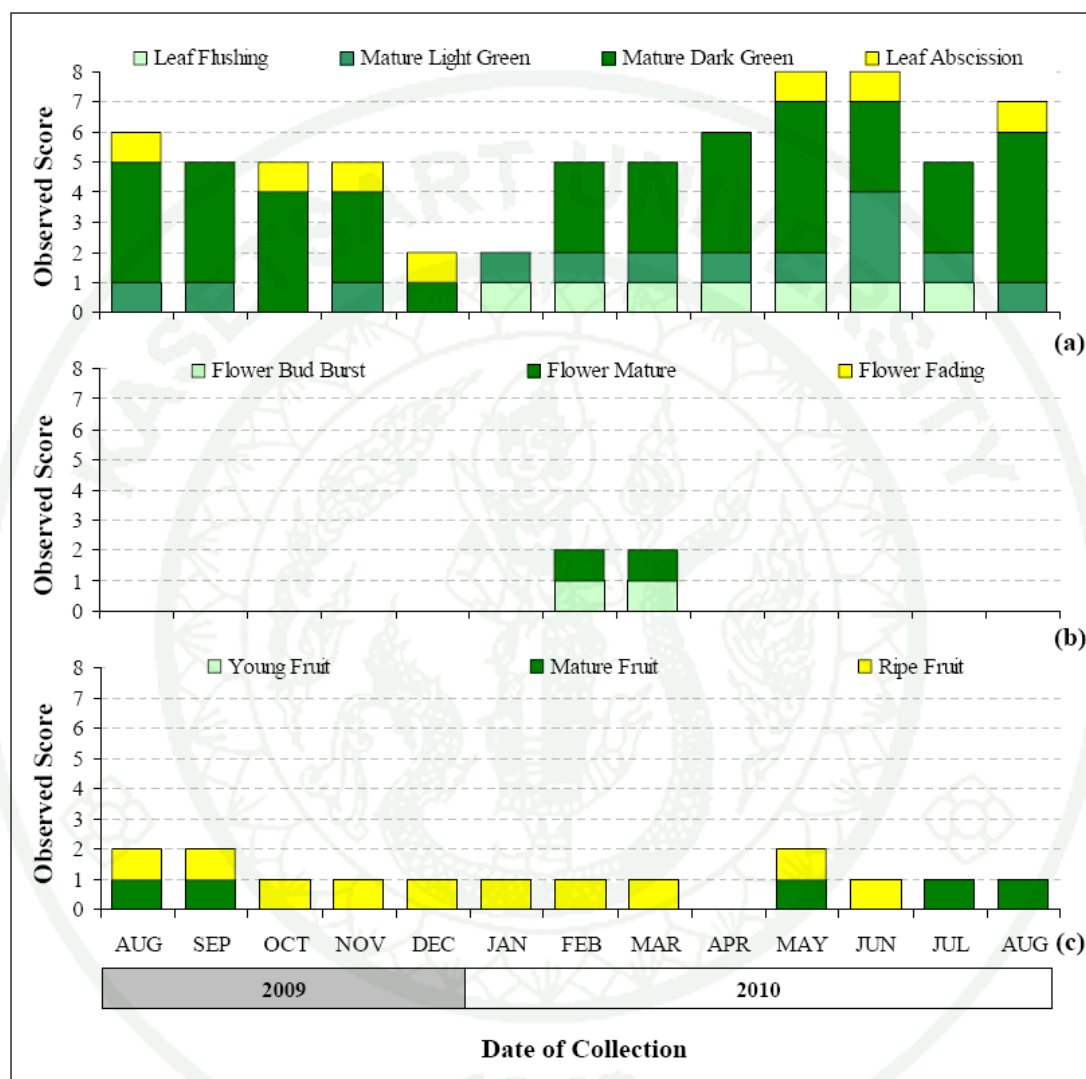
**Table 9** Phenological data of *Melia azedarach*.

Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	0	1	4	1	0	0	0	0	1	1
Sep 09	0	1	4	0	0	0	0	0	1	1
Oct 09	0	0	4	1	0	0	0	0	0	1
Nov 09	0	1	3	1	0	0	0	0	0	1
Dec 09	0	0	1	1	0	0	0	0	0	1
Jan 10	1	1	0	0	0	0	0	0	0	1
Feb 10	1	1	3	0	1	1	0	0	0	1
Mar 10	1	1	3	0	1	1	0	0	0	1
Apr 10	1	1	4	0	0	0	0	0	0	0
May 10	1	1	5	1	0	0	0	0	1	1
Jun 10	1	3	3	1	0	0	0	0	0	1
Jul 10	1	1	3	0	0	0	0	0	1	0
Aug 10	0	1	5	1	0	0	0	0	1	0

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).

Flower pheno-phases, including flower bud burst (FB) and maturation (FM), of *M. azedarach* bloomed in the short period of February and March after LF firstly established in January (Table 9 and Figure 10b). Small amounts of mature fruit (MF) were found in May to September and were found associated ripe fruit (RF) in

May, August, and September. A few RF also found in October to March. (Table 9 and Figure 10c).



**Figure 10** Phenological investigation of *Melia azedarach*: (a) Leaf phenology; (b) Flower phenology; (c) Fruit phenology.

#### 2.4 *Lagerstroemia duperreana* Pierre ex Gagnep

Thorel's Crape Myrtle trees (*Lagerstroemia duperreana* – coded LD01 to LD06) were selected for phenological investigation. From phenological data of *L. duperreana* as shown in Table 10 and Figure 11a, the timing of leaf flushing phase

(LF) was recorded in 2 intervals of April to May and August to November. The mature light green leaf phase (MLL) developing from LF was commonly found in April-November. In April, the mature dark green leaf phase (MDL) firstly occurred and plentifully appeared from May to November. The quantities of MDL abruptly dropped in December and were not found in January till March. Leaves had started to senesce as indicated by a change in their coloration to yellowish and/or brown in May. The amounts of leaf abscission (LA) were higher than MDL in December. All leaf pheno-phases of *L. duperreana* were not found in March indicating the dormant period.

After mature dark green leaf (MDL) abundantly found in May, all flower pheno-phases of *L. duperreana* were found in June, while flower bud burst (FB) was continuously found in July (Table 10 and Figure 11b). Fruits were rarely found during investigated periods. Young fruit (YF) was found associated with all flower pheno-phases in June, while mature fruit (MF) was not found, and ripe fruit (RF) was found in January till March (Table 10 and Figure 11c).

### 2.5 *Aglaia odoratissima* Blume

*Aglaia odoratissima*, a plant of Southeast Asia – coded AO01 to AO03 and AO05 to AO06 were selected. The small amounts of leaf flushing (LF) could be found in August to November. Mature light green leaf (MLL) was commonly found associated with LF and abundantly found in April and May which was the beginning of rainy season. Mature dark green leaf (MDL) was abundantly found in every month, except in April and May which MLL abundantly found instead of other leaf pheno-phases. Leaf abscission (LA) was commonly found in dry period (December to March). Leaf pheno-phases of *A. odoratissima* were illustrated in Table 11 and Figure 12, while flower and fruit phenological features were not found during the investigated periods.

**Table 10** Phenological data of *Lagerstroemia duperreana*.

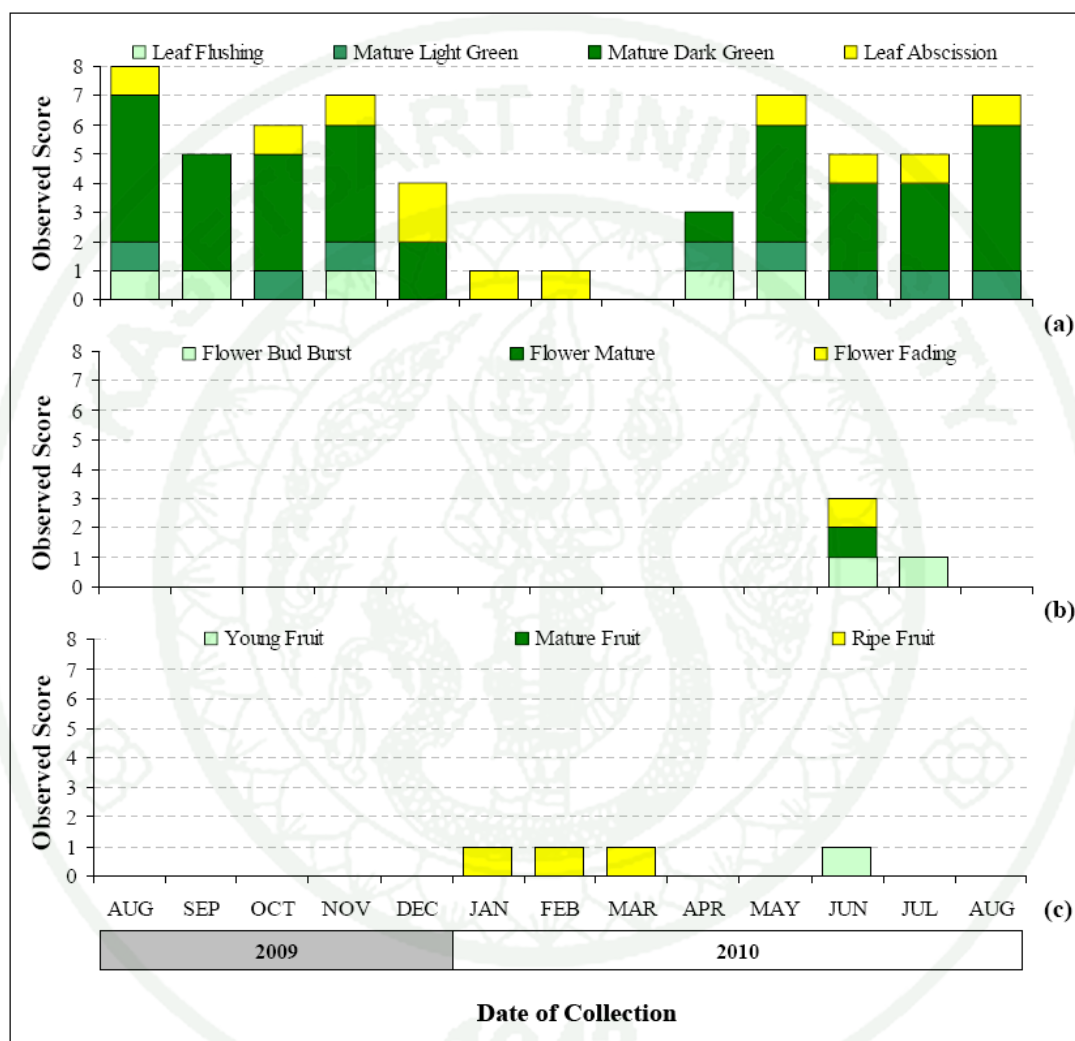
Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	1	1	5	1	0	0	0	0	0	0
Sep 09	1	0	4	0	0	0	0	0	0	0
Oct 09	0	1	4	1	0	0	0	0	0	0
Nov 09	1	1	4	1	0	0	0	0	0	0
Dec 09	0	0	2	2	0	0	0	0	0	0
Jan 10	0	0	0	1	0	0	0	0	0	1
Feb 10	0	0	0	1	0	0	0	0	0	1
Mar 10	0	0	0	0	0	0	0	0	0	1
Apr 10	1	1	1	0	0	0	0	0	0	0
May 10	1	1	4	1	0	0	0	0	0	0
Jun 10	0	1	3	1	1	1	1	1	0	0
Jul 10	0	1	3	1	1	0	0	0	0	0
Aug 10	0	1	5	1	0	0	0	0	0	0

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).

### 2.6 *Hydnocarpus ilicifolia* King

In case of *Hydnocarpus ilicifolia*, six mature trees (coded HI01 to HI06) were selected for phenological studies. Leaf flushing (LF) was not found during the investigated periods. The small amounts of mature light green leaves (MLL) were commonly found in May to August, while mature dark green leaves (MDL) were abundantly found in every month, especially in rainy season as similar as *A. odoratissima*. Small amounts of Leaf abscission (LA) were commonly found

throughout the investigated periods. Leaf pheno-phases of *H. ilicifolia* were illustrated in Table 12 and Figure 13, while flower and fruit pheno-phases were not found during the investigated periods.



**Figure 11** Phenological investigation of *Lagerstroemia duperreana*: (a) Leaf phenology; (b) Flower phenology; (c) Fruit phenology.

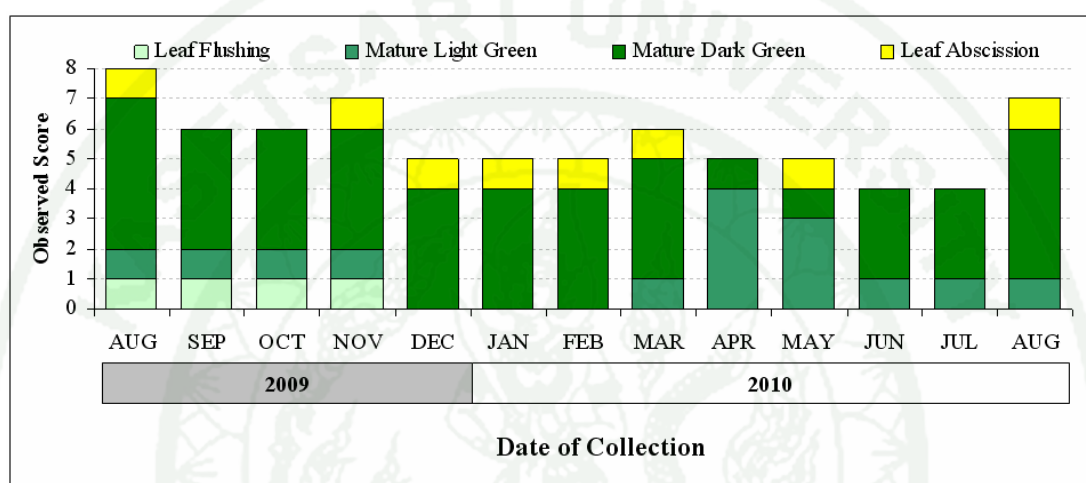
**Table 11** Phenological data of *Aglaia odoratissima*.

Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	1	1	5	1	0	0	0	0	0	0
Sep 09	1	1	4	0	0	0	0	0	0	0
Oct 09	1	1	4	0	0	0	0	0	0	0
Nov 09	1	1	4	1	0	0	0	0	0	0
Dec 09	0	0	4	1	0	0	0	0	0	0
Jan 10	0	0	4	1	0	0	0	0	0	0
Feb 10	0	0	4	1	0	0	0	0	0	0
Mar 10	0	1	4	1	0	0	0	0	0	0
Apr 10	0	4	1	0	0	0	0	0	0	0
May 10	0	3	1	1	0	0	0	0	0	0
Jun 10	0	1	3	0	0	0	0	0	0	0
Jul 10	0	1	3	0	0	0	0	0	0	0
Aug 10	0	1	5	1	0	0	0	0	0	0

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).

Based on leaf phenology, all tree species produced abundant leaf crowns throughout the rainy season (Gutierrez-Soto *et al.*, 2008), while *A. odoratissima* and *H. ilicifolia* produced leaf crowns throughout the year. Four deciduous tree species of *T. grandis*, *A. xylocarpa*, *M. azedarach*, and *L. duperreana* illustrated leaf-flushing at the beginning of rainy season following by leaf maturation in rainy season and leaf-fall during the dry and cold season at the end of the year. The pattern of leaf production was similar to the observation of several deciduous species in India, Brazil, Mexico, Argentina, Africa, Costa Rica, Java and Thailand (Venugopal and

Liangkuwang, 2007; Lisi *et al.*, 2008; Sun *et al.*, 1996; Rivera *et al.*, 2002; Valdez-Hernandez *et al.*, 2010). Sun *et al.* (1996) and Valdez-Hernandez *et al.* (2010) also explained that, in deciduous and tropical species, leaf flushing was generally determined by the beginning of the rainy season, while leaf fall depended on the duration of dry periods.



**Figure 12** Leaf phenology of *Aglaia odoratissima*.

Two species of the tropical evergreen species (*A. odoratissima* and *H. ilicifolia*) illustrated leaf maturation throughout the year, while young leaves were abundantly found in rainy season and leaf abscission rarely found throughout the year. Xiao *et al.* (2006) suggested that leaf phenology in tropical evergreen forests was not determined by the seasonality of precipitation. Instead, leaf phenological process may be driven by availability of solar radiation. Williams *et al.* (2008) studied leaf phenology of *A. odorata* and *A. spectabilis* growing in western Thailand and also found the evergreen and leaf flushed characteristics at the beginning of rainy season.

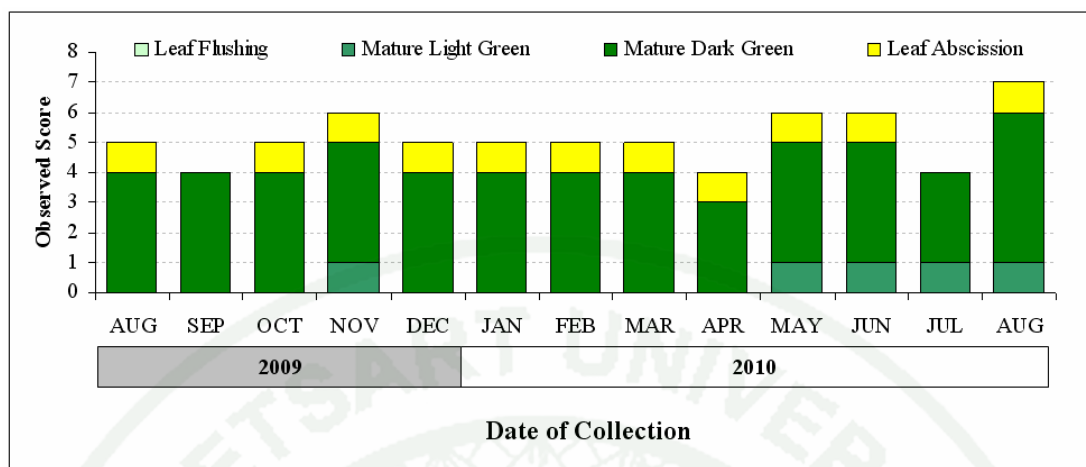
In case of flower phenology, available evidences of the selected tropical tree species could be suggested that flowering shortly occurred either during or after leaf flushing or when trees were leafless during the dry season as described by Reich and Borchert (1984). In some species, lack of moisture in the dry season might inhibit flowering (Borchert 1980, 1996; Reich and Borchert 1984). Chapman *et al.* (1999)

suggested that flowering occurred immediately after peak periods of irradiance explored. Van Schaik *et al.* (1993) also explained that leaf and flower flushing abundantly occurred when irradiance was at peak levels except where water stress made this impossible.

**Table 12** Phenological data of *Hydnocarpus ilicifolia*.

Month	Leaf Phenology				Flower Phenology			Fruit Phenology		
	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
Aug 09	0	0	4	1	0	0	0	0	0	0
Sep 09	0	0	4	0	0	0	0	0	0	0
Oct 09	0	0	4	1	0	0	0	0	0	0
Nov 09	0	1	4	1	0	0	0	0	0	0
Dec 09	0	0	4	1	0	0	0	0	0	0
Jan 10	0	0	4	1	0	0	0	0	0	0
Feb 10	0	0	4	1	0	0	0	0	0	0
Mar 10	0	0	4	1	0	0	0	0	0	0
Apr 10	0	0	3	1	0	0	0	0	0	0
May 10	0	1	4	1	0	0	0	0	0	0
Jun 10	0	1	4	1	0	0	0	0	0	0
Jul 10	0	1	3	0	0	0	0	0	0	0
Aug 10	0	1	5	1	0	0	0	0	0	0

**Remark:** Phenological phases including leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), leaf abscission (LA), flower bud burst (FB), flowers maturation (FM), flower fading (FF), young fruits (YF), mature fruit (MF), and ripe fruit (RF).



**Figure 13** Leaf phenology of *Hydnocarpus ilicifolia*

During the investigated periods, fruit pheno-phases were rarely found in 4 deciduous species and disappear in 2 evergreen species. Vieira and da Silva (1977) suggested that 84% of flowers aborted before fertilization. It was agreed by Chapman *et al.* (1999), who stated that fruiting did not necessarily followed flowering events if pollination failed, or if young fruits were aborted or destroyed. Fruiting tended to peak when the first half of rainy season was ending and short dry season occurred before the second half of rainy season began. Chapman *et al.* (1999) also found fruit phenology in the transitional periods of the first rainy and dry seasons at Kanyawara in Uganda. Thus, it might be stated that the beginning of the dry season was a time when energy became readily available to the tree in order to permit the build-up of the assimilative need for fruiting (Chapman *et al.*, 1999).

### 3. Outside bark diameter investigation

In order to investigate wood formative periodicity, outside bark diameter at breast height (130 cm) of 6 selected tree species were monthly measured and described below. Not only directly read of outside bark diameter increment, but standardized values of outside bark diameter increments were also calculated. Both of directly read and standardized data exhibited growth variations with phases of shrinkage and fast increment. The standardization was the application of time series analysis which normalized tree growth in different age class to the comparable level. In this case, z-score which was the value of the element minus by the population mean and divided by the standard deviation were calculated as standardized tree growth. If a z-score was positive or negative, it could interpret that directly read data was above (greater than) or below (less than) the mean, respectively. Z-score formula was shown as below.

$$Z = \frac{X - \bar{X}}{SD} \dots\dots\dots(4)$$

where  $X$  was the measurement of monthly outside bark diameter,  $\bar{X}$  was the mean of the measurement and  $SD$  was the standard deviation of the measurement.

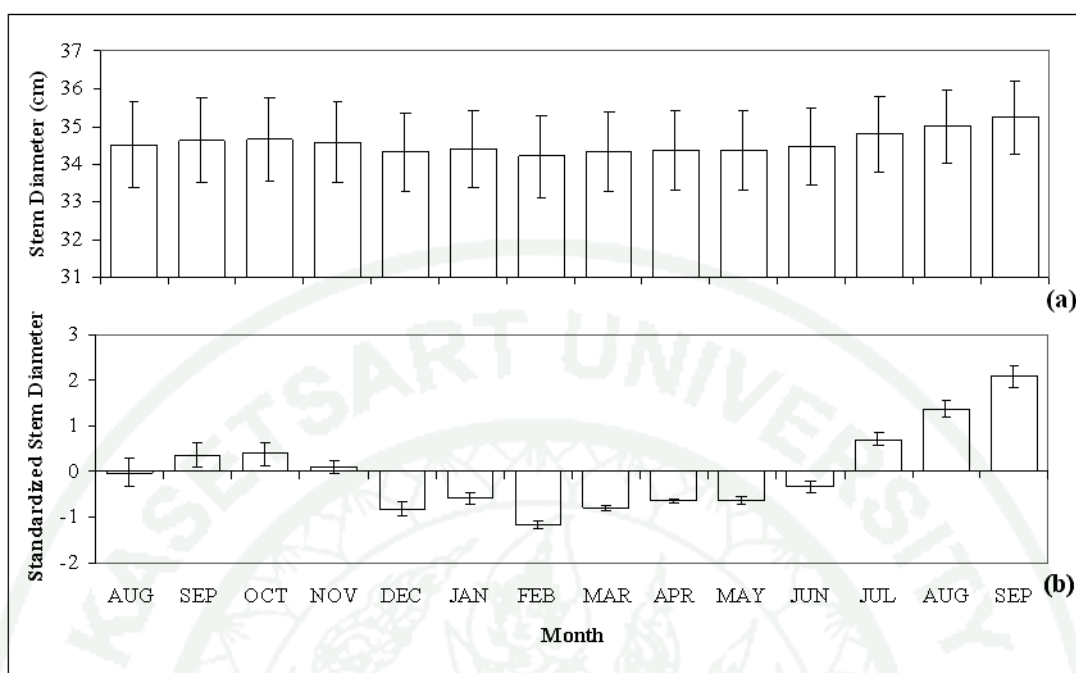
In this section, outside bark diameter of *T. grandis* was firstly explained followed by *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.

#### 3.1 *Tectona grandis* L.f.

According to the cumulative diameter data of six *T. grandis* measured using manual band dendrometers from August 2009 to September 2010, monthly outside bark diameter variations and standardized growth profile, resulting from the dendrometer scale movement and the average of z-scores of all teak trees, were shown in Table 13 and Figure 14.

**Table 13** Outside bark diameter increment data of *Tectona grandis* measured by using band dendrometers.

Month	Cumulative outside bark diameter (cm)							Standardized outside bark diameter						
	TG04	TG05	TG06	TG07	TG08	TG09	MEAN	TG04	TG05	TG06	TG07	TG08	TG09	MEAN
Aug 2009	33.94	40.02	33.15	33.25	34.04	32.67	34.51	0.59	1.17	-0.59	-0.54	-0.06	-0.68	-0.02
Sep 2009	33.99	40.10	33.29	33.40	34.14	32.88	34.63	0.80	1.50	-0.25	-0.07	0.31	-0.16	0.36
Oct 2009	34.01	40.07	33.35	33.41	34.16	32.87	34.65	0.89	1.38	-0.10	-0.03	0.39	-0.19	0.39
Nov 2009	33.95	39.79	33.29	33.39	34.15	32.85	34.57	0.63	0.21	-0.25	-0.10	0.35	-0.24	0.10
Dec 2009	33.52	39.43	33.11	33.30	33.90	32.65	34.32	-1.20	-1.29	-0.68	-0.38	-0.58	-0.73	-0.81
Jan 2010	33.61	39.48	33.31	33.29	33.91	32.76	34.39	-0.81	-1.08	-0.20	-0.41	-0.55	-0.46	-0.59
Feb 2010	33.45	39.48	33.02	33.06	33.75	32.47	34.21	-1.49	-1.08	-0.90	-1.14	-1.14	-1.18	-1.16
Mar 2010	33.58	39.57	33.09	33.16	33.81	32.68	34.32	-0.94	-0.71	-0.73	-0.83	-0.92	-0.66	-0.80
Apr 2010	33.66	39.55	33.15	33.19	33.87	32.75	34.36	-0.60	-0.79	-0.59	-0.73	-0.70	-0.48	-0.65
May 2010	33.62	39.63	33.12	33.24	33.79	32.81	34.37	-0.77	-0.46	-0.66	-0.57	-0.99	-0.34	-0.63
Jun 2010	33.69	39.57	33.34	33.36	33.92	32.95	34.47	-0.47	-0.71	-0.13	-0.19	-0.51	0.01	-0.33
Jul 2010	33.94	39.77	33.74	33.72	34.22	33.39	34.80	0.59	0.13	0.84	0.95	0.61	1.11	0.70
Aug 2010	34.06	39.89	34.14	33.92	34.43	33.60	35.01	1.10	0.63	1.80	1.58	1.40	1.63	1.36
Sep 2010	34.20	40.00	34.40	34.20	34.70	33.90	35.23	1.69	1.09	2.43	2.47	2.40	2.37	2.08
Total														
Increment	0.26	-0.02	1.25	0.95	0.66	1.23	0.72	-	-	-	-	-	-	-



**Figure 14** Cumulative increment of outside bark diameters in *Tectona grandis* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

In December 2009 to June 2010, teak diameters read from band dendrometer scales were lower than the value at the started point which may due to bark drying and shrinking. The lowest point of the shrinkage occurred in February 2010 and gently increased to June 2010. Outside bark diameter rapidly increased from July 2010 toward September 2010. The cumulative diameters of all teak trees were average and exhibited the increment for 0.72 cm/year.

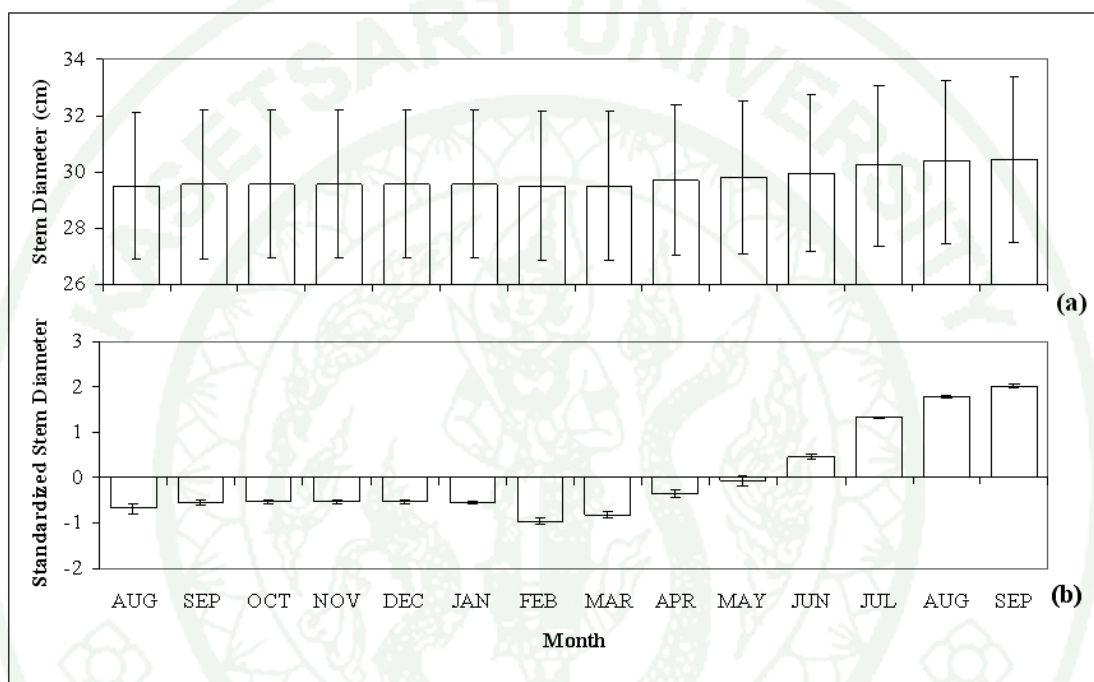
### 3.2 *Azelia xylocarpa* (Kurz) Craib.

Outside bark diameters of five *A. xylocarpa* directly measured using band dendrometers from August 2009 - September 2010 and their standardized values, resulting from the average of z-scores, were shown in Table 14 and Figure 15.

**Table 14** Outside bark diameter increment data of *Azelaia xylocarpa* measured by using band dendrometers.

Month	Cumulative outside bark diameter (cm)						Standardized outside bark diameter					
	AX02	AX03	AX04	AX05	AX06	MEAN	AX02	AX03	AX04	AX05	AX06	MEAN
Aug 09	33.98	35.70	30.76	24.67	22.38	29.50	-0.83	-1.01	-0.47	-0.49	-0.57	-0.67
Sep 09	34.10	35.88	30.76	24.67	22.40	29.56	-0.62	-0.77	-0.47	-0.49	-0.44	-0.56
Oct 09	34.12	35.96	30.76	24.67	22.40	29.58	-0.59	-0.66	-0.47	-0.49	-0.44	-0.53
Nov 09	34.12	35.96	30.76	24.67	22.40	29.58	-0.59	-0.66	-0.47	-0.49	-0.44	-0.53
Dec 09	34.12	35.97	30.76	24.67	22.40	29.58	-0.59	-0.64	-0.47	-0.49	-0.44	-0.52
Jan 10	34.13	35.97	30.75	24.67	22.40	29.58	-0.57	-0.64	-0.58	-0.49	-0.44	-0.54
Feb 10	33.98	35.93	30.70	24.59	22.30	29.50	-0.83	-0.70	-1.11	-1.09	-1.07	-0.96
Mar 10	34.00	35.95	30.72	24.63	22.32	29.52	-0.80	-0.67	-0.90	-0.79	-0.94	-0.82
Apr 10	34.33	36.37	30.76	24.67	22.39	29.70	-0.22	-0.09	-0.47	-0.49	-0.50	-0.35
May 10	34.45	36.63	30.80	24.69	22.43	29.80	-0.01	0.26	-0.04	-0.33	-0.25	-0.07
Jun 10	34.76	36.88	30.83	24.79	22.53	29.96	0.53	0.61	0.28	0.42	0.37	0.44
Jul 10	35.22	37.44	30.92	24.91	22.68	30.23	1.33	1.38	1.25	1.33	1.31	1.32
Aug 10	35.47	37.68	30.97	24.98	22.76	30.37	1.77	1.71	1.79	1.86	1.81	1.79
Sep 10	35.60	37.80	31.00	25.00	22.80	30.44	2.00	1.87	2.11	2.01	2.06	2.01
Total Increment	1.62	2.10	0.24	0.33	0.42	0.94	-	-	-	-	-	-

Since September 2009, the installed dendrometer scales were not changed for 5 months. Band dendrometers were shrinkage in February - March 2010 which may due to bark drying and shrinking and rapidly increased from April 2010 toward September 2010. The cumulative diameters of all *A. xylocarpa* were monthly average and exhibited the increment for 0.94 cm/year as shown in Table 14.



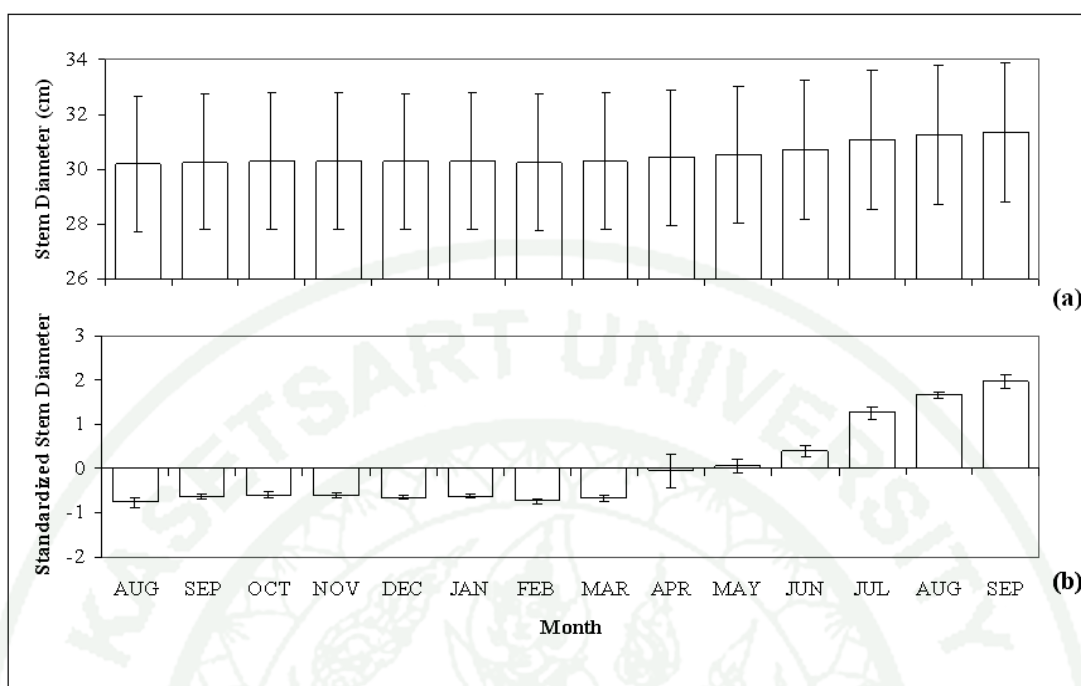
**Figure 15** Cumulative increment of outside bark diameters in *Afzelia xylocarpa* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

### 3.3 *Melia azedarach* L.

The installed band dendrometers on six *M. azedarach* illustrated the fluctuation of outside bark diameters in August 2009 - September 2010. The average of diameter increments was 1.18 cm/year (Table 15). Both of directly read and standardized data exhibited growth variations with phases of slow increment in September - October 2009 and shrinkage in December 2009 - February 2010. Later, the fast increment occurred until the end of September 2010 (Figure 16).

**Table 15** Outside bark diameter increment data of *Melia azedarach* measured by using band dendrometers.

Month	Cumulative outside bark diameter (cm)						Standardized outside bark diameter							
	MA01	MA02	MA03	MA04	MA05	MA06	MEAN	MA01	MA02	MA03	MA04	MA05	MA06	MEAN
Aug 09	29.45	30.80	40.33	31.13	27.92	21.58	30.20	-0.93	-0.63	-0.75	-1.08	-0.43	-0.76	-0.77
Sep 09	29.57	30.79	40.35	31.38	27.93	21.58	30.27	-0.73	-0.65	-0.69	-0.63	-0.41	-0.76	-0.65
Oct 09	29.61	30.78	40.34	31.47	27.97	21.58	30.29	-0.66	-0.67	-0.72	-0.47	-0.30	-0.76	-0.60
Nov 09	29.61	30.78	40.34	31.46	27.96	21.58	30.29	-0.66	-0.67	-0.72	-0.49	-0.33	-0.76	-0.61
Dec 09	29.61	30.76	40.32	31.43	27.91	21.58	30.27	-0.66	-0.71	-0.78	-0.54	-0.46	-0.76	-0.65
Jan 10	29.61	30.78	40.37	31.43	27.90	21.58	30.28	-0.66	-0.67	-0.63	-0.54	-0.49	-0.76	-0.62
Feb 10	29.62	30.71	40.35	31.38	27.74	21.58	30.23	-0.64	-0.81	-0.69	-0.63	-0.91	-0.76	-0.74
Mar 10	29.76	30.78	40.35	31.41	27.76	21.57	30.27	-0.41	-0.67	-0.69	-0.57	-0.85	-0.84	-0.67
Apr 10	29.80	30.97	40.50	31.41	27.92	21.91	30.42	-0.34	-0.31	-0.22	-0.57	-0.43	1.65	-0.04
May 10	30.04	31.18	40.62	31.76	27.89	21.75	30.54	0.06	0.09	0.16	0.05	-0.51	0.48	0.06
Jun 10	30.33	31.45	40.79	31.96	28.06	21.71	30.72	0.55	0.61	0.70	0.41	-0.07	0.19	0.40
Jul 10	30.79	31.91	41.12	32.35	28.47	21.81	31.08	1.32	1.49	1.74	1.11	1.00	0.92	1.26
Aug 10	31.04	32.05	41.08	32.66	28.78	21.87	31.25	1.74	1.76	1.61	1.67	1.81	1.36	1.66
Sep 10	31.20	32.10	41.10	33.00	29.00	21.90	31.38	2.01	1.85	1.67	2.28	2.39	1.58	1.96
Total														
Increment	1.75	1.30	0.77	1.87	1.08	0.32	1.18	-	-	-	-	-	-	-



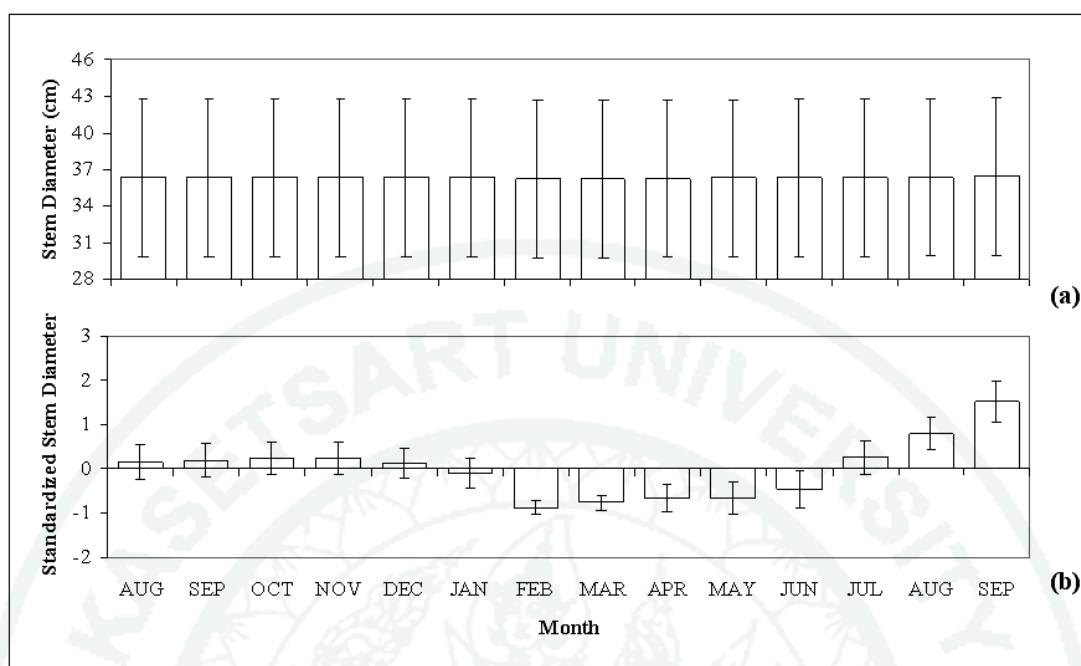
**Figure 16** Cumulative increment of outside bark diameters in *Melia azedarach* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

### 3.4 *Lagerstroemia duperreana* Pierre ex Gagnep

According to the cumulative outside bark diameters of six *L. duperreana* measured using band dendrometers from August 2009 - September 2010, directly read and standardized data were shown in Table 16 and Figure 17. Both of these data exhibited the small increment in September and October 2009. Outside bark diameters were not changed in November 2009, gently shrunk in December 2009 - January 2010, and rapidly shrunk in February 2010. Dendrometer scales were mildly increased from March-June 2010 and rapidly increased from July 2010 toward September 2010. The cumulative diameters of these 6 trees were average and exhibited the increment for 0.12 cm/year.

**Table 16** Outside bark diameter increment data of *Lagerstroemia duperreana* measured by using band dendrometers.

Month	Cumulative outside bark diameter (cm)						Standardized outside bark diameter								
	LD01	LD02	LD03	LD04	LD05	LD06	MEAN	LD01	LD02	LD03	LD04	LD05	LD06	MEAN	
Aug 09	21.22	11.57	48.74	48.37	43.14	44.81	36.31	0.91	-0.92	1.20	-0.68	0.76	-0.35	0.15	
Sep 09	21.22	11.60	48.74	48.37	43.14	44.81	36.31	0.91	-0.67	1.20	-0.68	0.76	-0.35	0.19	
Oct 09	21.22	11.60	48.74	48.37	43.14	44.83	36.32	0.91	-0.67	1.20	-0.68	0.76	-0.10	0.24	
Nov 09	21.22	11.60	48.74	48.37	43.14	44.83	36.32	0.91	-0.67	1.20	-0.68	0.76	-0.10	0.24	
Dec 09	21.22	11.60	48.71	48.36	43.14	44.83	36.31	0.91	-0.67	0.70	-0.87	0.76	-0.10	0.12	
Jan 10	21.22	11.60	48.66	48.36	43.14	44.80	36.30	0.91	-0.67	-0.13	-0.87	0.76	-0.47	-0.08	
Feb 10	21.12	11.56	48.61	48.36	43.12	44.79	36.26	-1.40	-1.01	-0.96	-0.87	-0.42	-0.59	-0.88	
Mar 10	21.12	11.62	48.65	48.37	43.11	44.78	36.28	-1.40	-0.51	-0.30	-0.68	-1.02	-0.72	-0.77	
Apr 10	21.13	11.69	48.58	48.42	43.11	44.78	36.29	-1.17	0.07	-1.46	0.27	-1.02	-0.72	-0.67	
May 10	21.13	11.71	48.59	48.42	43.10	44.80	36.29	-1.17	0.24	-1.29	0.27	-1.61	-0.47	-0.67	
Jun 10	21.14	11.75	48.60	48.44	43.10	44.82	36.31	-0.94	0.57	-1.13	0.65	-1.61	-0.23	-0.45	
Jul 10	21.17	11.85	48.63	48.47	43.12	44.86	36.35	-0.25	1.40	-0.63	1.22	-0.42	0.26	0.26	
Aug 10	21.20	11.89	48.66	48.50	43.13	44.90	36.38	0.45	1.73	-0.13	1.79	0.17	0.75	0.79	
Sep 10	21.20	11.90	48.70	48.50	43.15	45.10	36.43	0.45	1.81	0.53	1.79	1.36	3.20	1.52	
Total															
Increment	-0.02	0.33	-0.04	0.13	0.01	0.29	0.12	-	-	-	-	-	-	-	-



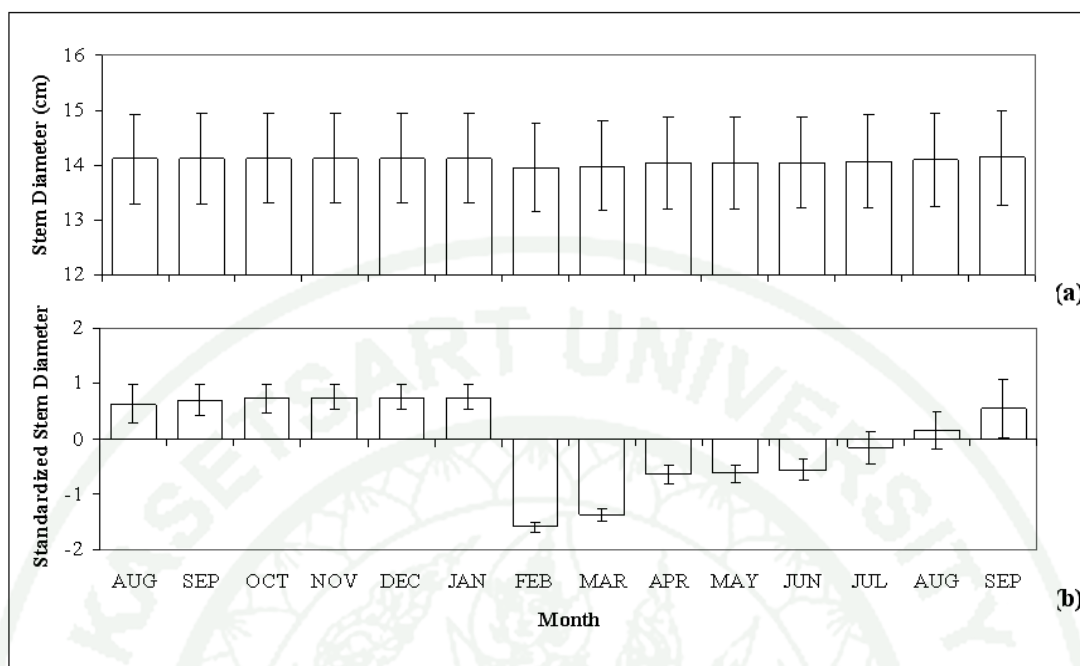
**Figure 17** Cumulative increment of outside bark diameters in *Lagerstroemia duperreana* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

### 3.5 *Aglaiia odoratissima* Blume

Monthly diameter variations and standardized z-score profile of 5 *A. odoratissima* from September 2009 - October 2010 were shown in Table 17 and Figure 18. During the investigated periods, the scales of all installed band dendrometers were not changed for 5 months in September 2009 to January 2010, except *A. odoratissima* coded AO01 which cumulative stem increment mildly increased for 0.07 mm. Outside bark diameters rapidly shrank in February 2010 and gently increased in March - April 2010, unchanged in May-June 2010, and gently increase in July-September 2010. The cumulative diameters of all *A. odoratissima* were averaged and exhibited the increment for 0.02 cm/year (Table 17).

**Table 17** Outside bark diameter increment data of *Aglaia odoratissima* measured by using band dendrometers.

Month	Cumulative outside bark diameter (cm)						Standardized outside bark diameter					
	AO01	AO02	AO03	AO05	AO06	MEAN	AO01	AO02	AO03	AO05	AO06	MEAN
Aug 09	16.35	14.17	15.43	12.17	12.46	14.12	-0.75	0.78	1.01	1.09	1.00	0.62
Sep 09	16.39	14.17	15.43	12.17	12.46	14.12	-0.41	0.78	1.01	1.09	1.00	0.69
Oct 09	16.41	14.17	15.43	12.17	12.46	14.13	-0.23	0.78	1.01	1.09	1.00	0.73
Nov 09	16.42	14.17	15.43	12.17	12.46	14.13	-0.15	0.78	1.01	1.09	1.00	0.75
Dec 09	16.42	14.17	15.43	12.17	12.46	14.13	-0.15	0.78	1.01	1.09	1.00	0.75
Jan 10	16.42	14.17	15.43	12.17	12.46	14.13	-0.15	0.78	1.01	1.09	1.00	0.75
Feb 10	16.24	14.01	15.18	12.06	12.30	13.96	-1.70	-1.71	-1.73	-1.30	-1.55	-1.60
Mar 10	16.31	14.02	15.19	12.07	12.30	13.98	-1.10	-1.55	-1.62	-1.09	-1.55	-1.38
Apr 10	16.43	14.06	15.30	12.08	12.34	14.04	-0.06	-0.93	-0.42	-0.87	-0.91	-0.64
May 10	16.43	14.06	15.29	12.08	12.35	14.04	-0.06	-0.93	-0.52	-0.87	-0.75	-0.63
Jun 10	16.45	14.07	15.29	12.08	12.35	14.05	0.11	-0.78	-0.52	-0.87	-0.75	-0.56
Jul 10	16.55	14.10	15.30	12.09	12.37	14.08	0.97	-0.31	-0.42	-0.65	-0.43	-0.17
Aug 10	16.60	14.14	15.30	12.10	12.39	14.11	1.40	0.31	-0.42	-0.43	-0.11	0.15
Sep 10	16.70	14.20	15.30	12.10	12.40	14.14	2.26	1.24	-0.42	-0.43	0.05	0.54
Total Increment	0.35	0.03	-0.13	-0.07	-0.06	0.02	-	-	-	-	-	-



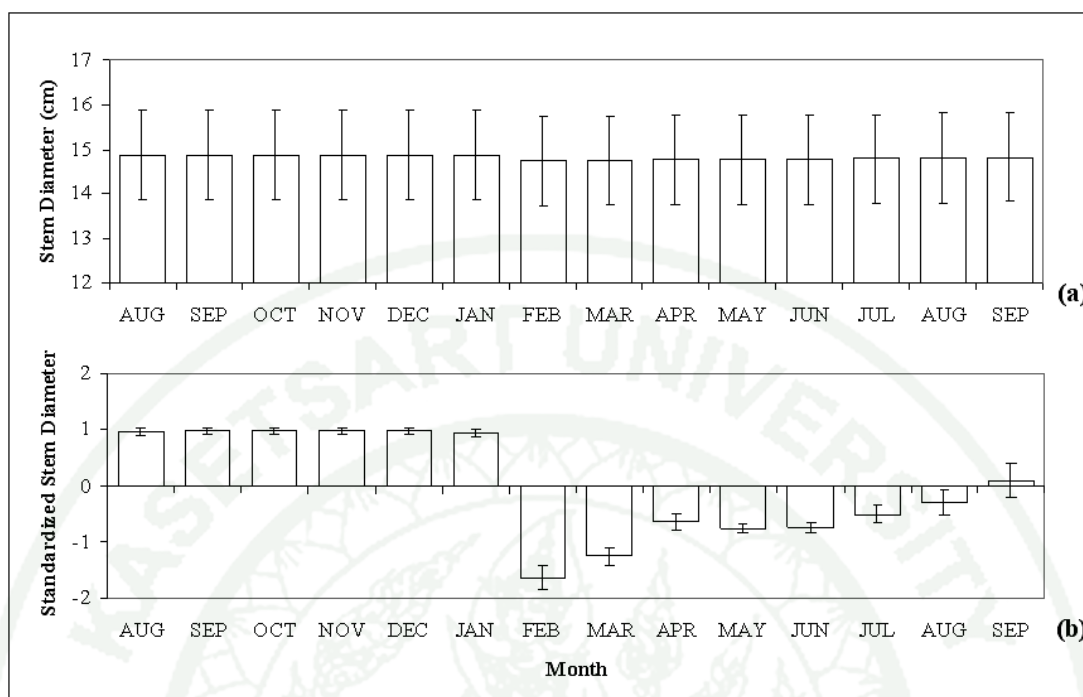
**Figure 18** Cumulative increment of outside bark diameters in *Aglaia odoratissima* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

### 3.6 *Hydnocarpus ilicifolia* King

According to the cumulative outside bark diameter of six *H. ilicifolia* as shown in Table 18 and Figure 19, both of directly read and standardized increment data exhibited dormant growth from September 2009 till January 2010. Outside bark diameters rapidly shrank in February 2010 and speedily increased in March-April 2010. Diameters mildly dropped in May 2010 and gently increased until September 2010. However, the cumulative diameters of *H. ilicifolius* at the end of the investigated period were lower than the baseline data recorded in September 2009 for 0.05 cm as shown in Table 18.

**Table 18** Outside bark diameter increment data of *Hydnocarpus ilicifolia* measured by using manual dendrometer bands.

Month	Cumulative outside bark diameter (cm)						Standardized outside bark diameter							
	HI01	HI02	HI03	HI04	HI05	HI06	MEAN	HI01	HI02	HI03	HI04	HI05	HI06	MEAN
Aug 09	18.14	15.58	13.47	17.02	13.22	11.74	14.86	0.96	0.73	0.92	1.18	1.02	0.95	0.96
Sep 09	18.14	15.58	13.48	17.01	13.22	11.74	14.86	0.96	0.73	1.14	1.04	1.02	0.95	0.97
Oct 09	18.14	15.58	13.48	17.01	13.22	11.74	14.86	0.96	0.73	1.14	1.04	1.02	0.95	0.97
Nov 09	18.14	15.58	13.48	17.01	13.22	11.74	14.86	0.96	0.73	1.14	1.04	1.02	0.95	0.97
Dec 09	18.14	15.58	13.48	17.01	13.22	11.74	14.86	0.96	0.73	1.14	1.04	1.02	0.95	0.97
Jan 10	18.13	15.58	13.48	17.01	13.22	11.74	14.86	0.70	0.73	1.14	1.04	1.02	0.95	0.93
Feb 10	18.01	15.48	13.38	16.82	13.14	11.61	14.74	-2.40	-1.65	-1.11	-1.53	-1.21	-1.89	-1.63
Mar 10	18.06	15.48	13.40	16.84	13.14	11.62	14.76	-1.11	-1.65	-0.66	-1.26	-1.21	-1.67	-1.26
Apr 10	18.10	15.51	13.40	16.88	13.15	11.67	14.79	-0.07	-0.94	-0.66	-0.72	-0.94	-0.58	-0.65
May 10	18.08	15.51	13.39	16.88	13.15	11.67	14.78	-0.59	-0.94	-0.88	-0.72	-0.94	-0.58	-0.77
Jun 10	18.08	15.51	13.39	16.89	13.15	11.67	14.78	-0.59	-0.94	-0.88	-0.58	-0.94	-0.58	-0.75
Jul 10	18.09	15.55	13.39	16.89	13.15	11.68	14.79	-0.33	0.02	-0.88	-0.58	-0.94	-0.36	-0.51
Aug 10	18.09	15.57	13.39	16.89	13.17	11.69	14.80	-0.33	0.49	-0.88	-0.58	-0.38	-0.14	-0.30
Sep 10	18.10	15.60	13.40	16.90	13.20	11.70	14.82	-0.07	1.21	-0.66	-0.44	0.46	0.08	0.09
Total														
Increment	-0.04	0.02	-0.07	-0.12	-0.02	-0.04	-0.05	-	-	-	-	-	-	-



**Figure 19** Cumulative increment of outside bark diameters in *Hydnocarpus ilicifolia* and standard error bars measured by using band dendrometers with the standard error of the mean (SEM): (a) cumulative outside bark diameter increment; (b) standardized cumulative outside bark diameter increment.

The increments of outside bark diameters manually recorded by dendrometer bands continuously declined from the installed period in the second half of rainy season to the end of dry season (September 2009 - February 2010). In rainy season, outside bark diameters rapidly increased from March 2010 until the end of the investigated period in September 2010 as similar as the periods of monthly wood formation and annual ring investigations. However, from the studies of outside bark diameter increments in 6 tree species, patterns of outside bark diameter variation were divided to 2 types. The first type of deciduous tree species including *T. grandis*, *A. xylocarpa*, *M. azedarach* and *L. duperreana* illustrated the fast increment at the beginning of the rainy season and slow increment at the end of the rainy season. Diameter shrinkage of these deciduous trees occurred in the dry season at the end and the beginning of the year. The second type was the evergreen tree species – *A. odoratissima* and *H. ilicifolius* – showed the fast increment at the beginning of the

rainy season as similar as deciduous tree species but illustrated the stable outside bark diameter at the end of rainy season to the dry season at the end and the beginning of the year. The extreme shrinkage of outside bark diameter occurred for one month in February before rainfall coming in March.

All selected deciduous and evergreen species at Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station (WKNFSPS) illustrated the extreme shrinkage of outside bark diameter in February before diameter increment gently increased in March. Therefore, the suitable period of band dendrometer installation for tree growth measurement at SERS and WKNFSPS should be the transition of dry and wet periods at the end of February.

Pelissier and Pascal (2000) stated that outside bark diameter variations originated from hydrostatic stem flexibility which depended on rainfall through the soil moisture status and the degree of turgidity or water stress of the tree. It was similar to the study of radial stem variations of several tree species relating water status including precipitation and vapor pressure deficit (Volland-Voigt *et al.*, 2011; Oberhuber and Gruber, 2010; Brauning and Burchardt, 2005; Lisi *et al.*, 2008).

As dendrometer bands were installed over bark in order to continued measurement of tree growth, it was important to understand the contribution of changes in phloem and bark width to total outside bark diameter increment. It had been found by a number of authors that most of the shrinkage in stems occurred in the cambial zone, bark and phloem, while variation in the xylem cylinder was relatively small (Dobbs and Scott, 1971; Molz and Klepper, 1973; Brough *et al.*, 1986; Zweifel *et al.*, 2000; Daudet *et al.*, 2005). In *Eucalyptus nitens*, approximately 40% of variation in outside bark diameter had been attributed to shrinkage in tissue external to the xylem including both bark and phloem (Downes *et al.*, 1999). This must be taken in to consideration when interpreting dendrometer data.

#### 4. Periodic wood and annual ring formations

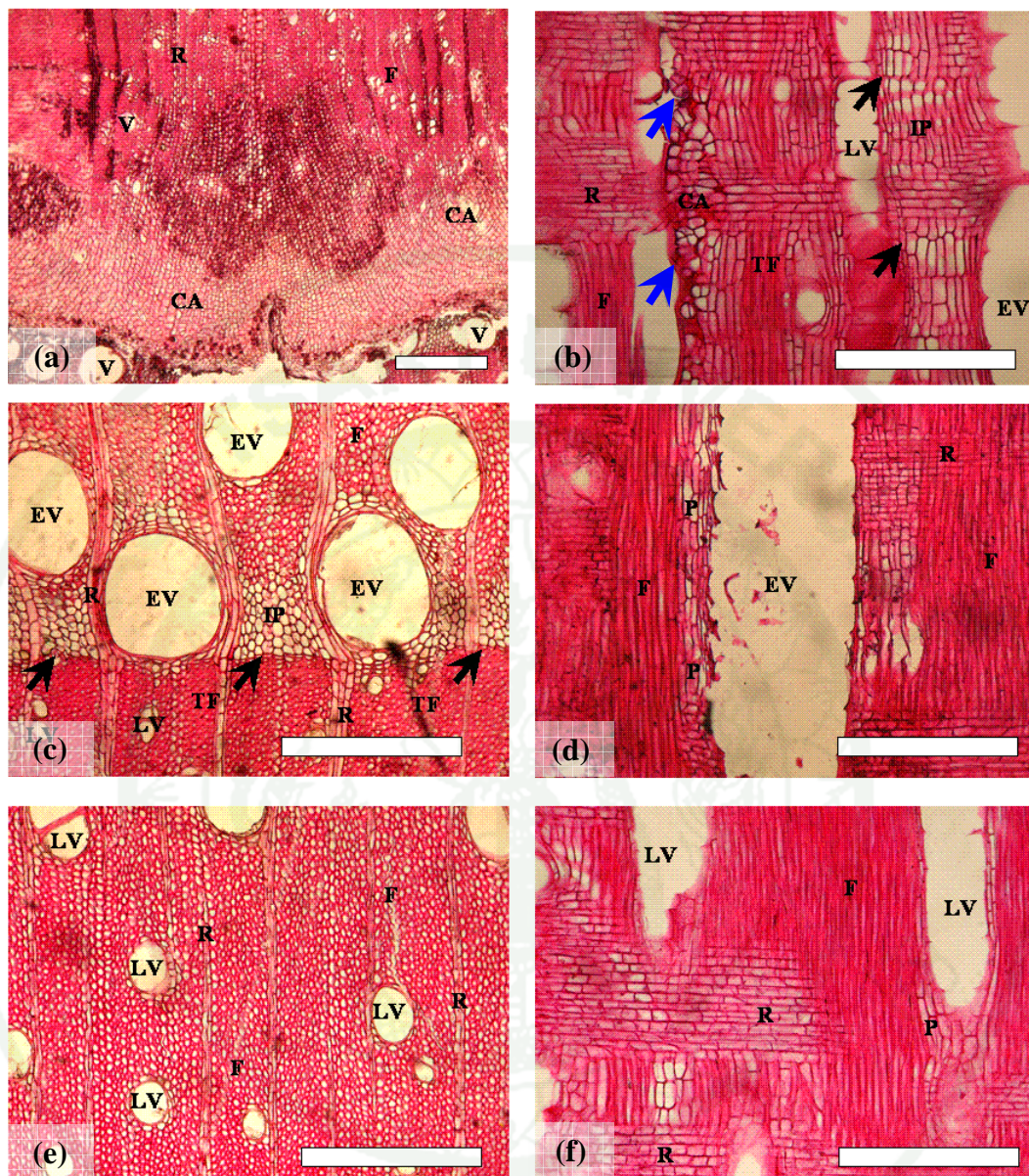
Not only the measurement of outside bark diameter as described in the previous section but periodic wood increment and annual ring formation were also investigated to explain wood formative periodicity and finding the marked point of annual ring boundaries. In this section, the explanations of monthly wood increments and annual ring characteristics were separately explained in each species. *T. grandis* was firstly explained followed by *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.

##### 4.1 *Tectona grandis* L.f.

Cambial cells of six mature teak trees (*Tectona grandis*), coded TG04-TG09, were marked once a month for a year. Teak could be defined as distinct annual ring species due to the characteristics of semi-ring porous. Pores were solitary and multiple of which diameters gradually changed from large to narrow in the progression from earlywood (Figure 20c) to latewood (Figure 20e). In each normal annual ring, initial banded parenchyma was found associated with large vessels at the beginning of growing season (Figure 20c and 20d). Callus cell formed after cambial cells were marked as shown in Figure 20a and 20b. After cambial marking at the beginning of September 2009, monthly wood increments gradually decreased and small vessels were formed continuously until the end of November 2009 (Table 19, Figure 21 and 22). Stop producing tissue mean stop growing which would be the end of annual ring formation (Figure 21d-21g). Compared with the total growth during the observed intervals (4.97 mm), wood increment in September - November was only 0.91 mm (16.75%), and average vessel diameter was 0.094 mm. In December 2009, all trees were dormancy, except TG05 and TG07 which wood increment were 0.1 and 0.5 mm, respectively. In the first 3 months of 2010 (January - March), all trees were still continuous dormancy because of the wood increments of five trees were not changed, except a tree coded TG05 which wood increment associated with initial banded parenchyma initiated in March 2010 for 0.15 mm. Initial banded parenchyma in other teak trees formed in April 2010 associated with the largest vessels of 0.194

mm diameter, approximately. Appearing the large vessel explained that the dormancy had gone and growth had started as the beginning of annual ring formation around April 2010. Wood formation in most of teak trees which started in April and completed in November (Table 19 and Figure 22) indicated growing duration for 8 months in teak trees at WNKFPS. However, the period of annual ring formation in teak were varied upon trees even they stood growing near each other in a small area. During April 2010 to the end of September 2010, rates of monthly wood increment were continuously increased from 0.15 mm/month to 1.38 mm/month as shown in Table 19 and Figure 22. Figure 22 also illustrated the fluctuations of directly measured and relative monthly wood increments of teaks during investigated periods. In this case, relative monthly wood increments were calculated as the ratios of monthly and total wood increment.

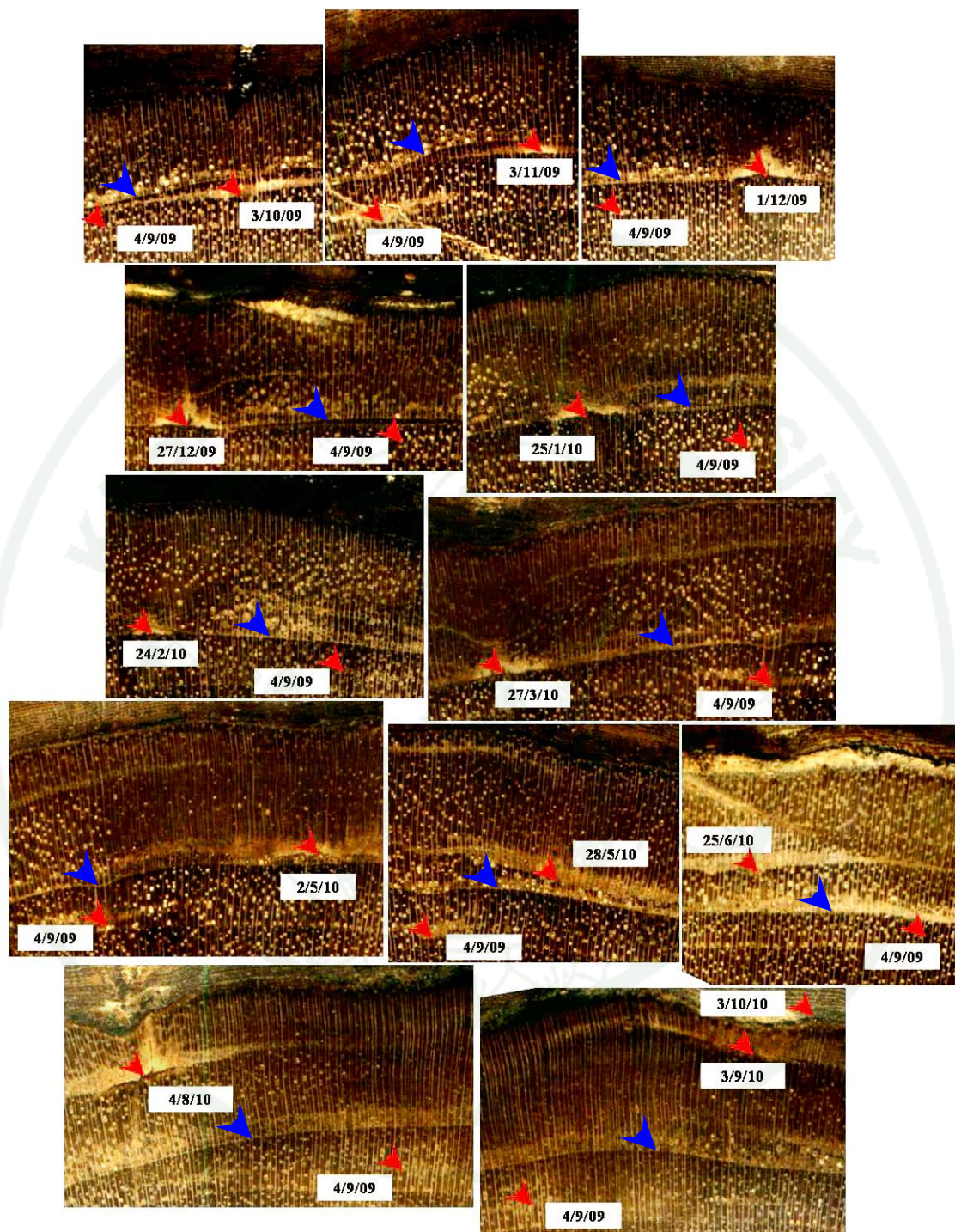
Cambial markings were not only made referable points on wood stems, but also generated anomalous cells to cure and protect injured cells. For low magnified scanner or stereomicroscope, these anomalous cells which were formed from the effect of cambial markings were looked similar to initial parenchyma at the beginning of each annual ring (Figure 21). However, the investigation of cell sizes and cell types from thin section could be used for callus cell (Figure 20a) and marginal parenchyma (Figure 20c) classification. The actual annual ring of teak was shown as blue arrow in Figure 21.



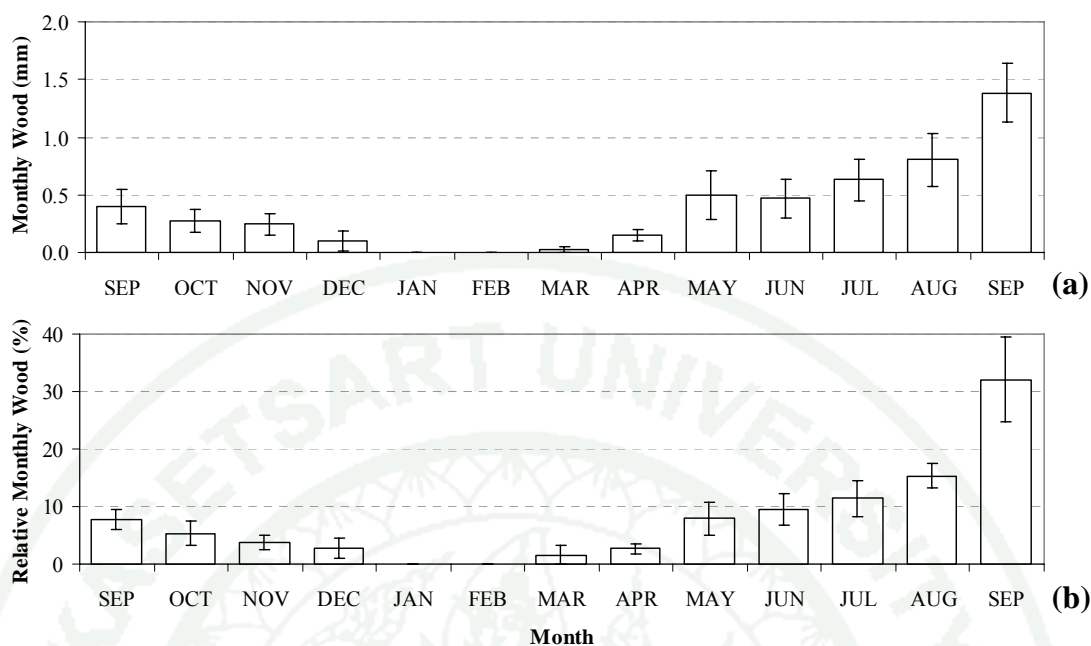
**Figure 20** Microscopic features of *Tectona grandis*: (a-b) callus cells (CA) from cambial marking; (c-d) initial banded parenchyma (IP) with large earlywood vessels (EV) at the beginning of growing season compared with small latewood vessel (LV) and dense thick wall fibers (TF); (e-f) latewood cell with small latewood vessels (LV). White bands indicated the length of 500  $\mu\text{m}$ . Black arrows indicated the beginning of annual ring formation and blue arrows indicated the callus cells caused from cambial marking. Figure 20a, 20c, 20e were cross-section and Figure 20b, 20d, 20f were radial section.

**Table 19** Measured and relative monthly wood increments of *Tectona grandis*. Dash box indicated the common periods of growth dormancy.

Marked Date	Measured monthly wood increment (mm)							Relative monthly wood increment						
	TG 04	TG 05	TG 06	TG 07	TG 08	TG 09	Mean	TG 04	TG 05	TG 06	TG 07	TG 08	TG 09	Mean
Mo.0: 4-6 Sep 09	First marking as the baseline of measurement													
Mo.1: 3-5 Oct 09	0.44	0.14	0.34	0.39	0.00	1.06	0.39	0.07	0.09	0.11	0.08	0.00	0.12	0.08
Mo.2: 3-5 Nov 09	0.55	0.00	0.42	0.03	0.19	0.45	0.27	0.09	0.00	0.13	0.01	0.04	0.05	0.05
Mo.3: 1-3 Dec 09	0.37	0.00	0.00	0.18	0.30	0.60	0.24	0.06	0.00	0.00	0.04	0.06	0.07	0.04
Mo.4: 27-29 Dec 09	0.00	0.10	0.00	0.50	0.00	0.00	0.10	0.00	0.06	0.00	0.10	0.00	0.00	0.03
Mo.5: 25-27 Jan 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.6: 24-26 Feb 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.7: 27-29 Mar 10	0.00	0.15	0.00	0.00	0.00	0.00	0.03	0.00	0.10	0.00	0.00	0.00	0.00	0.02
Mo.8: 2-4 May 10	0.20	0.00	0.17	0.00	0.20	0.30	0.15	0.03	0.00	0.06	0.00	0.04	0.03	0.03
Mo.9: 28-30 May 10	1.26	0.00	0.19	0.21	0.28	1.01	0.49	0.20	0.00	0.06	0.04	0.06	0.11	0.08
Mo.10: 25-26 Jun 10	0.02	0.06	0.61	0.40	0.62	1.12	0.47	0.00	0.04	0.19	0.08	0.13	0.12	0.09
Mo.11: 4-6 Aug 10	0.68	0.00	0.33	1.16	0.55	1.06	0.63	0.11	0.00	0.11	0.24	0.11	0.12	0.11
Mo.12: 3-5 Sep 10	0.68	0.15	0.68	0.65	0.79	1.87	0.80	0.11	0.09	0.21	0.13	0.16	0.21	0.15
Extraction: 3-5 Oct 10	2.08	1.00	0.40	1.32	1.97	1.53	1.38	0.33	0.62	0.13	0.27	0.40	0.17	0.32
TOTAL	6.29	1.61	3.15	4.85	4.90	9.00	4.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DBH (cm)	34.2	40.0	34.4	34.2	34.7	33.9	-	-	-	-	-	-	-	-



**Figure 21** Scanned images of cambial marked points on stem section in *Tectona grandis* (tree no. TG09). Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.



**Figure 22** Fluctuations of (a) measured and (b) relative monthly wood increments of *Tectona grandis* with the standard error of the mean (SEM).

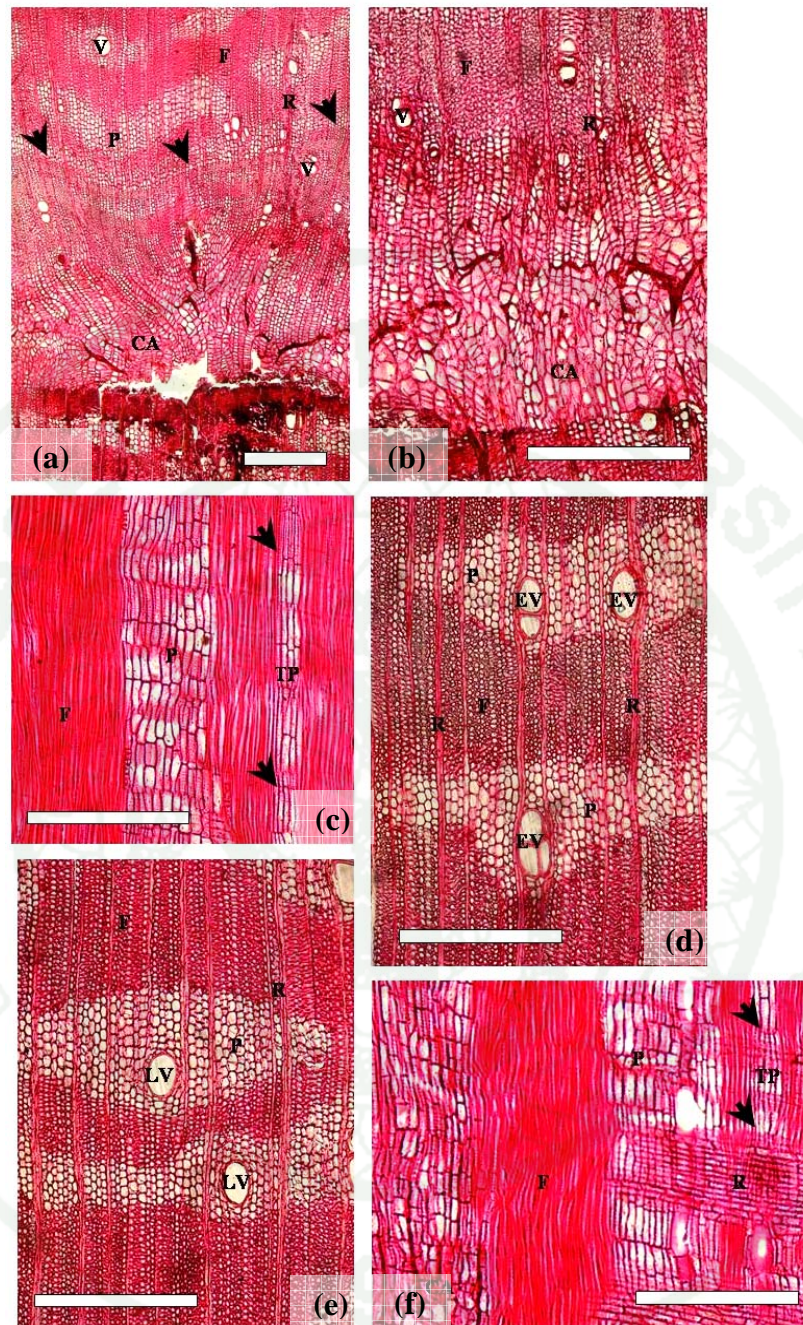
#### 4.2 *Azelia xylocarpa* (Kurz) Craib.

*Azelia xylocarpa*, which was known as a distinct growth ring species, was selected for five trees to study periodic wood and annual ring formation and coded as AF02 to AF06. Wood porosity was diffuse-ring porous with solitary and multiple pores associated with aliform and confluent parenchyma (Figure 23d and 23e). The thin line of terminal banded parenchyma mostly found in November 2009 (Figure 23a and 23c), while AF02 and AF06 were found terminal banded parenchyma in December and October 2009, respectively (Table 20). From monthly wood increment data in Figure 24-25 and Table 20, total wood increment was 13.88 mm while stop producing tissue in each tree was found in different month and varied in November 2009 to January 2010. Appearing the terminal banded parenchyma associated with the dormancy of wood increment indicated the end of growing season. The terminal banded parenchyma which was found one time each year could be used as the indicator of annual ring boundaries. Monthly wood increments gradually decreased from September 2009 till the end of January 2010, which cumulative wood increment

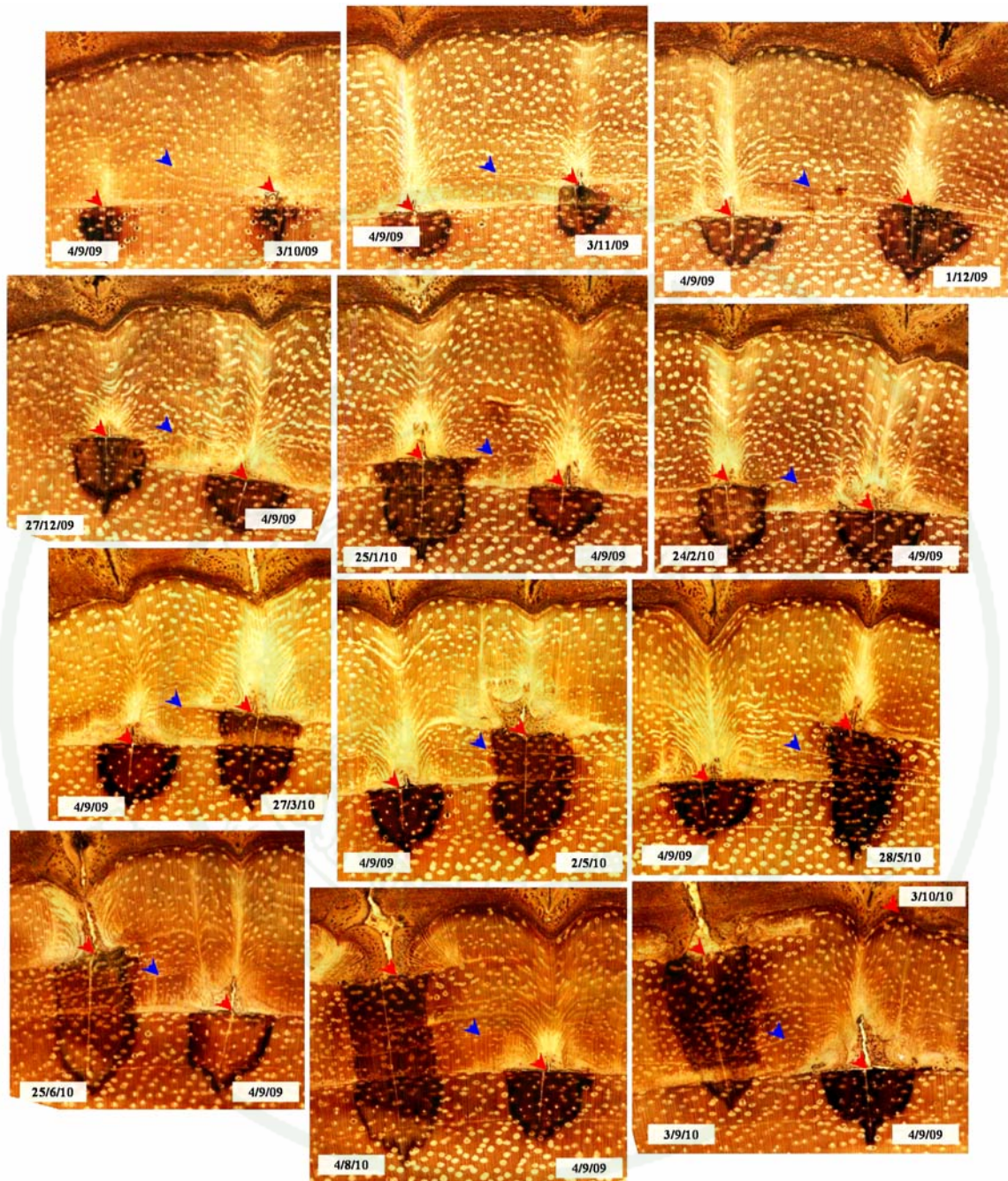
was only 2.64 mm. or 18.17% of total growth during the observed intervals (Table 20). Average vessel diameter in these intervals was 0.08 mm. Monthly wood increment was rapidly increasing in February 2010 for 0.68 mm. and suddenly declined in March 2010 for 0.19 mm. Monthly wood increments in April rapidly increased and gently decreased till June 2010 for 2.17, 1.33 and 1.14 mm., respectively. Average vessel diameter from February till June 2010 was 0.098 mm. The last 3 month of the investigated periods illustrated the highest growth rate for 2.18, 1.82 and 1.73 mm, respectively, while vessel diameter was similar to other periods (0.11 mm). The fluctuations of monthly wood increments during the investigated periods might be affected from environmental factors, while diffuse porous characteristic illustrated non-relationship between vessel sizes and environmental factors. Figure 25 illustrated the fluctuations of measured and relative monthly wood increments of *A. xylocarpa* during investigated periods. Cambial injuries also illustrated the formation of anomalous cells as similar as the study in teak. However, thin line of terminal banded parenchyma and anomalous cells from cambial marking effects were not similar and could be classified using both of low magnified stereomicroscope or ordinary scanner (Figure 24) and cell structure from compound microscope (Figure 23).

#### 4.3 *Melia azedarach* L.

Bastard Cedar (*M. azedarach* – coded MA01 to MA07), which was known as a distinct growth ring species, was chosen to studies periodic wood and annual ring formation. Wood porosity was semi-ring porous with solitary and multiple pores (Figure 26c and 26e). Vessel diameter gradually changed from large diameter earlywood vessel to narrow diameter latewood vessel in the progression from earlywood to latewood. Initial banded parenchyma and vasicentric parenchyma were found associated with large vessels at the beginning of the growing season (Figure 26c to 26e). Callus cell and banded parenchyma formed after cambial cells were marked as shown in figure 26a and 26b. Cambial marking was done during September 2009 till September 2010 and total wood increment was 15.57 mm (Table 21 and Figure 27-28).



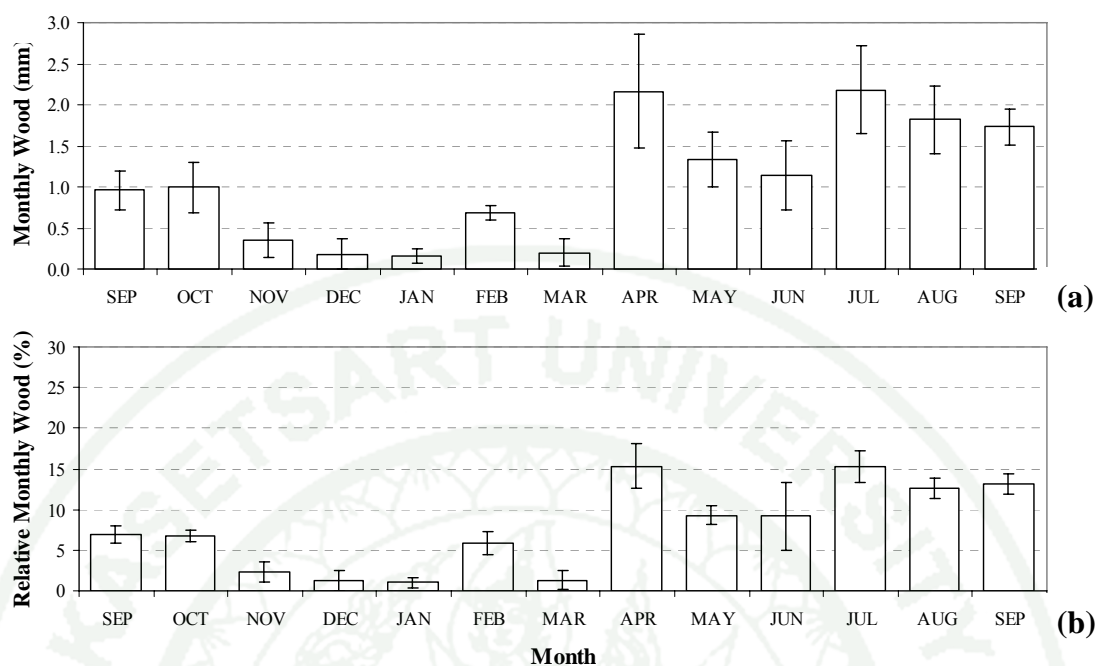
**Figure 23** Microscopic features of *Afzelia xylocarpa*: (a-b) callus cells from cambial marking: (c) terminal parenchyma (TP); (d) earwood vessel (EV) with paratracheal parenchyma (P); (e) latewood vessel (LV) with paratracheal parenchyma; (f) latewood fiber closing to the cambial marked point. F = fibers and R = ray cells. White bands indicated the length of 500  $\mu\text{m}$ . Black arrow head indicated the terminal parenchyma. Figure 23a, 23b, 23d, 23e were cross-section and Figure 23c, 23f were radial section.



**Figure 24** Scanned images of cambial marking points on stem section in *Afzelia xylocarpa*, tree no. AF02. Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.

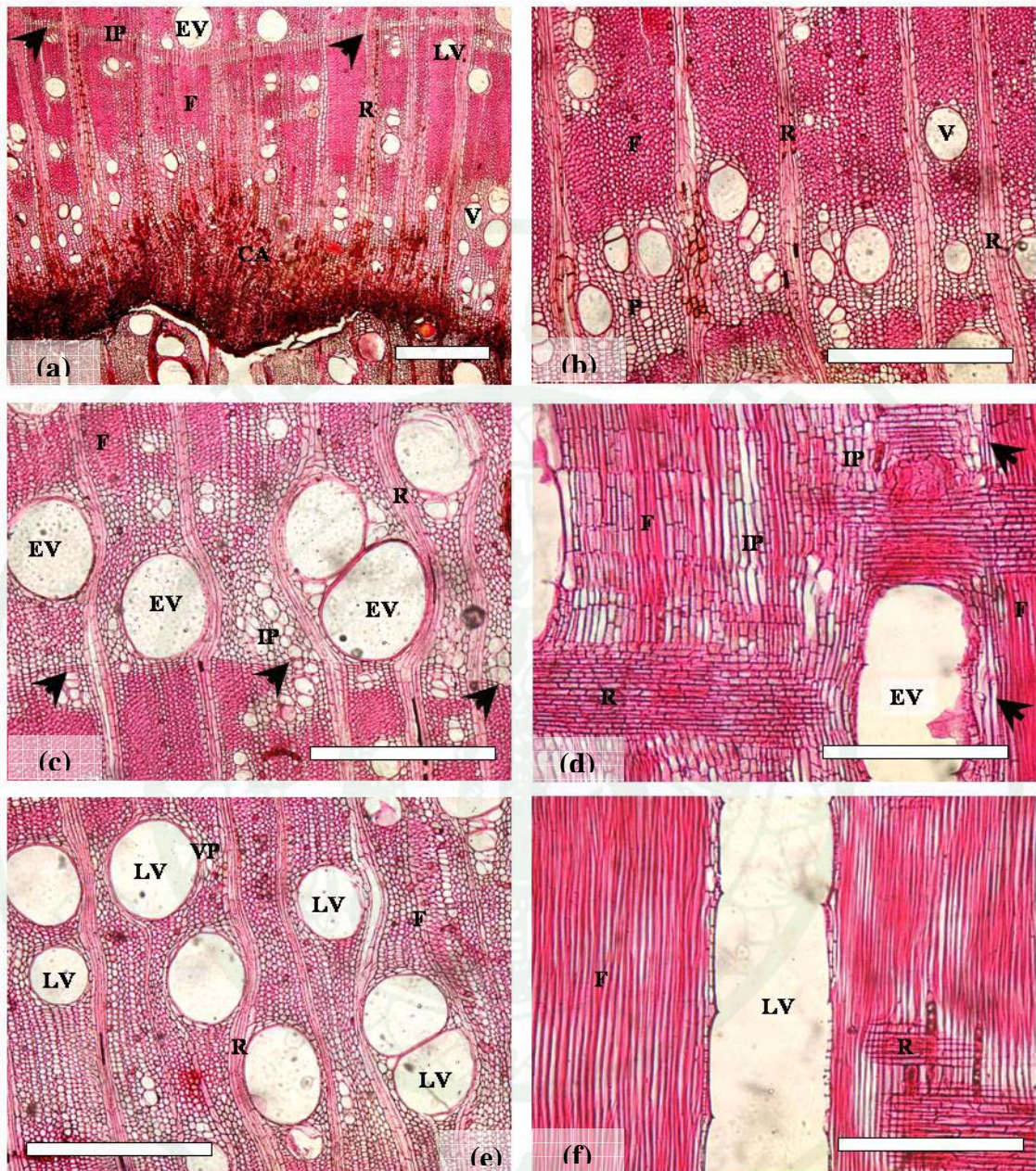
**Table 20** Measured and relative monthly wood increments of *Afzelia xylocarpa*. Dash box indicated the common periods of growth dormancy.

Marked Date	Measured monthly wood increment (mm)						Relative monthly wood increment					
	AF02	AF03	AF04	AF05	AF06	Mean	AF02	AF03	AF04	AF05	AF06	Mean
Mo.0: 4-6 Sep 09	0.98	1.87	0.49	0.79	0.65	0.96	0.07	0.08	0.04	0.09	0.07	0.07
Mo.1: 3-5 Oct 09	0.92	2.17	0.79	0.53	0.55	0.99	0.06	0.10	0.06	0.06	0.06	0.07
Mo.2: 3-5 Nov 09	0.04	1.14	0.12	0.45	0.00	0.35	0.00	0.05	0.01	0.05	0.00	0.02
Mo.3: 1-3 Dec 09	0.90	0.00	0.01	0.00	0.00	0.18	0.06	0.00	0.00	0.00	0.00	0.01
Mo.4: 27-29 Dec 09	0.00	0.26	0.45	0.05	0.00	0.15	0.00	0.01	0.03	0.01	0.00	0.01
Mo.5: 25-27 Jan 10	0.57	0.43	0.91	0.83	0.69	0.68	0.04	0.02	0.06	0.10	0.07	0.06
Mo.6: 24-26 Feb 10	0.00	0.11	0.85	0.00	0.00	0.19	0.00	0.01	0.06	0.00	0.00	0.01
Mo.7: 27-29 Mar 10	1.78	4.82	0.89	1.35	1.99	2.17	0.12	0.21	0.06	0.16	0.21	0.15
Mo.8: 2-4 May 10	1.10	2.45	1.68	0.86	0.56	1.33	0.08	0.11	0.12	0.10	0.06	0.09
Mo.9: 28-30 May 10	0.78	0.67	2.06	0.00	2.19	1.14	0.05	0.03	0.15	0.00	0.23	0.09
Mo.10: 25-26 Jun 10	2.88	3.87	1.80	1.49	0.86	2.18	0.20	0.17	0.13	0.18	0.09	0.15
Mo.11: 4-6 Aug 10	2.25	2.92	2.17	0.82	0.93	1.82	0.15	0.13	0.15	0.10	0.10	0.13
Mo.12: 3-5 Sep 10	2.34	2.04	1.82	1.29	1.17	1.73	0.16	0.09	0.13	0.15	0.12	0.13
Extraction: 3-5 Oct 10	14.54	22.76	14.05	8.46	9.57	13.88	1.00	1.00	1.00	1.00	1.00	1.00
TOTAL	35.6	37.8	31.0	25.0	22.8	-	-	-	-	-	-	-
DBH (cm)												



**Figure 25** Fluctuations of (a) measured and (b) relative monthly wood increments of *Afzelia xylocarpa* with the standard error of the mean (SEM).

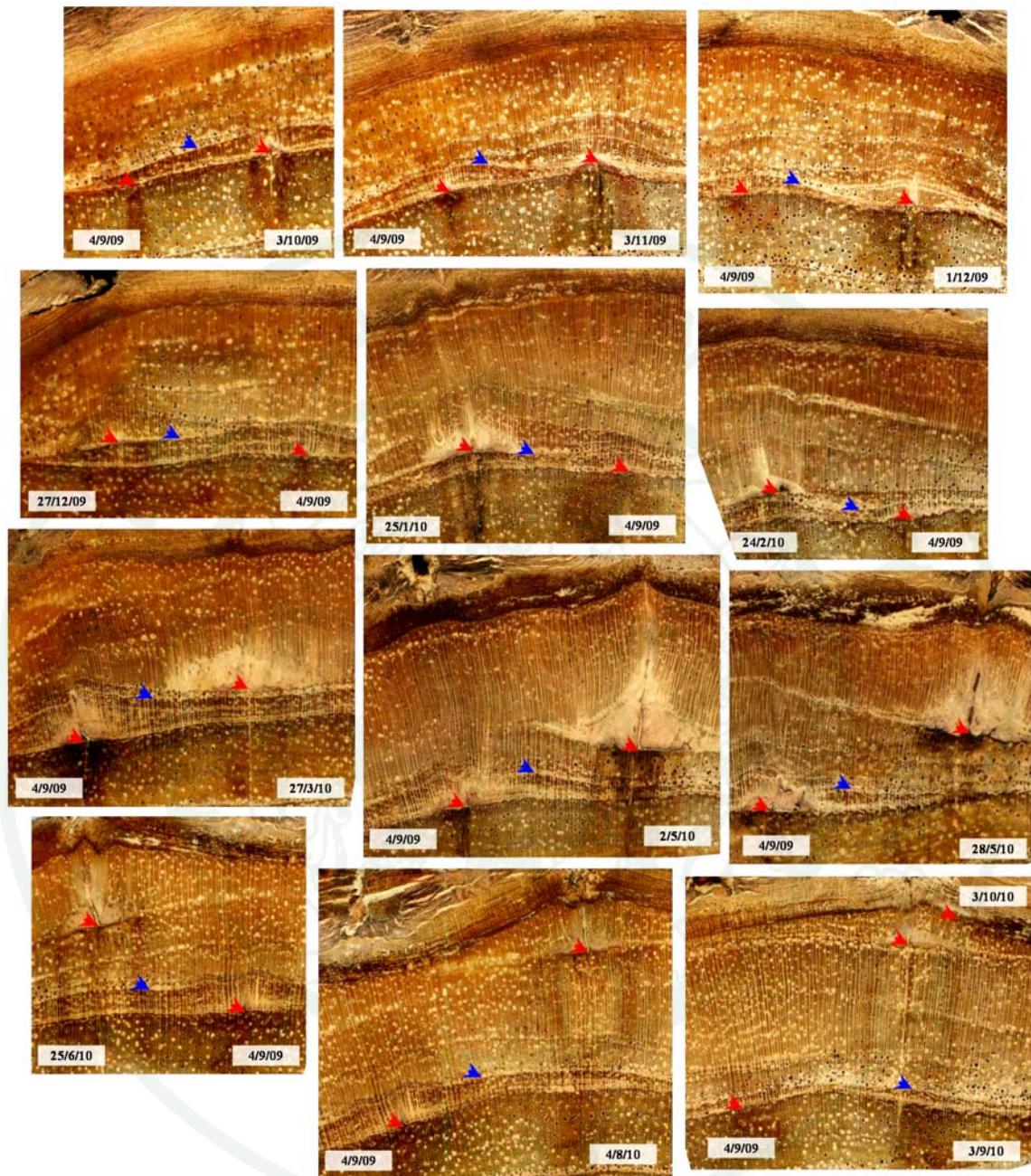
After marking at the beginning of September 2009, monthly wood increments of *M. azedarach* gradually decreased and small vessels were found until the end of November 2009 (Figure 26a) as similar as the narrow diameter vessel formation in latewood zone of teak. Wood increment in these 3 months was 3.55 mm (22.96% from total increment) and average vessel diameter was 0.12 mm. Stop producing tissue mean stop growing (wood increment seem to be unchanged) occurred for 2 months in December 2009-January 2010 and could be stated as the dormant period of *M. azedarach* as similar as *A. xylocarpa*. Wood increment was stimulated in February 2010 for 0.44 mm (3.68%) which was faster than teak for 1 month. In this month, initial banded parenchyma was found associated with large vessel diameters (0.23 mm) (Figure 26c). Appearing the large vessel explained that the dormancy was gone and growth had started as the beginning of annual ring formation in February 2010.



**Figure 26** Microscopic features of *Melia azedarach*: (a-b) callus cells (CA) and parenchyma (P) from cambial marking effect; (c-d) earlywood vessel (EV) associated with initial parenchyma (IP); (e-f) latewood vessel (LV) associated with vasicentric parenchyma (VP). F = fibers and R = ray cells. White bands indicated the length of 500  $\mu\text{m}$ . Black arrow head indicated the initial parenchyma. Figure 26a, 26b, 26c, 26e were cross-section and Figure 26d, 26f were radial section.

**Table 21** Measured and relative monthly wood increments of *Melia azedarach*. Dash box indicated the common periods of growth dormancy.

Marked Date	Measured monthly wood increment (mm)						Relative monthly wood increment								
	MA 01	MA 02	MA 03	MA 04	MA 05	MA 06	Mean	MA 01	MA 02	MA 03	MA 04	MA 05	MA 06	Mean	
Mo.0: 4-6 Sep 09	First marking as the baseline of measurement														
Mo.1: 3-5 Oct 09	2.56	0.54	1.14	3.27	1.77	0.35	1.61	0.14	0.04	0.12	0.11	0.11	0.05	0.10	
Mo.2: 3-5 Nov 09	2.03	1.47	0.66	1.72	2.66	0.78	1.55	0.11	0.11	0.07	0.06	0.17	0.11	0.10	
Mo.3: 1-3 Dec 09	0.26	0.21	0.25	0.88	0.23	0.50	0.39	0.01	0.02	0.03	0.03	0.01	0.07	0.03	
Mo.4: 27-29 Dec 09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Mo.5: 25-27 Jan 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Mo.6: 24-26 Feb 10	0.81	0.55	0.70	0.22	0.00	0.38	0.44	0.04	0.04	0.07	0.01	0.00	0.05	0.04	
Mo.7: 27-29 Mar 10	0.41	1.07	0.30	0.52	0.00	0.02	0.39	0.02	0.08	0.03	0.02	0.00	0.00	0.03	
Mo.8: 2-4 May 10	1.38	2.15	0.32	4.48	0.93	0.32	1.60	0.08	0.16	0.03	0.15	0.06	0.05	0.09	
Mo.9: 28-30 May 10	1.50	1.45	0.31	5.50	1.18	0.54	1.75	0.08	0.11	0.03	0.19	0.08	0.08	0.09	
Mo.10: 25-26 Jun 10	2.80	0.66	3.41	1.18	1.61	0.45	1.69	0.15	0.05	0.36	0.04	0.10	0.07	0.13	
Mo.11: 4-6 Aug 10	2.64	4.40	0.71	3.36	2.32	1.35	2.46	0.15	0.32	0.08	0.11	0.15	0.20	0.17	
Mo.12: 3-5 Sep 10	1.90	0.95	1.47	4.22	3.63	1.86	2.34	0.10	0.07	0.16	0.14	0.23	0.27	0.16	
Extraction: 3-5 Oct 10	1.91	0.39	0.16	4.09	1.27	0.36	1.36	0.11	0.03	0.02	0.14	0.08	0.05	0.07	
TOTAL	18.20	13.84	9.43	29.45	15.60	6.91	15.57	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
DBH (cm)	31.2	32.1	41.1	33.0	29.0	21.9	-	-	-	-	-	-	-	-	

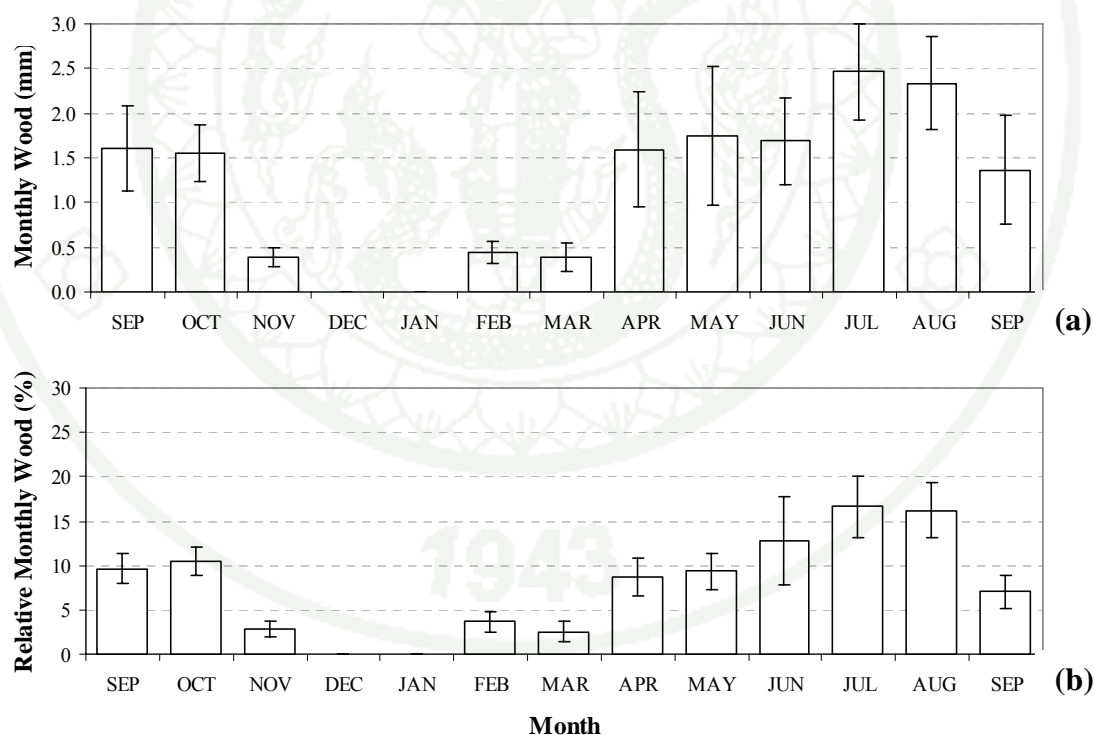


**Figure 27** Scanned images of cambial marking points in *Melia azedarach*, tree no. MA02. Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.

Wood increments of *M. azedarach* gently increased since the beginning of the growing season in February 2010 and maximized growth occurred in July and August 2010 for 2.46 and 2.34 mm, respectively, when vessel diameter mildly

decreased to 0.21 mm. Wood increment suddenly dropped in September 2010 (1.36 mm) and vessel sizes were continuously decreased to 0.19 mm (Figure 26e). Figure 26 illustrated directly measured and relative monthly wood increments of *M. azedarach* during the investigated periods.

In *M. azedarach*, cambial marking also generated the anomalous cell which disturbed the analysis of periodic wood and annual ring formation. Parenchyma formed closed to the injured point and looked similar to initial banded parenchyma. Vessel diameters which were gradually decreased from earlywood to latewood were useful characteristic to identify annual ring boundary. The actual annual ring was shown in Figure 26c, while parenchyma formed from the effect of cambial marking was shown in Figure 26b.

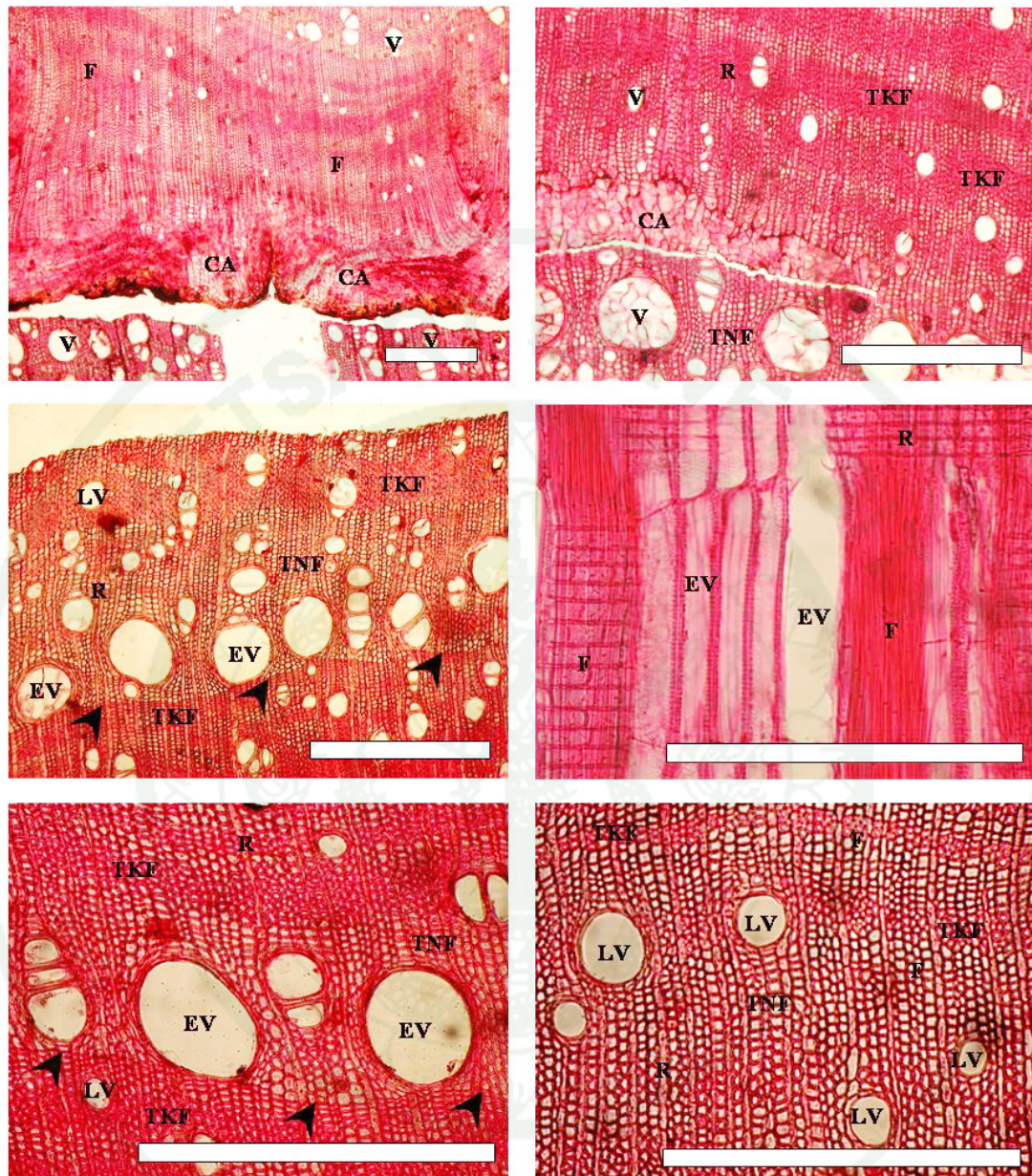


**Figure 28** Fluctuations of (a) measured and (b) relative monthly wood increments of *Melia azedarach* with the standard error of the mean (SEM).

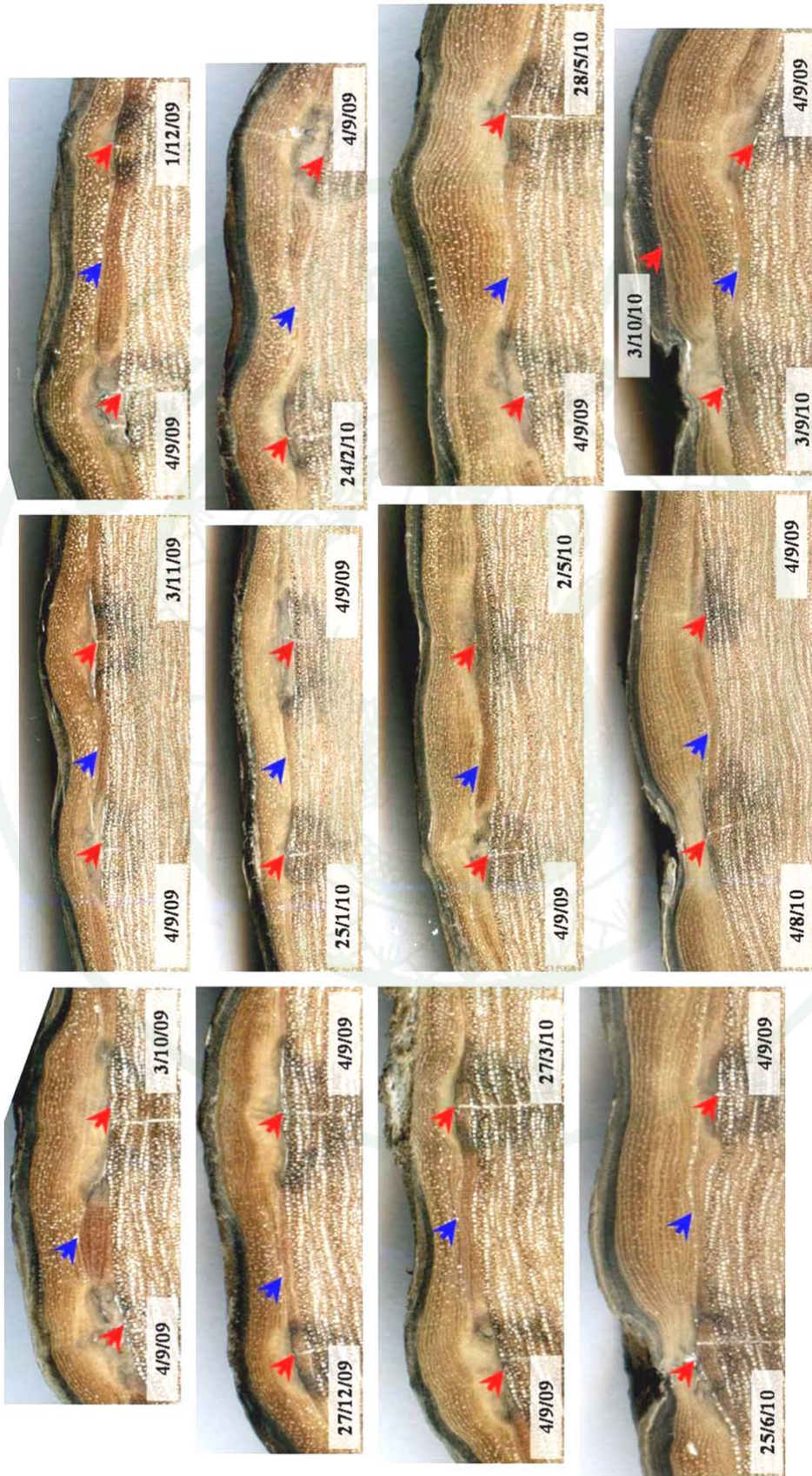
#### 4.4 *Lagerstroemia duperreana* Pierre ex Gagnep

Thorel's Crape Myrtle (*L. duperreana*) was defined as a distinct growth ring species. Six mature *L. duperreana* (coded LD01 to LD06) were selected for periodic wood and annual ring formation. Wood porosity was semi-ring porous with solitary and multiple pores which were gradually changed from large vessel diameters in earlywood to narrow vessel diameters in latewood (Figure 29c). Cambial markings induced both of callus cells formation (Figure 29a and 29b) and total wood increment during the investigated periods which was larger than the previous year (Figure 30). Band of thin wall fibers formed and looked similar to axial parenchyma. In this study, it was defined as “banded axial parenchyma-liked fibers” and was found associated with large vessels at the beginning of growing season (Figure 29c and 29d). After cambial marking at the beginning of September 2009, total wood increment till September 2010 was 2.86 mm (Figure 30-31 and Table 22). Monthly wood increments gradually decreased and vessels with small diameters were found associated with thick wall fiber until the end of November 2009 (Figure 29e). Wood increment in these periods was only 0.70 mm (23.20% of total growth during the observed intervals) and average vessel diameter was only 0.055 mm. In December 2009 and the first 4 months of 2010 (January till April 2010), stop producing wood tissue occurred and could be indicated by unchanged wood increment. It seemed to be the dormant periods of *L. duperreana* at SERS, except a tree code LD02 which small wood increments were found in December 2009 and April 2010 for 0.14 and 0.24 mm, respectively.

Banded axial parenchyma-liked fibers of *L. duperreana* formed in May 2010 associated with the largest vessels of 0.085 mm diameter, approximately (Figure 29c to 29e). Appearing the large vessels indicated that the dormancy had gone and growth had started as the beginning of annual ring formation around May 2010. However, wood increments of *L. duperreana* at the beginning of rainy season (May to July 2010) were lower than the end of this season (August and September 2010).



**Figure 29** Microscopic features of *Lagerstroemia duperreana*; (a-b) callus cells (CA) from effect of cambial marking; (c) total wood increment with large earlywood vessel (EV) and small latewood vessel (LV); (d-e) vessels in earlywood associated with thin wall fibers; (f) latewood vessels (LV) with bands of thick (TKF) and thin (TNF) wall fibers alternately occurred along the wood increment zone. White bands indicated the length of 500  $\mu\text{m}$ . Black arrow head indicated the initial parenchyma. Figure 29a, 29b, 29c, 29e, 29f were cross-section and Figure 29d was radial section.

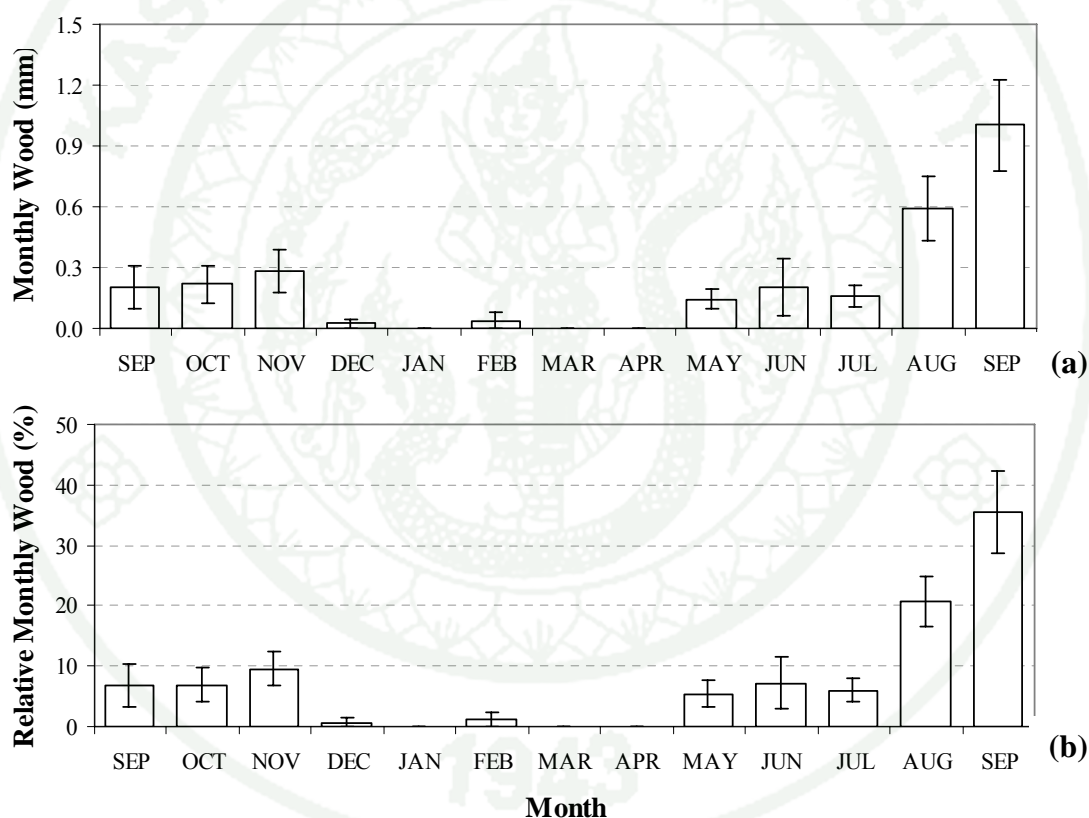


**Figure 30** Scanned images of cambial marking points in *Lagerstroemia duperreana*, tree no. LD06. Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.

**Table 22** Measured and relative monthly wood increments of *Lagerstroemia duperreana*. Dash box indicated the common periods of growth dormancy.

Marked Date	Measured monthly wood increment (mm)										Relative monthly wood increment										
	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	LD	
	01	02	03	04	05	06	Mean	01	02	03	04	05	06	Mean	01	02	03	04	05	06	Mean
Mo.0: 4-6 Sep 09	0.00	0.32	0.08	0.67	0.00	0.14	0.20	0.00	0.10	0.04	0.23	0.00	0.03	0.07	0.00	0.10	0.04	0.23	0.00	0.03	0.07
Mo.1: 3-5 Oct 09	0.00	0.57	0.05	0.38	0.08	0.23	0.22	0.00	0.18	0.02	0.13	0.03	0.06	0.07	0.00	0.18	0.02	0.13	0.03	0.06	0.07
Mo.2: 3-5 Nov 09	0.36	0.00	0.14	0.20	0.23	0.75	0.28	0.17	0.00	0.07	0.07	0.08	0.18	0.10	0.17	0.00	0.07	0.07	0.08	0.18	0.10
Mo.3: 1-3 Dec 09	0.00	0.14	0.00	0.00	0.00	0.00	0.02	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.00	0.00	0.01
Mo.4: 27-29 Dec 09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.5: 25-27 Jan 10	0.00	0.24	0.00	0.00	0.00	0.00	0.04	0.00	0.07	0.00	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.00	0.00	0.00	0.01
Mo.6: 24-26 Feb 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.7: 27-29 Mar 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.8: 2-4 May 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.9: 28-30 May 10	0.00	0.00	0.26	0.25	0.21	0.13	0.14	0.00	0.00	0.14	0.09	0.07	0.03	0.05	0.00	0.00	0.14	0.09	0.07	0.03	0.05
Mo.10: 25-26 Jun 10	0.14	0.91	0.13	0.00	0.00	0.06	0.21	0.07	0.28	0.07	0.00	0.00	0.01	0.07	0.07	0.28	0.07	0.00	0.00	0.01	0.07
Mo.11: 4-6 Aug 10	0.10	0.37	0.21	0.19	0.00	0.09	0.16	0.05	0.11	0.11	0.06	0.00	0.02	0.06	0.05	0.11	0.11	0.06	0.00	0.02	0.06
Mo.12: 3-5 Sep 10	0.68	0.32	0.42	0.24	0.56	1.30	0.59	0.32	0.10	0.22	0.08	0.19	0.32	0.21	0.32	0.10	0.22	0.08	0.19	0.32	0.21
Extraction: 3-5 Oct 10	0.81	0.36	0.59	1.02	1.84	1.39	1.00	0.39	0.11	0.31	0.35	0.63	0.34	0.35	0.39	0.11	0.31	0.35	0.63	0.34	0.35
TOTAL	2.09	3.22	1.88	2.93	2.93	4.09	2.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DBH (cm)	21.2	11.9	48.7	48.5	43.15	45.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Monthly wood increments of *L. duperreana* rapidly in May till July 2010 were only 0.14, 0.21 and 0.16 mm (5.43, 7.22, and 6.00%, respectively), while monthly growths in August and September 2010 were 0.59 and 1.0 mm (20.73, and 35.50%, respectively). Although, wood increments increased at the end of rainy season, the vessel sizes gradually declined to 0.062 mm (Figure 29f). Bands of thick and thin wall fibers alternately occurred along the wood increment zone (Figure 29c, 29e and 29f). Table 22 and Figure 31 illustrated the fluctuation of directly measured and relative monthly wood increments of *L. duperreana* during investigated periods.

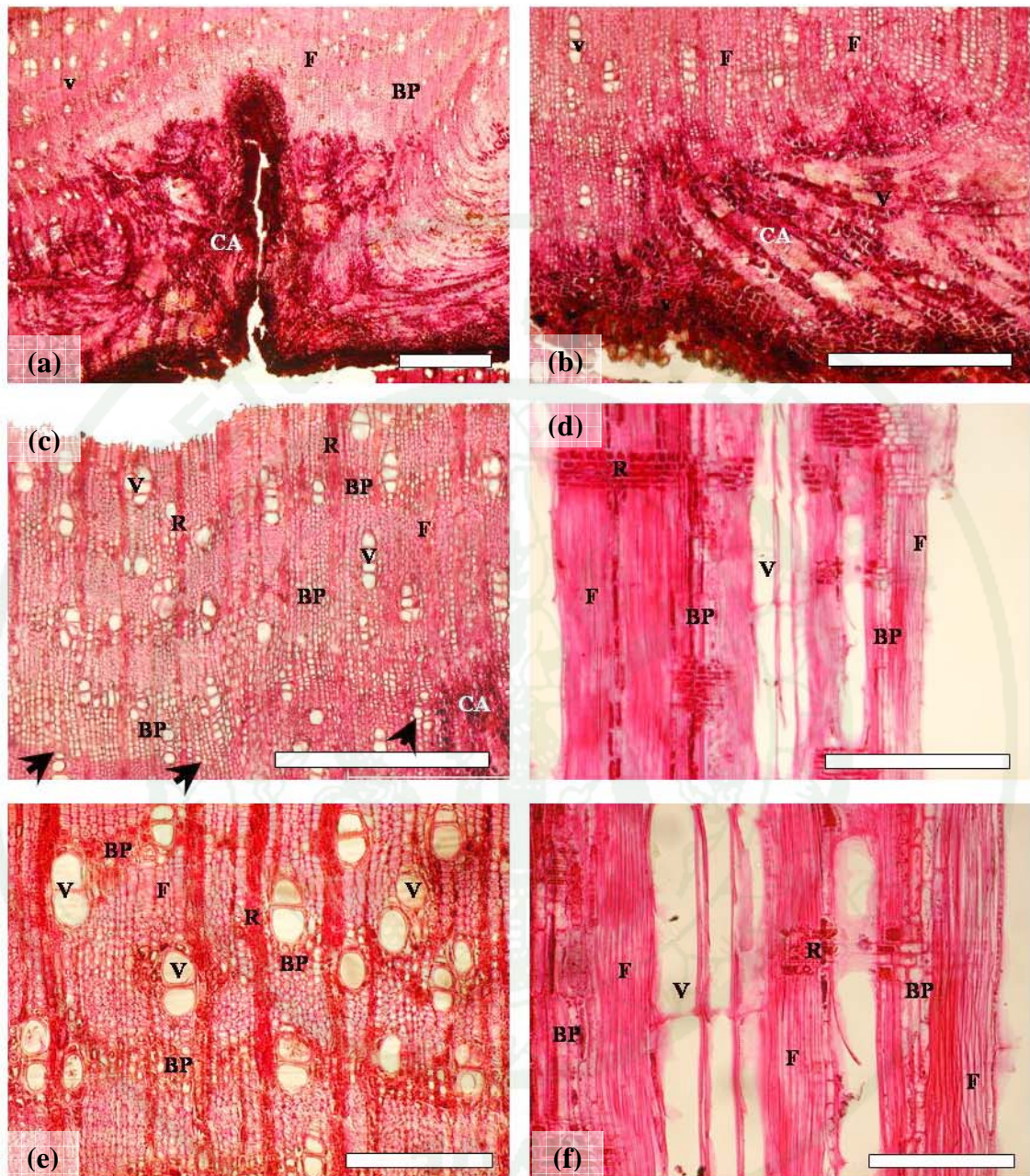


**Figure 31** Fluctuations of (a) measured and (b) relative monthly wood increments of *Lagerstroemia duperreana* with the standard error of the mean (SEM).

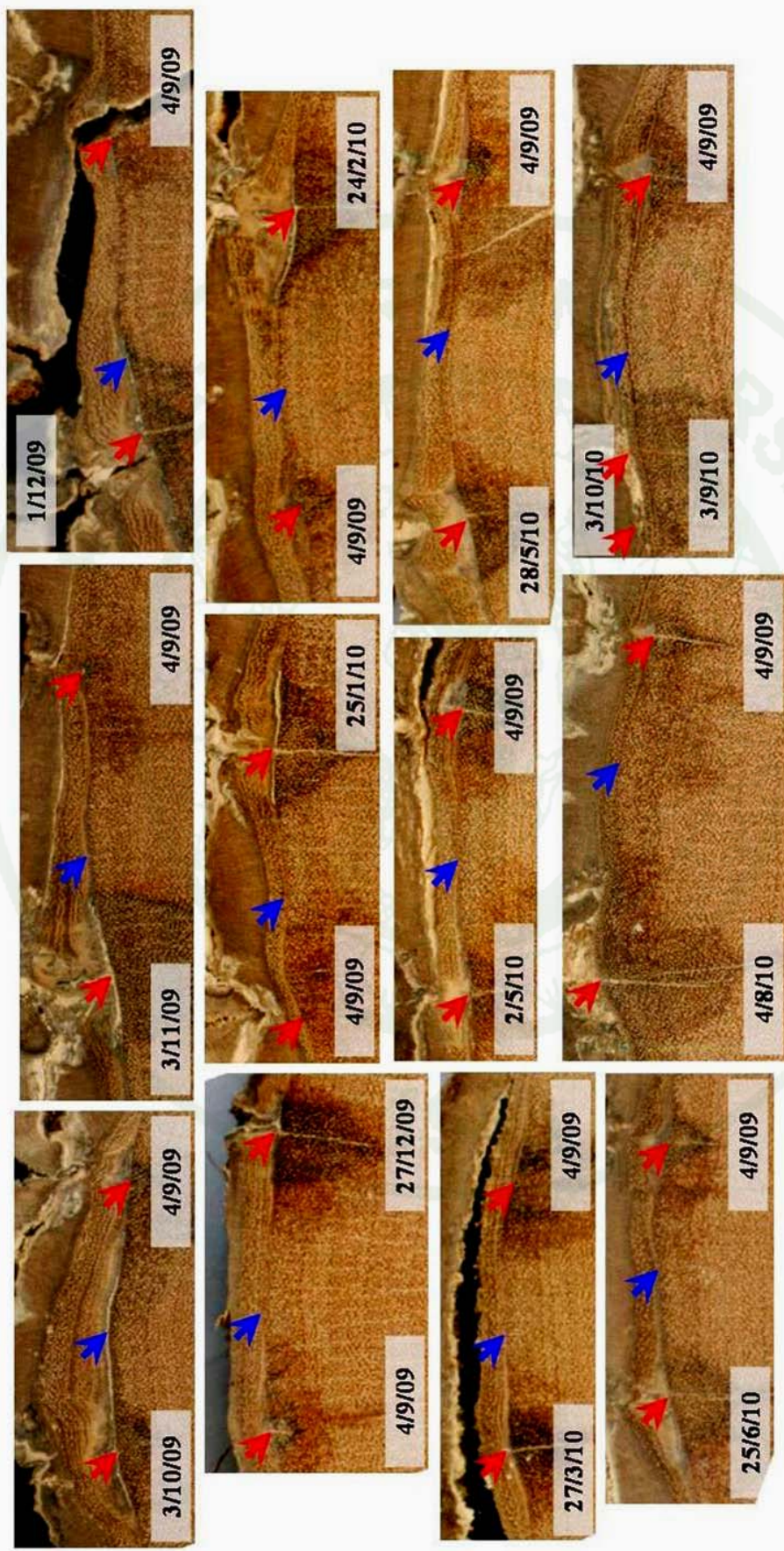
#### 4.5 *Aglaia odoratissima* Blume

*Aglaia odoratissima*, coded AO01 to AO03 and AO05 to AO06, was an indistinct growth ring species. Large diameter vessels in earlywood and narrow

diameter vessels in latewood were not found, while wood porosity detected from five *A. odoratissima* were diffuse ring porous with solitary and multiple pores (Figure 32c and 32e). Banded parenchyma, a common wood characteristic using for annual ring boundaries identification in *T. grandis*, *A. xylocarpa* and *M. azedarach* were found 2-3 times during investigated periods (Figure 32c to 32f). Dense fibers which were found before cambial making in September 2009 might be used for annual ring identification (Figure 32c: below the arrowheads), but sample preparation of thin section was necessary for microscopic investigation instead of the direct investigation using macroscopic technique. Additionally, there were difficult to identify these dense fibers using a low magnified stereo microscope in tree-ring analysis instrument. Total wood increment in September 2009 till September 2010 was 1.56 mm. (Figure 33 and Table 23). Dormant period was shortly found and monthly wood increment was not changed in September 2009 after cambial markings. However, it was difficult to identify this period as a stop growing or dormant period of *A. odoratissima* due to the continuous occurrences of wood increment in September 2010. Wood increment stopped in September 2009 and re-stimulated in October 2009 for 0.03 mm (1.34% of total wood increment) and continuously increased for 0.13 mm (8.46%) in both of November and December 2009. The average of vessel diameters in October till December 2009 was 0.034 mm. Wood increment gradually declined and fluctuated from 0.03 till 0.09 mm in January till June 2010. Total wood increment in these six months was 0.39 mm (24.89% of overall increment) and mean vessel diameter was 0.035 mm. In July till September 2010, woods were rapidly increased for 0.87 mm (55.97%) and mean vessel diameter generated in this period was 0.05 mm. Although wood increments could be detected in every month during the investigated periods, the patterns of wood increments in these 5 trees were not similar. It might be assumed that wood increments of *A. odoratissima* were not depended on factors affecting tree growth, especially in climatic factors. Wood increments were continuously increased as shown in Table 23. Figure 34 illustrated the fluctuation of directly measured and relative monthly wood increments of *A. odoratissima* during investigated periods.



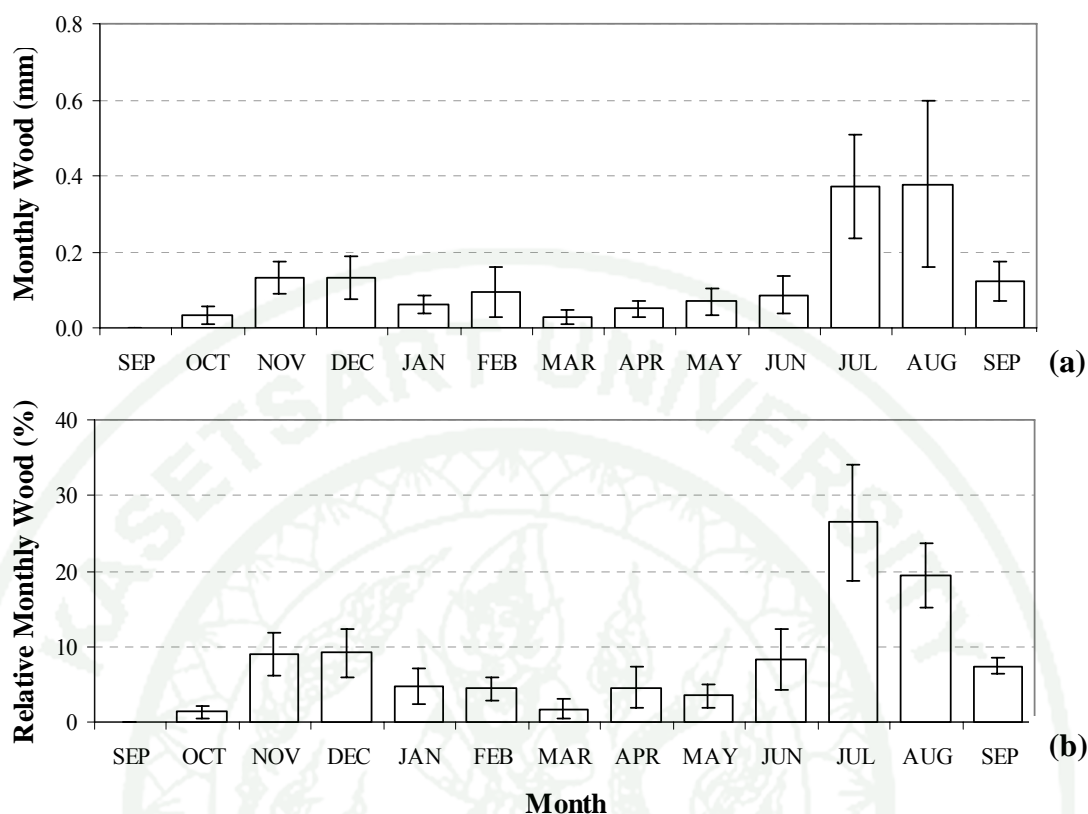
**Figure 32** Microscopic features of *Aglaia odoratissima*; (a-b) callus cells (CA) from cambial marking; (c-d) total wood increment; (e-f) several banded parenchyma (BP) during investigated periods. V = vessels, F = fibers and R = ray cells. White bands in a-d and e-f indicated the length of 500 and 100  $\mu\text{m}$ , respectively. Black arrow head indicated the transition zone of dense fiber and banded parenchyma. Figure 32a, 32b, 32c, 32e were cross-section and Figure 32d, 32f were radial section.



**Figure 33** Scanned images of cambial marking points in *Aglaia odoratissima*, tree no. AO02. Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.

**Table 23** Measured and relative monthly wood increments of *Aglaia odoratissima*.

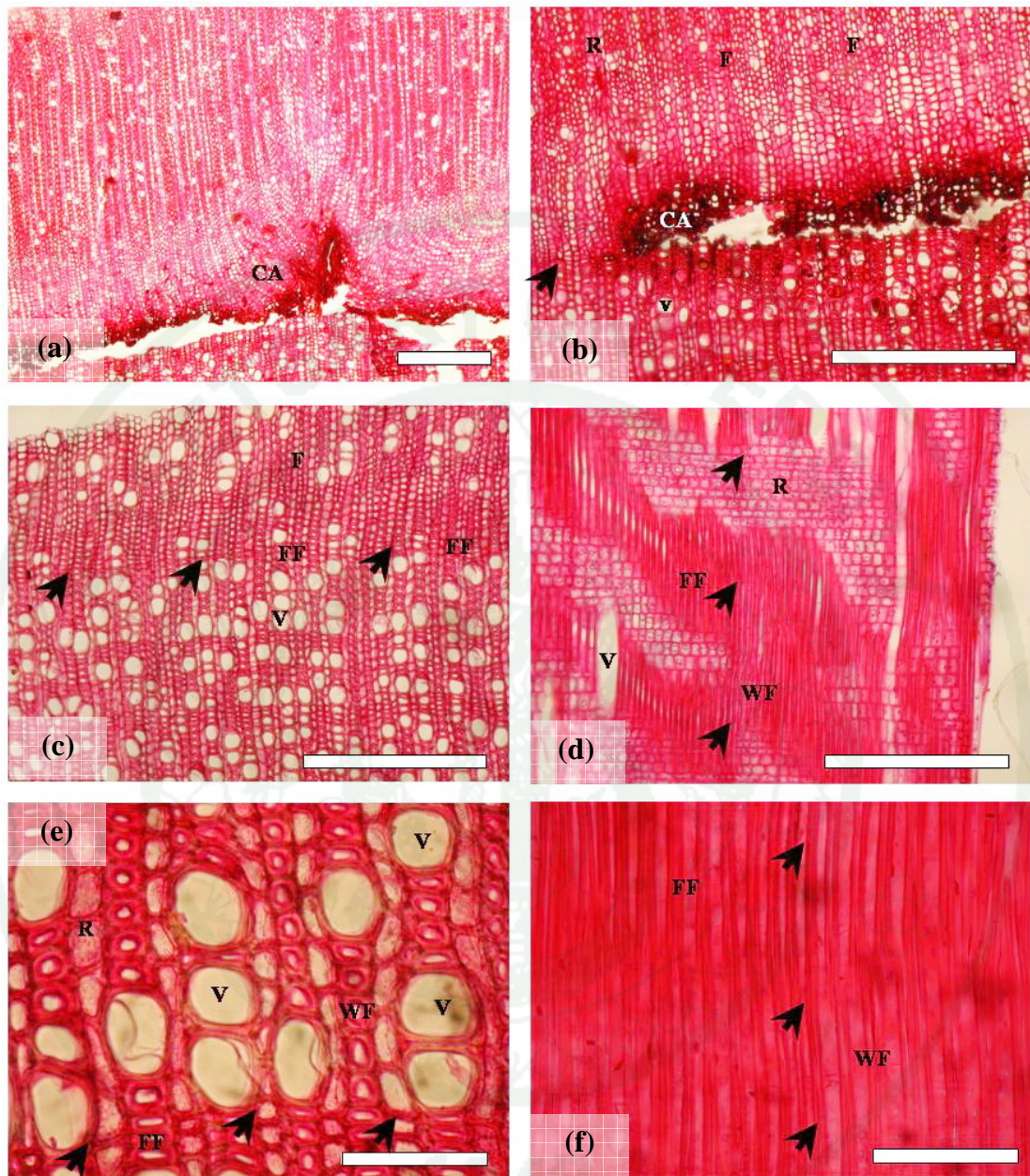
Marked Date	Measured monthly wood increment (mm)						Relative monthly wood increment					
	AO01	AO02	AO03	AO05	AO06	Mean	AO01	AO02	AO03	AO05	AO06	Mean
Mo.0: 4-6 Sep 09												
	First marking as the baseline of measurement											
Mo.1: 3-5 Oct 09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.2: 3-5 Nov 09	0.00	0.00	0.05	0.00	0.12	0.03	0.00	0.00	0.03	0.00	0.03	0.01
Mo.3: 1-3 Dec 09	0.09	0.14	0.21	0.00	0.22	0.13	0.10	0.14	0.16	0.00	0.06	0.09
Mo.4: 27-29 Dec 09	0.16	0.00	0.07	0.10	0.34	0.13	0.18	0.00	0.05	0.14	0.09	0.09
Mo.5: 25-27 Jan 10	0.00	0.00	0.12	0.09	0.10	0.06	0.00	0.00	0.09	0.12	0.03	0.05
Mo.6: 24-26 Feb 10	0.00	0.05	0.02	0.05	0.35	0.09	0.00	0.05	0.02	0.07	0.09	0.04
Mo.7: 27-29 Mar 10	0.06	0.00	0.00	0.00	0.09	0.03	0.06	0.00	0.00	0.00	0.02	0.02
Mo.8: 2-4 May 10	0.00	0.00	0.10	0.10	0.05	0.05	0.00	0.00	0.07	0.14	0.01	0.05
Mo.9: 28-30 May 10	0.00	0.05	0.10	0.00	0.20	0.07	0.00	0.05	0.07	0.00	0.05	0.03
Mo.10: 25-26 Jun 10	0.06	0.00	0.27	0.11	0.00	0.09	0.06	0.00	0.20	0.15	0.00	0.08
Mo.11: 4-6 Aug 10	0.22	0.54	0.09	0.19	0.82	0.37	0.24	0.54	0.07	0.26	0.21	0.26
Mo.12: 3-5 Sep 10	0.24	0.15	0.20	0.06	1.24	0.38	0.26	0.15	0.15	0.09	0.32	0.19
Extraction: 3-5 Oct 10	0.09	0.08	0.11	0.02	0.32	0.12	0.10	0.08	0.08	0.03	0.08	0.07
TOTAL	0.90	1.01	1.33	0.71	3.86	1.56	1.00	1.00	1.00	1.00	1.00	1.00
DBH (cm)	16.7	14.2	15.3	12.1	12.4	-	-	-	-	-	-	-



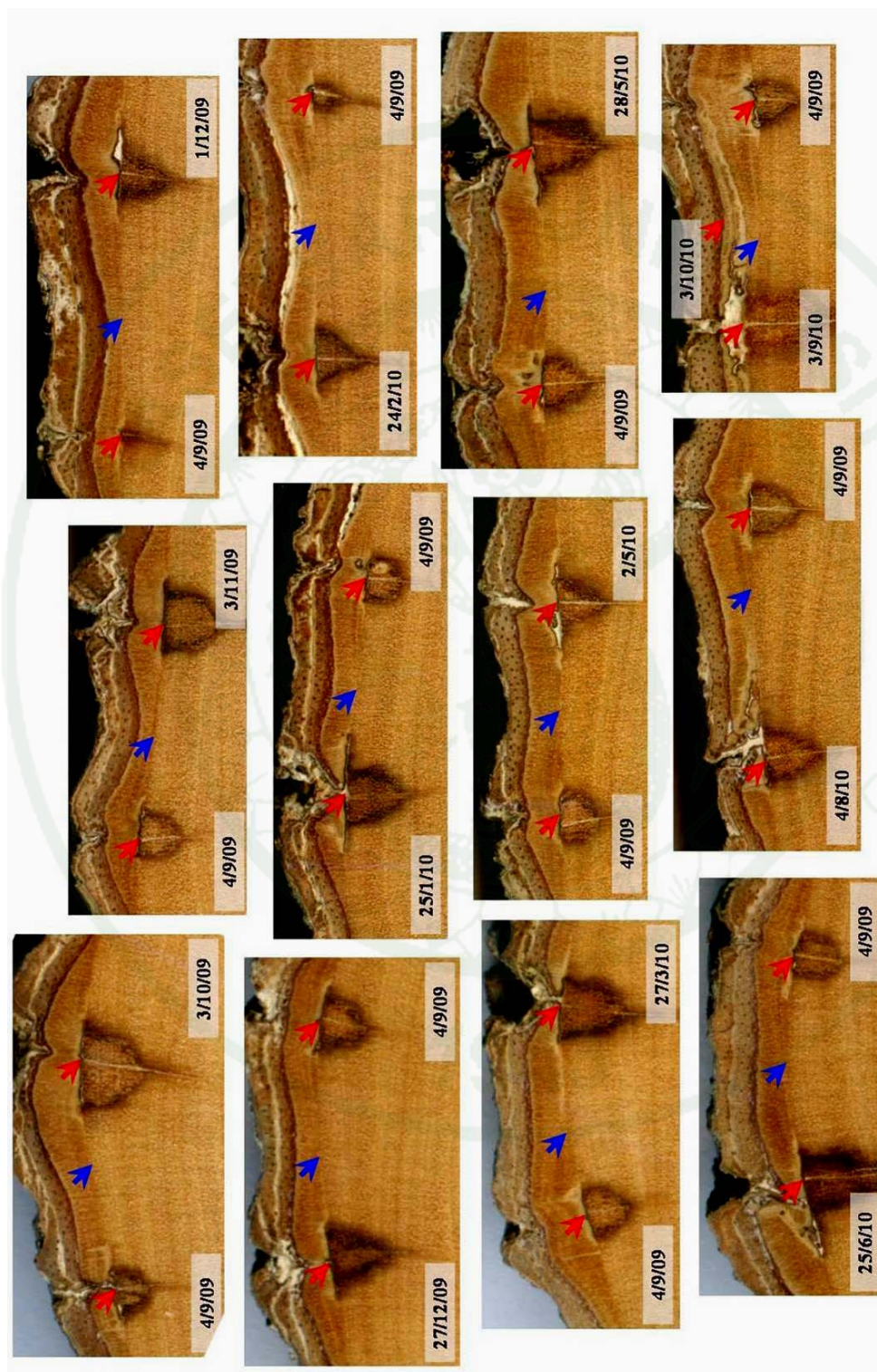
**Figure 34** Fluctuation of (a) measured and (b) relative monthly wood increments of *Aglaia odoratissima* with the standard error of the mean (SEM).

#### 4.6 *Hydnocarpus ilicifolia* King

*Hydnocarpus ilicifolia* (coded HI01 to HI06) was an indistinct annual ring species as similar as *A. odoratissima*. Its porosity was diffuse ring porous with solitary and multiple pores (Figure 35c and 35e). Terminal parenchyma and vascentric parenchyma were not found, but the changing of fiber dense and flatted fiber shape as similar as *L. duperreana* could be used for annual ring identification (Figure 35c and 35e). During September 2009 till September 2010, total wood increment was 1.03 mm (Figure 36-37 and Table 24). In order to investigate annual ring formation, sample preparation of thin section was necessary for microscopic investigation instead of the direct investigation using macroscopic technique. Additionally, there were difficult to identify these dense fibers using a low magnified stereo microscope in tree-ring analysis instrument.



**Figure 35** Microscopic features of *Hydnocarpus ilicifolia*: (a-b) callus cells (CA) from cambial marking; (c-d) diffuse porous vessels (V) and flatted fibers (FF) indicated annual ring boundary; (e-f) flatted fibers (FF) and large diameter fibers (WF) at the transition of annual ring. F = fibers and R = ray cells. White bands in a-d and e-f indicated the length of 500 and 100  $\mu\text{m}$ , respectively. Black arrow head indicated the transition zone of annual ring boundary. Figure 35a, 35b, 35c, 35e were cross-section and Figure 35d, 35f were radial section.

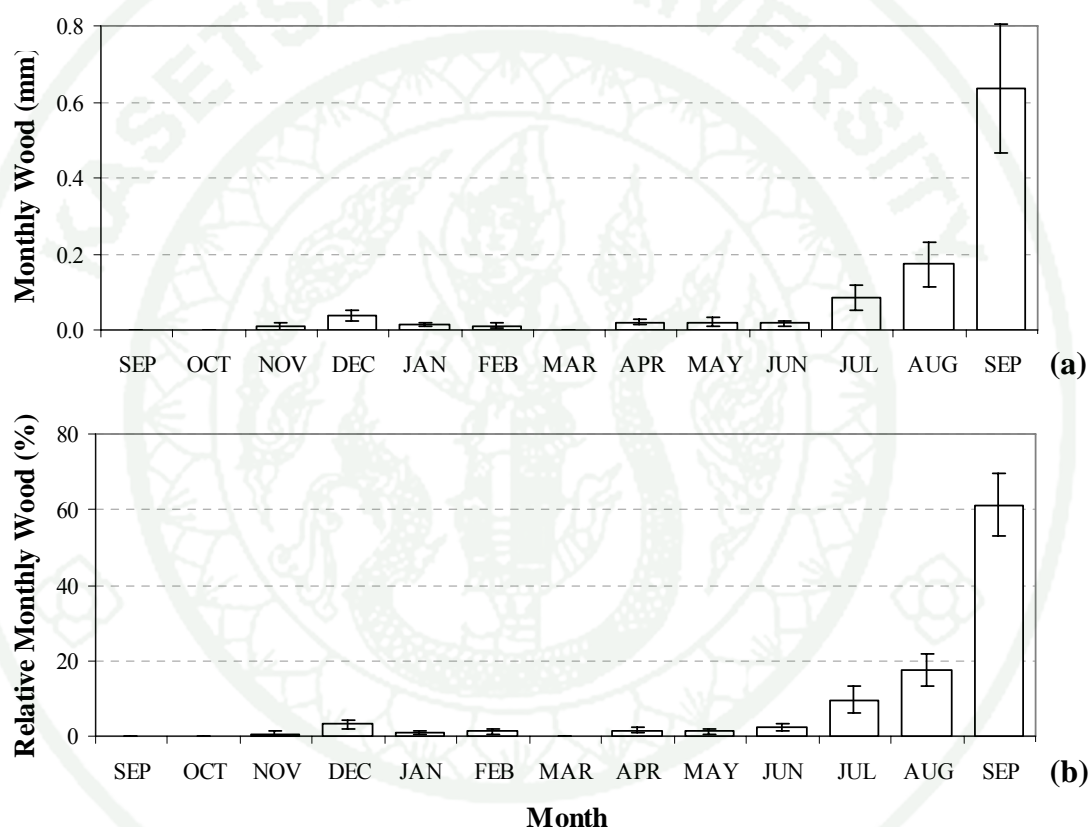


**Figure 36** Scanned images of cambial marking points in *Hydnocarpus ilicifolia*, tree no. HI05. Red and blue arrowheads indicated cambial injured points and annual ring started point, respectively.

**Table 24** Measured and relative monthly wood increments of *Hydnocarpus ilicifolia*. Dash box indicated the common periods of growth dormancy.

Marked Date	Monthly wood increment (mm)							Relative monthly wood increment						
	HI 01	HI 02	HI 03	HI 04	HI 05	HI 06	Mean	HI 01	HI 02	HI 03	HI 04	HI 05	HI 06	Mean
Mo.0: 4-6 Sep 09	First marking as the baseline of measurement													
Mo.1: 3-5 Oct 09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.2: 3-5 Nov 09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.3: 1-3 Dec 09	0.00	0.00	0.00	0.00	0.06	0.00	0.01	0.00	0.00	0.00	0.00	0.04	0.00	0.01
Mo.4: 27-29 Dec 09	0.06	0.00	0.07	0.07	0.03	0.00	0.04	0.05	0.00	0.05	0.08	0.02	0.00	0.03
Mo.5: 25-27 Jan 10	0.01	0.00	0.01	0.03	0.03	0.00	0.01	0.00	0.00	0.01	0.03	0.02	0.00	0.01
Mo.6: 24-26 Feb 10	0.02	0.00	0.02	0.00	0.00	0.03	0.01	0.02	0.00	0.02	0.00	0.00	0.04	0.01
Mo.7: 27-29 Mar 10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mo.8: 2-4 May 10	0.04	0.00	0.01	0.03	0.03	0.00	0.02	0.03	0.00	0.01	0.03	0.02	0.00	0.02
Mo.9: 28-30 May 10	0.04	0.00	0.01	0.00	0.07	0.00	0.02	0.03	0.00	0.01	0.00	0.04	0.00	0.01
Mo.10: 25-26 Jun 10	0.04	0.02	0.00	0.04	0.01	0.00	0.02	0.03	0.06	0.00	0.04	0.01	0.00	0.02
Mo.11: 4-6 Aug 10	0.11	0.06	0.00	0.11	0.23	0.00	0.08	0.09	0.24	0.00	0.11	0.14	0.00	0.10
Mo.12: 3-5 Sep 10	0.26	0.05	0.01	0.28	0.36	0.06	0.17	0.21	0.21	0.01	0.29	0.22	0.11	0.18
Extraction: 3-5 Oct 10	0.64	0.12	1.34	0.41	0.80	0.50	0.64	0.53	0.49	0.90	0.42	0.49	0.85	0.61
TOTAL	1.20	0.26	1.49	0.98	1.64	0.59	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DBH (cm)	18.1	15.6	13.4	16.9	13.2	11.7	-	-	-	-	-	-	-	-

After cambial marking at the beginning of September 2009, monthly wood increments were not changed for 3 months in September – November 2009, except a tree coded HI05 which wood increment in November 2009 was 0.06 mm (4.31% from total growth of HI05) (Table 24). Unchanged wood increment in these 3 months seemed to be the dormant periods of *H. ilicifolia* at SERS, except a tree code HI05 which small wood increments formed earlier than other *H. ilicifolia* trees.



**Figure 37** Fluctuation of (a) measured and (b) relative monthly wood increments of *Hydnocarpus ilicifolia* with the standard error of the mean (SEM).

Wood increments of other *H. ilicifolia* trees started in December 2009 and continuously grew until February 2010. Tree growth in these periods were 0.07 mm (5.59% of total growth) and the average vessel diameters were 0.0285 mm. Dense fibers were found before cambial marking in December 2009 indicating the end of tree growth in previous year. The short period of stop producing tissue was found in March 2010. In April to June 2010, wood increment was 0.06 mm (5.29%) and the

average vessel size was 0.0289 mm. It could be stated that, after dormant periods, wood increment in December 2009 till June 2010 was very slow. In July to September 2010, woods were rapidly increased for 0.89 mm (88.49%) and the vessel diameters generated in this period for 0.0387 mm. The rate of wood increment was continuously increased as shown in Table 24. Figure 37 illustrated the variations of directly and relative monthly wood increments of *H. ilicifolia* during investigated periods.

*T. grandis*, *M. azedarach*, and *L. duperreana* were grouped as ring porous to semi-ring porous species, while *A. xylocarpa*, *A. odoratissima* and *H. ilicifolia* were defined as diffuse ring porous species. As shown in other studies (Gottwald and Parameswaran, 1980; Carlquist, 2001; Chamberlain, 1921; Ohashi *et al.*, 2009), vessel size variations of *T. grandis*, *M. azedarach*, and *A. xylocarpa* were similar to this study. Baas (1986) studied wood anatomy of Lythraceae and also found the semi-ring porous characteristics in *Lagerstroemia sp.* Miller (1975) studying the systematic anatomy of the xylem of Flacourtiaceae and also found the diffuse porous structure as similar as the study in *H. ilicifolia*. It was supported by Benyasuta (2003), who studied wood anatomy of several petrified woods and found the diffuse porous structure in Flacourtiaceae. According to *A. odoratissima*, Pennington and Styles (1975) and Lemmens *et al.* (1995) also found the diffuse porous characteristic in *A. odoratissima* as similar as this study.

According to the studies of de Pernia and Melandri (2006), Marcati *et al.* (2006) and Roig *et al.* (2005), wood anatomical investigation was indicated that the presences of marginal parenchyma, vessel diameter in earlywood and latewood, and thick wall fiber in latewood were the most common and most identifiable characteristics to identify tree-ring boundaries. However, the researches of these authors did not explain the structures and detectable markers of annual rings. Using cambial marking technique as similar as our studies, several studies suggested that tree species produced annual rings and were indicated by marginal parenchyma and thick walled latewood (Lisi *et al.*, 2008; Marcati *et al.*, 2008; Nobushi *et al.*, 1995). Additionally, other techniques, including the counting of growth rings corresponded with the documented tree age (Chowdhury *et al.*, 2008) and radiocarbon dating (Wils

*et al.*, 2009; Westbrook *et al.*, 2006; Pearson *et al.*, 2011) were useful for annual ring identification.

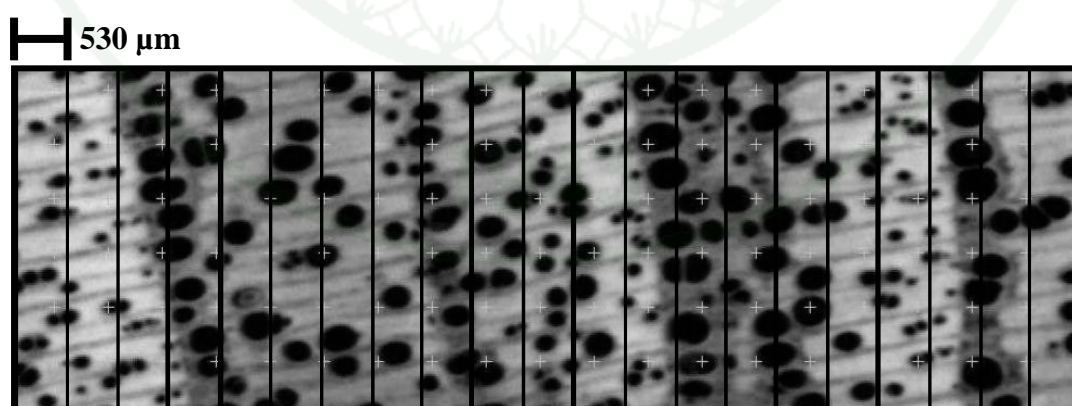
Monthly wood increments of deciduous trees, including *T. grandis*, *A. xylocarpa*, *M. azedarach*, and *L. duperreana*, which were detected by cambial marking technique initiated on the same periods of leaf flushing or a month later at the beginning of rainy season and cessation occurred in the month of leaf abscission at the end of the year, especially in December and January. The periods of wood dormancy in *A. xylocarpa* and *M. azedarach* were similar in December and January, while longer dormant periods in *T. grandis* and *L. duperreana* occurred in December till March and December till May, respectively. Wood increments of evergreen trees illustrated the dissimilar results when *A. odoratissima* was found a continuous process in wood formation as similar as its leaf phenology. For another evergreen species, *H. ilicifolius* was dormancy earlier than deciduous tree in September till November, although its leaves still presented throughout the year. Growth rates of all species rapidly increased and maximized in rainy season. Several authors claimed that lower rainfall during the winter strongly reduced wood increment, while wet condition during the rainy season induced wood increment in both of broad leaf and long leaf trees (Lisi *et al.*, 2008; Marcati *et al.*, 2006; Marcati *et al.*, 2008; Singh and Venugopal, 2011). Additionally, Cufar *et al.* (2008) found the leaf unfolding immediately following by reactivation of cambial cells and the 75% of the tree-ring width was formed in the first half of the average time of cambial activity. They also explained the function of active leaves capable for photosynthesis after the cessation of cell division. The products of photosynthesis in the period of cessation were probably accumulated as reserves in storage tissues and may explain the effect of the climatic of the previous year on current growth. In case of evergreen tree species, there were few investigations on wood formation such as Sass *et al.* (1995) who found a continuous process in wood formation of *Dryobalanops sumatrensis* and *Shorea leprosula*, which was not related to seasonality in rainfall and phenology.

## 5. False ring investigation and formation

The studies of false ring characteristics and formation were focused on *T. grandis*, which 28 sample cores were collected from cardinal directions at breast height of 7 mature teak trees.

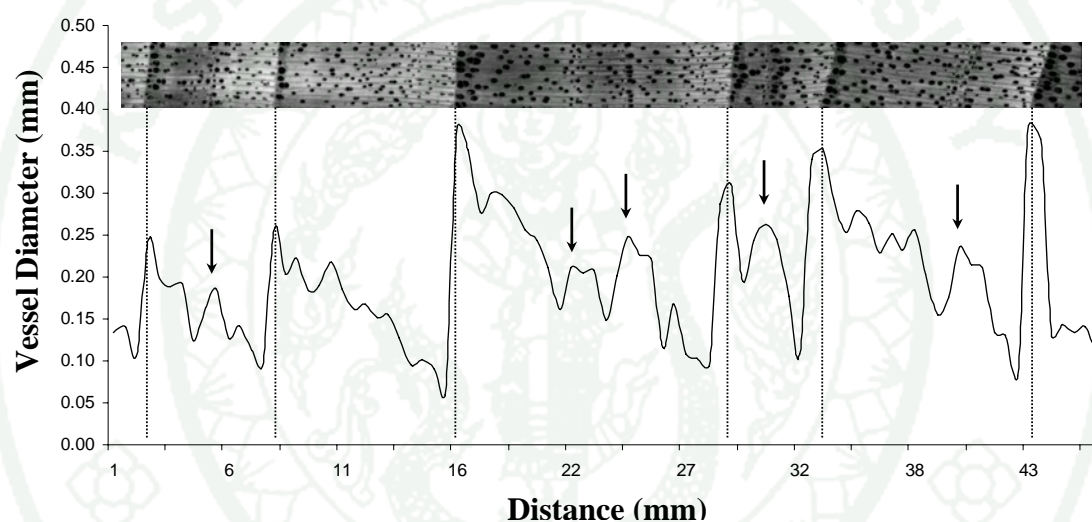
### 5.1 Vessel size and tree-ring identification

Within teak normal annual rings, the largest vessels were found at the beginning of each annual ring and gradually decreased to the end of the ring. To measure vessel sizes along wood core, the scanned images of polished increment core on transverse surface was divided to several segments as shown in Figure 38. In each rectangular segment of 50 pixel widths (530  $\mu\text{m}$ ), five vessels were randomly selected for measurement. Vessel diameters were measured, averaged and plotted to examine the variations of vessel diameter sizes from the pith to the bark. The abrupt changes of vessel diameters at the transition zone of the adjacent annual rings were used as the marker of annual ring boundaries (Figure 39). Similar observations and approaches were made in the studies of other broad leaf tree vessel and long leaf tree tracheid diameter variations (Eilmann *et al.* 2006, Park *et al.* 2006, De Micco *et al.* 2007).



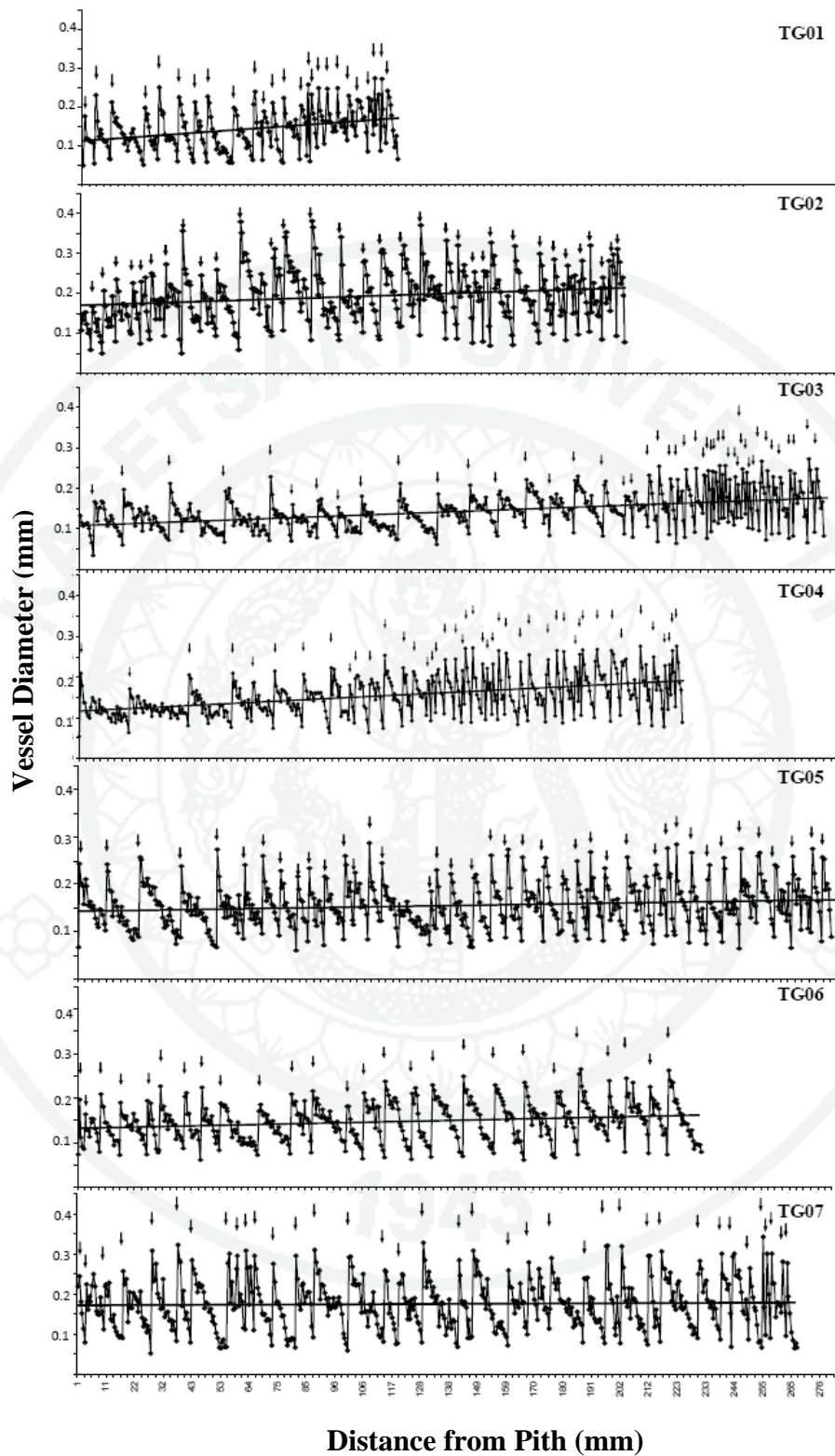
**Figure 38** The scanned image of *Tectona grandis* in transverse surface overlaid with the quadrilaterals of 50 pixels (530  $\mu\text{m}$ ) width along wood cores.

Although the variation of vessel diameters within each annual ring decreased from the beginning (earlywood) to the end (latewood) of the annual ring, trends of vessel diameter variations among annual rings gradually increased from the pith toward the bark (Figure 40). Helinska-Raczkowska & Fabisiak (1999) found increasing vessel diameters of *Fraxinus excelsior* L. from immature (juvenile) to mature wood. Their result was similar to Dunisch *et al.* (2004) who also found the increments of vessel member lengths and vessel diameters of *Ilex paraguariensis* from immature (juvenile) to mature wood.

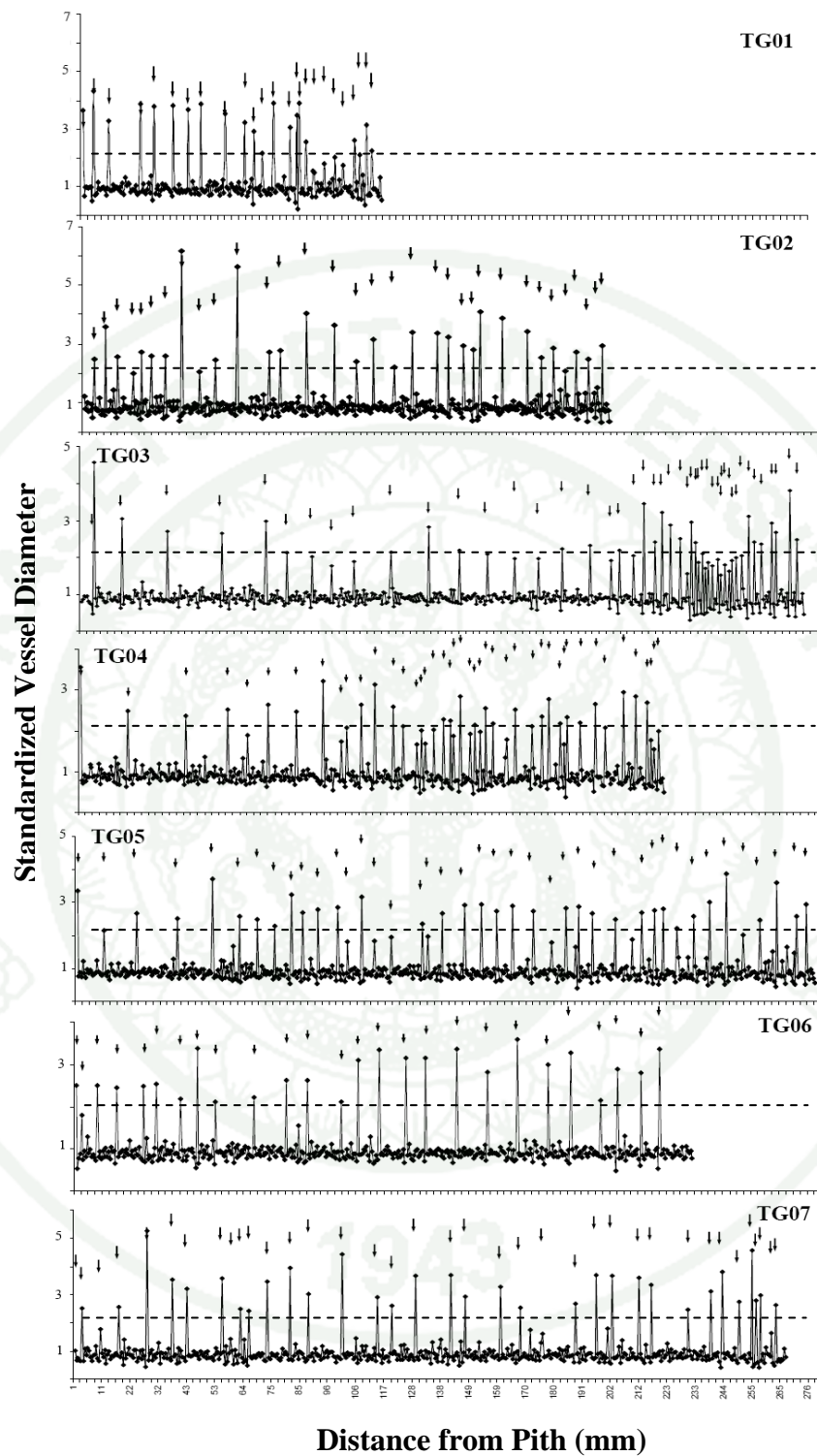


**Figure 39** The variation of vessel diameters in teak indicated annual ring boundaries. Dotted lines and arrows indicate the abrupt changes at the border of each annual ring and intra annual fluctuation, respectively.

Trends of vessel size variation due to the age effect were then standardized or removed by using the proportion of the average vessel diameters of current and prior rectangular segments (50 dpi width) as shown in Figure 40. These transformed data, called standardized vessel diameters, were then plotted to examine the variation of vessel diameters from pith to bark and to indicate annual ring boundaries and false rings (Figure 41).



**Figure 40** Teak vessel diameter variations from pith to bark (TG01 to TG07). The straight lines showed the gently increasing trend of vessel diameters and the arrows indicate annual ring width boundaries.



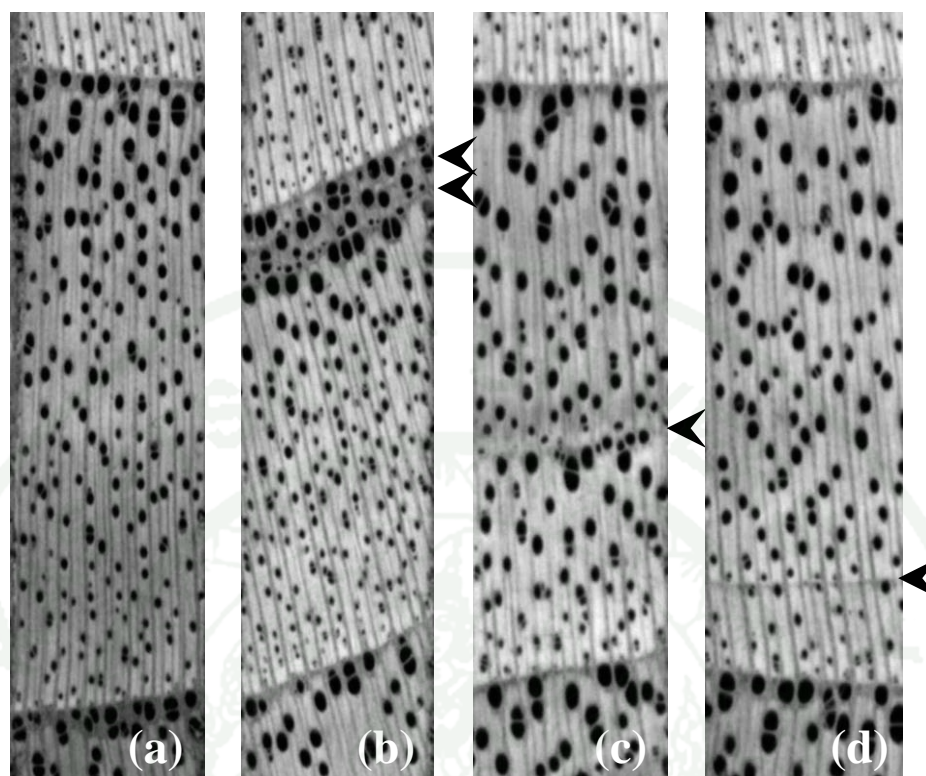
**Figure 41** Standardized vessel diameters of teak from the pith to the bark for the seven sample trees (TG01 to TG07). Arrows indicate annual ring boundaries. Dash lines indicated the standardized value of 2 which was referred to the edge of each annual ring.

In each annual ring, semi-ring porous characteristic illustrated the gradually declined vessel diameters and the proportion of the average vessel diameters of current and prior quadrilateral segments seem to be equal and were commonly closed to 1 while abrupt changes of vessel diameters at the transition zones of adjacent annual rings indicated the high proportion of the average vessel diameters equal or greater than 2 indicating the edge of each annual ring (Figure 41). Other standardized vessel diameters varying between 1 and 2 were mostly defined as false rings.

## 5.2 Anatomical features of teak false rings

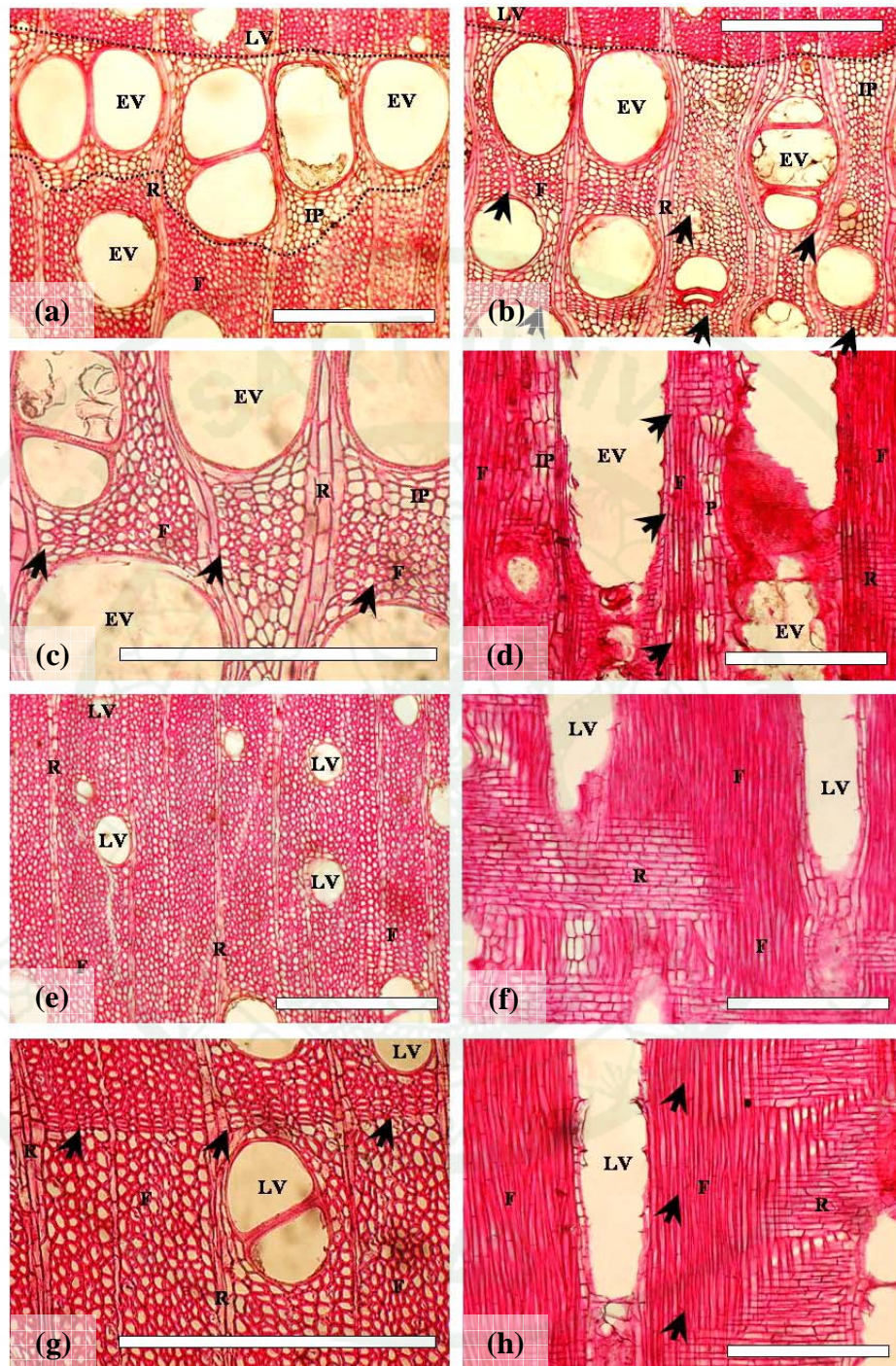
Vessel size variation helped to identify false rings; however, the anatomical features of cell types forming tree rings were important to confirm the difference of false rings and normal annual rings. From the macroscopic investigation of all teak sample cores and microscopic investigation of thin wood sections, we found that normal annual rings composed of paratracheal banded parenchyma associated with the largest vessels at the beginning of the annual ring (Figure 42a, Figure 43b). Vessel diameters gradually changed from large vessel diameter in earlywood to narrow vessel diameter in latewood (Figure 42a).

False rings were found and exhibited different features in both earlywood and latewood zones. Similar to the study of Priya and Bhat (1998), we also defined the occurrences of false rings nearby the large vessels and thick banded parenchyma at the beginning of the annual ring as false ring-type I. It was the zone resembling earlywood, which one or more rows of paratracheal parenchyma and large vessels generated (Figure 42b, 43b-43d). False ring occurrence in the latewood zone was called false ring-type II. It was the aggregation of large vessels associated with paratracheal parenchyma after dense and flatted fiber formation (Figure 42c-42d, Figure 43f-43h).



**Figure 42** Macroscopic structures of false rings and their relative positions within annual tree rings of *Tectona grandis*: (a) normal annual ring, (b) false ring-type I in earlywood, (c-d) false ring-type II: the aggregation of vessels multiplied with paratracheal parenchyma and dense fiber in latewood. Arrowheads indicate false ring position.

Both of false ring-type I and type II was the obstacle in growing year identification. Numbers of rings were increased and ring widths were decreased when false rings were identified as annual rings. However, false ring-type I which was similar to thick initial banded parenchyma (Figure 42b) was not the main problem to identify annual ring boundaries and most dendrochronologists were remiss to investigate this characteristic of each annual ring. False ring-type II occurring in latewood was more difficult to identify due to the formation of dense fibers similar to the border of annual rings (Figure 42c and 42d). The technique of vessel size measurement and investigation of vessel size variation association with cross-matching technique could help dendrochronologists to get the actual annual ring widths and construct their precise ring width index.



**Figure 43** Microscopic structures of normal and false rings in *Tectona grandis*: (a) normal annual ring with initial banded parenchyma (IP) and large earlywood vessel (EV); (b-d) false ring- type I: (e-f) normal annual ring with narrow latewood vessel (LV): (g-h) false ring- type II. White bands indicated the length of 500  $\mu\text{m}$ . Dash line indicated the zone of IP. Black arrow head indicated the occurrences of false rings.

## 6. Tree-ring analysis of teak

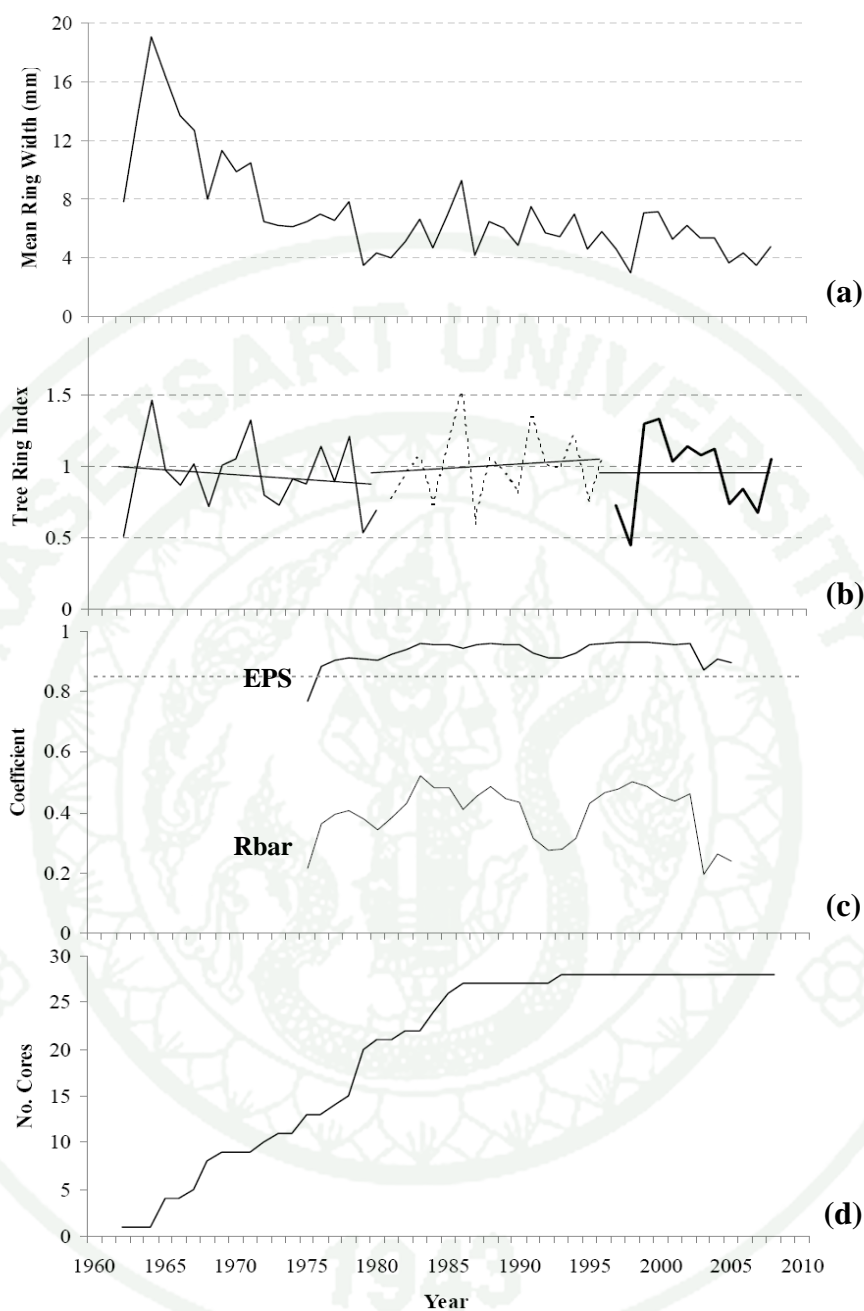
Tree-ring analysis was focused on *Tectona grandis*, which 28 sample cores were collected to study the effect of climate on growth and false ring formation. All sample cores were successfully crossdated, standardized, and constructed the tree-ring index. The index was constructed covering the past 47 years from 1962-2008 (Figure 44a-44b). The mean segment length of the tree ring index was 33 years. The mean series intercorrelation which was used to denote the correlation within tree and among themselves was 0.58. The mean sensitivity which was used to explain the degree of changing from the present year to the previous and the next year was 0.43.

From 1976-2008, tree ring index was defined as the reliable chronology for climatic response analysis due to receive the EPS value higher than the critical point of 0.85. Tree-ring chronology from 1962-1975 was rejected in case of the EPS value lower than the critical point. Based on teak growth fluctuation as shown in Figure 44b, tree ring index could be divided to 3 segments of 19 years (1962-1980), 16 years (1981-1996), and 12 years (1997-2008), respectively. The trend of teak growth in the first segment was gradually decreased, while the second and the third segments played as the increased and the stable trends, respectively.

## 7. Factors affecting periodic wood and annual ring formation

### 7.1 Climate and soil moisture at the growing site

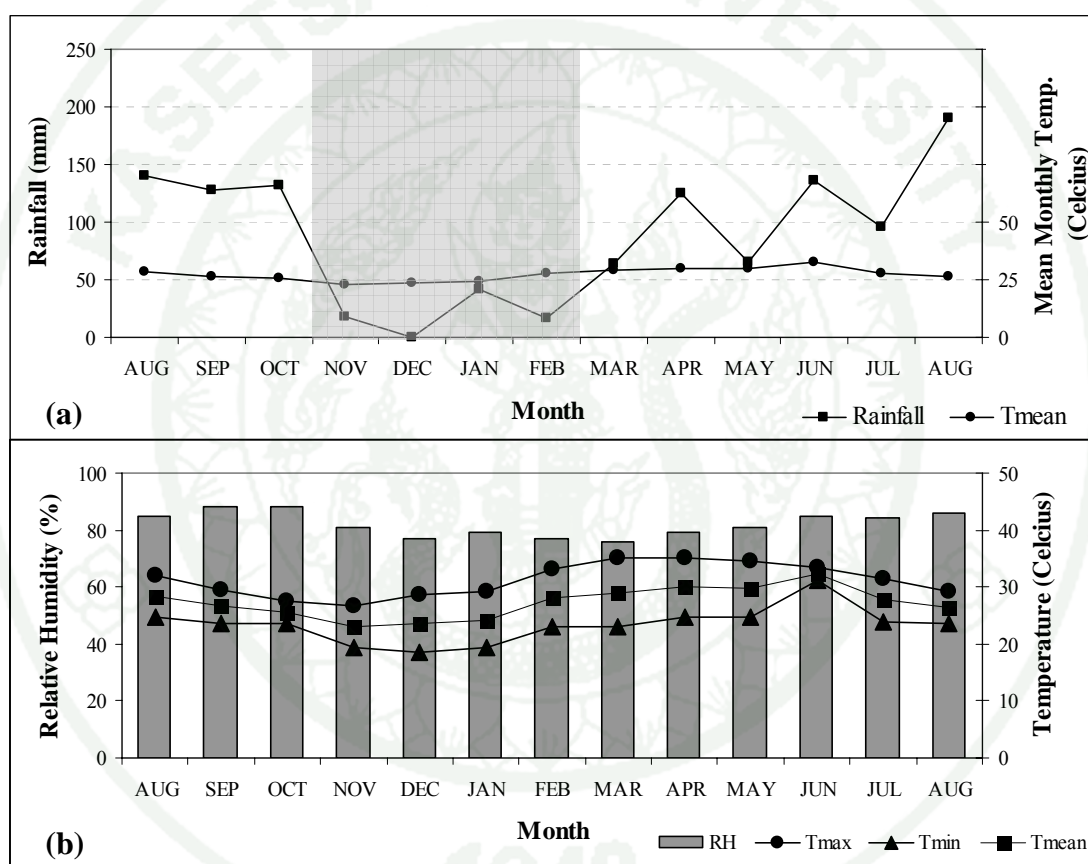
During the investigated periods of September 2009-August 2010, the recorded climatic data derived from SERS were shown in Figure 45. Following the criteria of Walter and Lieth (1964), the curve of mean monthly temperature ( $T_{\text{mean}}$ ) which was higher than the curve of total monthly rainfall (Rainfall) as shown in Figure 45a indicated dry period in November -February, while increased rainfall curve in other months generated wet condition. Relative humidity (RH) and mean monthly maximum ( $T_{\text{max}}$ ) - minimum ( $T_{\text{min}}$ ) temperatures also illustrated their characteristics as shown in Figure 45b.



**Figure 44** Tree ring data of *Tectona grandis*: (a) mean ring width; (b) tree-ring index; (c) statistical values of EPS and Rbar; and (d) sample depth. EPS and Rbar were indicated by using thick and thin lines, respectively.

Using simple correlation analysis, Tmax was not significantly correlated with Tmin, but these 2 parameters were significantly correlated with Tmean ( $r = 0.88$  and  $0.90$ , respectively at  $p = 0.00$ ). Similar to Rainfall and RH, these 2 parameters

also showed a significant correlation ( $r = 0.76$ ,  $p = 0.01$ ). Moreover,  $T_{min}$  also exhibited the significant correlation with Rainfall ( $r = 0.63$ ,  $p = 0.03$ ). Therefore, to minimize the effect of the multicollinearity on these independent variables, these variables might be set as covariance factors in path analysis or transformed to new variables which were able to explain all independent variables when analyzed factors affecting tree growth using multiple regression analysis.



**Figure 45** Recorded climatic data derived from SERS (August 2009-August 2010). Gray band in figure 40a indicated dry period in November 2009-February 2010.

Soil moisture contents at Wang Nam Khiao Forestry Student Practice Station (WKNFSPS) and 3 points at Sakaerat Environmental Research Station (SERS: SERS1, SERS2 and SERS3) as shown in Figure 6 were determined once a month in August 2009 till August 2010. In each point, 3 replications of soil samples at the

depth of 5, 10, 15, 20, 25, 30, 50, 70 and >70 cm were cored by using a soil auger. However, soil samples could not collect deeper than 30 cm depth in several months of dry periods. Therefore, the common intervals of soil depth using in this study was ranged from 0-30 cm. As shown in Table 25 and Figure 46, soil moisture contents in the wet period from the upper soil, especially in 0-5 and 5-10 cm, were higher than other soil depths. Soil moisture contents in every soil depths seem to be equalized in the common dry periods of November 2009 till February 2010, while soil moisture contents in the dry evergreen forest of SERS were higher than WNKFSPS.

Soil moistures in all depths and all sites gently declined from August 2009 till February 2010 (Figure 46) as similar as declined rainfall and relative humidity in the same periods (Figure 45a). Although rainfall were diminutive increase in January and February, the increased temperature (Figure 45a and 45b) also induced high evaporation and soil moisture in all soil depths still continuously declined in these 2 months (Figure 46).

## 7.2 The description of phenology and wood formation relating to climate

Based on the calendar date from January-December, *A. xylocarpa* firstly flushed their leaves in January as similar as *M. azedarach* and were followed by *T. grandis* in March, *L. duperreana* in April, and *A. odoratissima* in August, while the period of leaf flushing could not detected in *H. illicifolia*. Mature light and dark green leaves commonly found in monsoon season (March-November). Mature light green leaves of *A. xylocarpa* also found associated with leaf flushing in the late of cool and dry period (January), while mature light green leaves of other species occurred in the first half of rainy season (March-July). Mature light green leaves of *A. odoratissima* and *T. grandis* were abundantly found in April-May, while *M. azedarach* and *L. duperreana* plentifully occurred in June. Mature light green leaves of *H. illicifolia* were rarely detected at the beginning of the second half of rainy season in August. Mature dark green leaves were abundantly found associated with mature light green leaves and continuously occurred until the end of rainy season. Phenologies of these 6 tree species were shown in Figure 8-13 and Table 7-12.

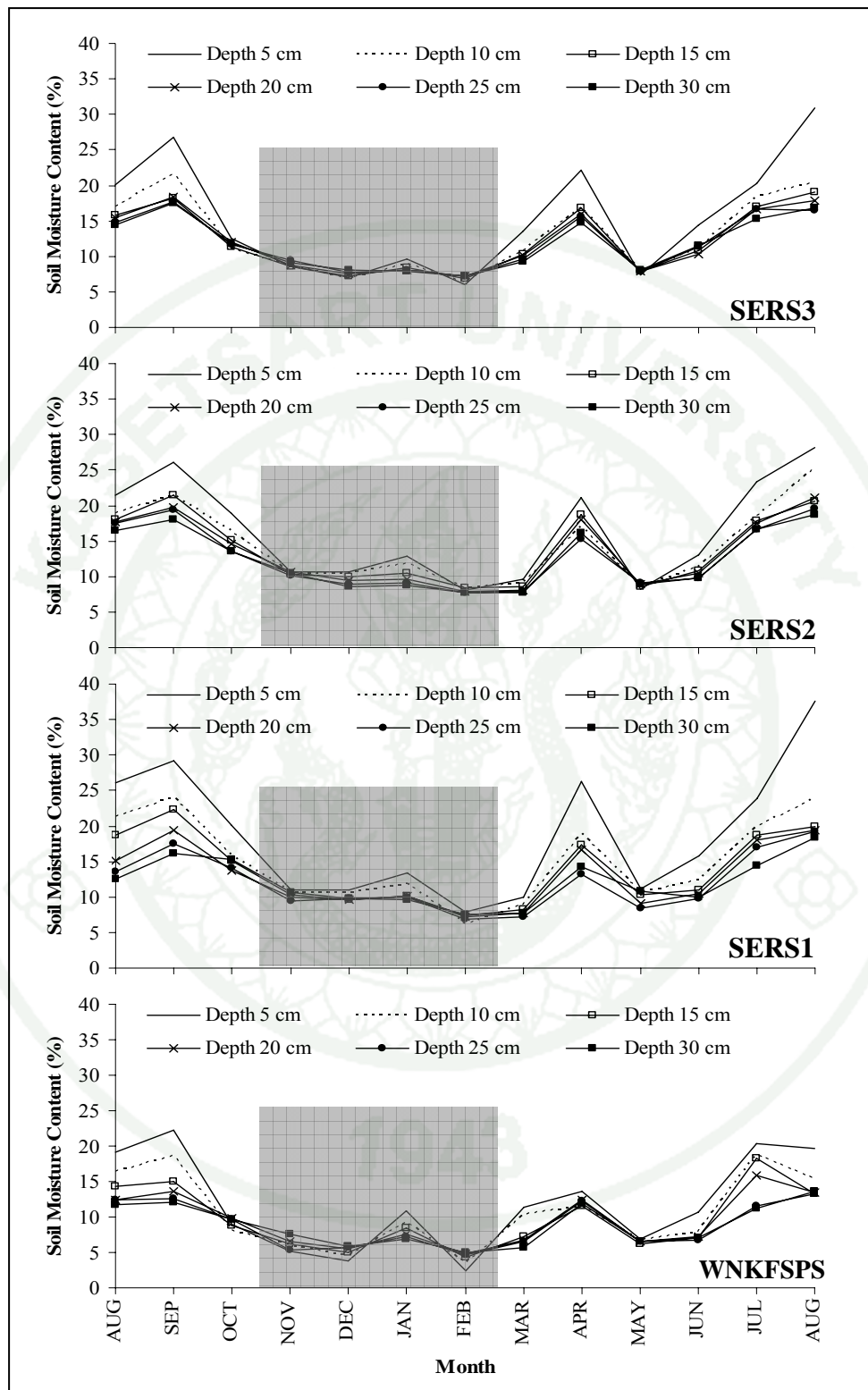
**Table 25** Monthly soil moisture contents (%) in August 2009 – August 2010 from WNKFSPS and SERS.

Month	WNKFSPS							SERS1						
	0-5	5-10	10-15	15-20	20-25	25-30	Mean	0-5	5-10	10-15	15-20	20-25	25-30	Mean
AUG	19.1	16.4	14.4	12.4	12.4	11.7	14.4	26.2	21.3	18.7	15.1	13.6	12.6	17.9
SEP	22.2	18.6	15.1	13.6	12.6	12.1	15.7	29.2	24.0	22.4	19.4	17.6	16.1	21.5
OCT	9.0	8.0	8.8	9.8	9.7	9.6	9.1	20.1	15.8	15.0	13.8	14.0	15.3	15.7
NOV	5.2	6.0	6.2	6.5	5.3	7.6	6.1	11.0	10.7	10.4	10.0	9.4	10.6	10.3
DEC	3.7	4.5	5.0	5.6	5.7	5.8	5.0	11.0	10.7	9.6	9.6	9.8	9.8	10.1
JAN	10.9	9.3	8.4	7.6	7.2	6.8	8.4	13.3	11.8	10.1	10.1	9.9	9.6	10.8
FEB	2.5	3.5	4.3	4.8	4.7	4.9	4.1	7.8	6.2	7.3	7.2	6.9	7.6	7.2
MAR	11.4	10.4	7.3	6.8	6.5	5.6	8.0	10.0	9.0	8.3	7.8	7.2	7.8	8.3
APR	13.6	11.5	11.6	12.3	12.2	12.0	12.2	26.2	18.8	17.3	16.6	13.2	14.3	17.8
MAY	6.9	6.6	6.2	6.5	6.6	6.6	6.6	11.2	10.7	10.3	9.1	8.3	10.8	10.1
JUN	10.7	8.0	7.2	7.2	6.7	7.0	7.8	15.8	12.3	11.0	10.5	9.8	9.9	11.5
JUL	20.3	18.8	18.3	15.9	11.6	11.3	16.0	23.8	19.9	18.7	18.0	17.0	14.4	18.6
AUG	19.6	15.4	13.3	13.5	13.2	13.7	14.8	37.5	23.9	19.9	19.4	19.2	18.4	23.1
<b>Mean</b>	11.9	10.5	9.7	9.4	8.8	8.8	9.9	18.7	15.0	13.8	12.8	12.0	12.1	14.1

Table 25 (Continued)

Month	SERS2						SERS3							
	0-5	5-10	10-15	15-20	20-25	25-30	Mean	0-5	5-10	10-15	15-20	20-25	25-30	Mean
AUG	21.5	18.8	18.1	17.7	17.5	16.5	18.4	20.1	17.1	15.7	15.5	14.7	14.4	16.2
SEP	26.0	21.5	21.4	19.7	19.5	18.0	21.0	26.8	21.6	18.3	18.3	17.6	17.4	20.0
OCT	18.9	16.3	15.2	14.5	13.6	13.6	15.4	12.6	11.0	11.3	11.9	11.7	11.9	11.7
NOV	10.7	10.5	10.2	10.7	10.1	10.4	10.4	8.6	8.7	8.5	8.8	9.4	9.1	8.8
DEC	10.6	10.5	10.0	9.5	8.9	8.6	9.7	7.0	6.8	7.2	7.5	7.6	8.1	7.4
JAN	12.9	11.8	10.4	9.6	9.1	8.7	10.4	9.6	9.0	8.4	8.1	8.1	7.9	8.5
FEB	8.0	8.4	8.3	7.9	7.8	7.7	8.0	6.0	6.4	6.8	7.3	7.2	7.2	6.8
MAR	9.6	9.1	8.5	8.1	7.9	7.8	8.5	13.6	10.8	10.3	10.1	9.7	9.3	10.6
APR	21.0	16.9	18.7	18.0	15.3	16.1	17.7	22.1	16.9	16.8	16.0	15.7	14.8	17.0
MAY	8.2	8.5	8.6	9.0	9.1	8.9	8.7	7.4	7.9	7.9	7.9	7.9	8.1	7.8
JUN	13.1	11.3	10.9	10.4	9.8	9.8	10.9	14.3	11.1	10.7	10.3	11.3	11.5	11.6
JUL	23.3	18.5	17.8	17.4	16.7	16.7	18.4	20.3	18.4	17.0	16.7	16.6	15.3	17.4
AUG	28.2	25.2	20.7	21.1	19.6	18.8	22.2	30.9	20.5	19.0	17.8	16.5	16.8	20.2
<b>Mean</b>	21.5	18.8	18.1	17.7	17.5	16.5	18.4	20.1	17.1	15.7	15.5	14.7	14.4	16.2

**Remark:** Soil moisture contents in the dry periods were shown in dash box.



**Figure 46** Percents of soil moisture contents in August 2009-August 2010 from WNKFSPS and SERS. Gray bands indicated common dry periods of all selected locations in November 2009-February 2010.

In cool and dry period (December-February), leaf abscission occurred in *A. xylocarpa*, *M. azedarach*, *T. grandis*, and *L. duperreana*, while mature dark green leaves still plentifully occurred in *A. odoratissima* and *H. illicifolia*. Based on the pheno-phase of leafless, these 6 tropical tree species could be divided to 2 groups of deciduous (*A. xylocarpa*, *M. azedarach*, *T. grandis*, and *L. duperreana*) and evergreen species (*A. odoratissima* and *H. illicifolia*). In case of flower and fruit phenology of deciduous trees, flower bud burst occurred after leaf flushing for 1-3 months. It was similar to young fruits which were found after flower bud burst for 1-3 months. However, flower and fruit phenology of 2 evergreen species were not found over the investigated periods.

All tree species produced abundant leaves throughout the rainy season, while *A. odoratissima* and *H. illicifolia* produced leaf crowns throughout the year. Four deciduous tree species illustrated leaf flushing at the beginning of rainy season following by leaf maturation in rainy season and leaf abscission during the dry and cold season at the end of the year. The patterns of leaf production were similar to the observation of deciduous species in several regions (Venugopal and Liangkuwang, 2007; Lisi *et al.*, 2008; Sun *et al.*, 1996; Valdez-Hernandez *et al.*, 2010) also stated that, in deciduous and tropical species, leaf flushing was generally determined by the beginning of the rainy season, while leaf fall depended on the duration of dry periods.

The two tropical evergreen species illustrated leaf maturation throughout the year, while young leaves were abundantly found in rainy season and leaf abscission rarely found throughout the year. Xiao *et al.* (2006) suggested that leaf phenology in tropical evergreen forests was not determined by the seasonality of precipitation but was driven by availability of solar radiation. Williams *et al.* (2008) studied leaf phenology of *Aglaia odorata* and *A. spectabilis* growing in western Thailand and also found the evergreen characteristic and leaf flushing at the beginning of rainy season.

According to monthly wood increment in Table 19-24 and Figure 20-37, all of 4 deciduous tree species illustrated dormancy in cool and dry period at the end

of the year, while rapid growth occurred during the monsoon season followed by the slow growth at the end of this season. The rapid growth of *M. azedarach* were stimulated in February-September 2010 for 12.02 mm (77.04% of total annual growth), while the rapid growth of *T. grandis* and *A. xylocarpa* occurred in April-September 2010 for 3.93 mm (78.91% of total annual growth) and 10.36 mm (74.66% of total annual growth), respectively. Tree growth of *L. duperreana* rapidly occurred during May-September 2010 for 2.10 mm (74.87% of total annual growth) and slowly occurred during September-November 2009 for 0.72 mm (23.91% of total annual growth). In case of evergreen tree species, *A. odoratissima* and *H. illicifolia* illustrated the continuous growth through out the year, but rapid growth occurred in July-August 2010 for 0.75 mm (45.85% of total annual growth) and July-September 2010 for 0.89 mm (88.49% of total annual growth), respectively.

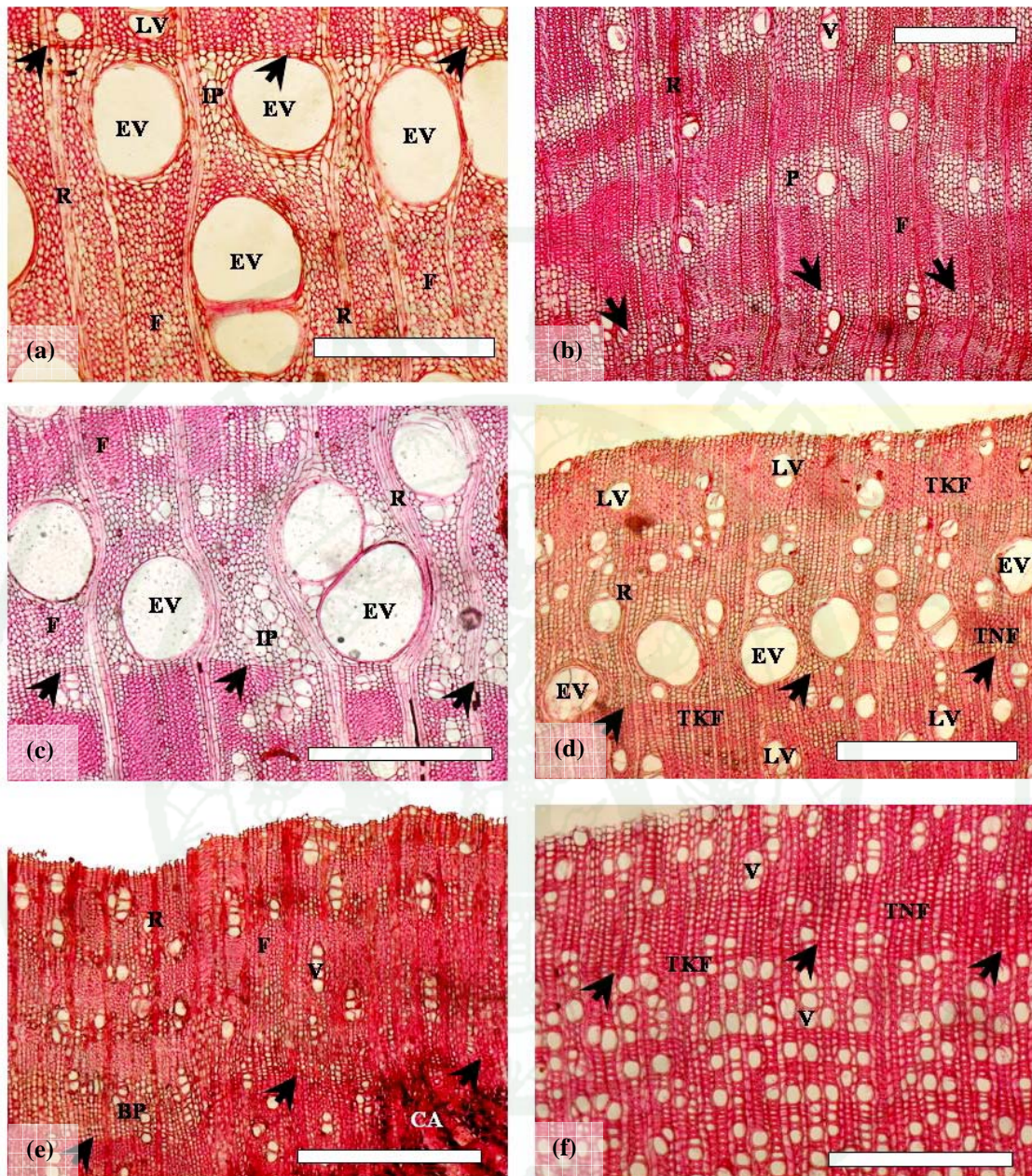
Monthly wood increment of all deciduous trees initiated in the month of leaf flushing or a month later and cessation occurred in the month of leaf shedding, while wood increment of evergreen trees illustrated the continuous growth throughout the year. However, growth rates of all species rapidly increased and maximized in the first half of rainy season. Several authors claimed that lower rainfall during the winter strongly reduced wood increment, while wet condition during the rainy season induced wood increment in both of broad leaf and long leaf trees (Lisi *et al.*, 2008; Singh and Venugopal, 2011). Cufar *et al.* (2008) found the leaf unfolding immediately following by reactivation of cambial cells and the 75% of the tree-ring was formed in the first half of the average time of cambial activity. In case of evergreen tree species, there are few investigations on wood formation. Sass *et al.* (1995) found a continuous process in wood formation of *Dryobalanops sumatrensis* and *Shorea leprosula*, which was not related to seasonality in rainfall and phenology.

Using manual band dendrometers, the averages of outside bark diameter increments of *T. grandis*, *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima*, and *H. illicifolius* during the investigated periods were 7.22, 9.42, 11.82, 1.17, 0.24, and -0.45 mm, respectively (Figure 14-19 and Table 13-18). Monthly outside bark diameter increment of each tree was normalized using z-score

calculation (Kirkwood and Sterne, 2003). Normalized monthly outside bark diameters of all trees in each species were averaged and illustrated outside bark diameter fluctuations during the investigated periods. Outside bark diameters of all tree species increased in rainy season (March-September) and shrank in cool and dry period at the end of the year (October-February).

In rainy season, outside bark diameters of all species rapidly increased until the end of investigated period in September 2010 as similar as the increment of wood formation. Pelissier and Pascal (2000) stated that circumference variations originated from hydrostatic stem flexibility were depended on rainfall through the soil moisture status and the degree of turgidity or water stress of the tree.

To evaluate annual ring characteristics occurring in each month, all of 4 deciduous tree species were defined as distinct annual ring species, while the rest of 2 evergreen tree species were defined as indistinct annual ring species. Based on vessel characteristics, wood porosity of *L. duperreana* was ring porous with solitary and multiple pores (Figure 29), while *T. grandis* (Figure 20) and *M. azedarach* (Figure 26) were semi-ring porous with solitary and multiple pores. Although, *A. xylocarpa* was a distinct ring species, its porosity was diffuse-ring porous with solitary and multiple pores (Figure 23) as similar as *A. odoratissima* (Figure 32), and *H. ilicifolia* (Figure 35). Initial banded parenchyma of *M. azedarach* (Figure 26) and *T. grandis* (Figure 20) and banded parenchyma-liked fiber of *L. duperreana* (Figure 29) differentiated at the beginning of growing season in hot and wet period (in February, April, and May, respectively), while the terminal parenchyma of *A. xylocarpa* (Figure 23) differentiated at the end of this growing season in September. Terminal parenchyma was not found in *A. odoratissima* (Figure 32) and *H. ilicifolia* (Figure 35). The changing of fiber diameters might be used as annual ring indicators of these two species, but it was difficulty to identify by using a low magnified microscope (4x-40x) which was widely used in tree-ring measuring system. Therefore, the additional technique in micro-sectioning of the transverse surfaces must be required for sample preparation in annual ring investigation. Annual ring characteristics in transverse surfaces of all selected species were shown in figure 47.



**Figure 47** Annual ring characteristics of 6 selected tree species: (a) *Tectona grandis*; (b) *Afzelia xylocarpa*; (c) *Melia azedarach*; (d) *Lagerstroemia duperreana*; (e) *Aglaia odoratissima*; (f) *Hydnocarpus ilicifolia*. White bands indicated the length of 500  $\mu\text{m}$ . Black arrow heads indicated annual ring boundaries.

Initial banded parenchyma associated with large diameter vessels in earlywood was the marked point for annual ring initiation in *T. grandis* (Figure 47a). It was similar to the occurrences of annual ring markers in *M. azedarach* which initial

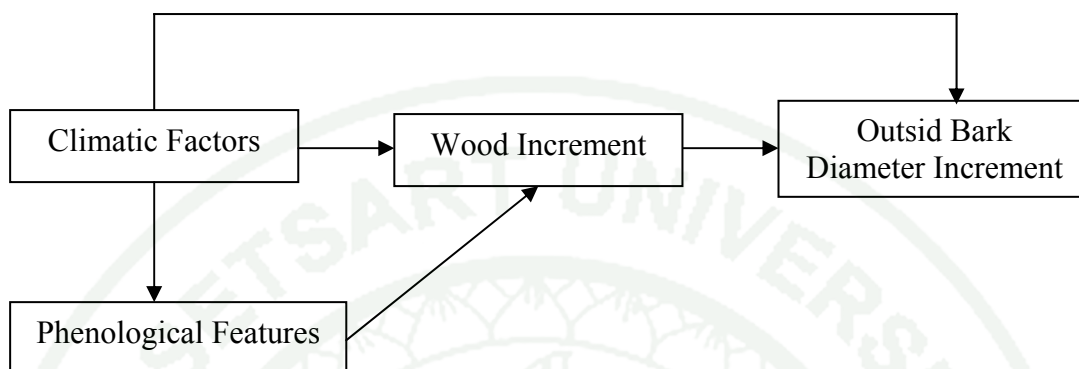
banded parenchyma (IP) was also found associating with large diameter vessels in earlywood (Figure 47c). The occurrences of annual rings in *L. duperreana* seem similar to *T. grandis* and *M. azedarch* but large diameter vessels in earlywood (EV) were found associated with thin wall fiber (TNF) instead of initial banded parenchyma (Figure 47d). Banded parenchyma in *A. xylocarpa* (Figure 47b) formed at the end of growing season while banded parenchyma in *T. grandis* and *M. azedarch* forming at the beginning of growing season. Banded parenchyma (BP) formed at the beginning of annual ring in *A. odoratissima* (Figure 47e), while thin wall fiber (TNF) formed at the beginning of annual ring in *H. ilicifolia* (Figure 47f). *A. odoratissima* and *H. ilicifolia* also illustrated thick wall fibers (TKF) at the end of growing season as similar as *L. duperreana* but wood porosity of these two evergreen species were diffuse while *L. duperreana* illustrated semi-ring porous characteristic.

According to the studies of de Pernia and Melandri (2006), Marcati *et al.* (2006) and Roig *et al.* (2005), the presences of marginal parenchyma, vessel diameter in earlywood and latewood, and thick wall fiber in latewood were the most common characteristics forming tree-ring. However, these authors did not give more details on the structures and detectable markers for annual ring identification on their selected tree species. Using cambial marking technique, several researches indicated tree species producing annual rings by marginal parenchyma and thick walled latewood (Lisi *et al.*, 2008; Marcati *et al.*, 2008; Nobushi *et al.*, 1995).

### 7.3 Intercorrelation between climatic factors on phenology and wood increment

As the activation of wood increment and phenological changes at the beginning of September 2009 to the end of September 2010, climatic data influenced both of the phenological events and the formation of wood. This section described how much climatic data induced monthly wood increment and phenological features and how much phenological events also induced tree growth. Following the general growth model of Fritts (1976), the variables were grouped, re-arranged, and illustrated

as the relationship among climatic factors, phenology, and wood increment as shown in figure 48.



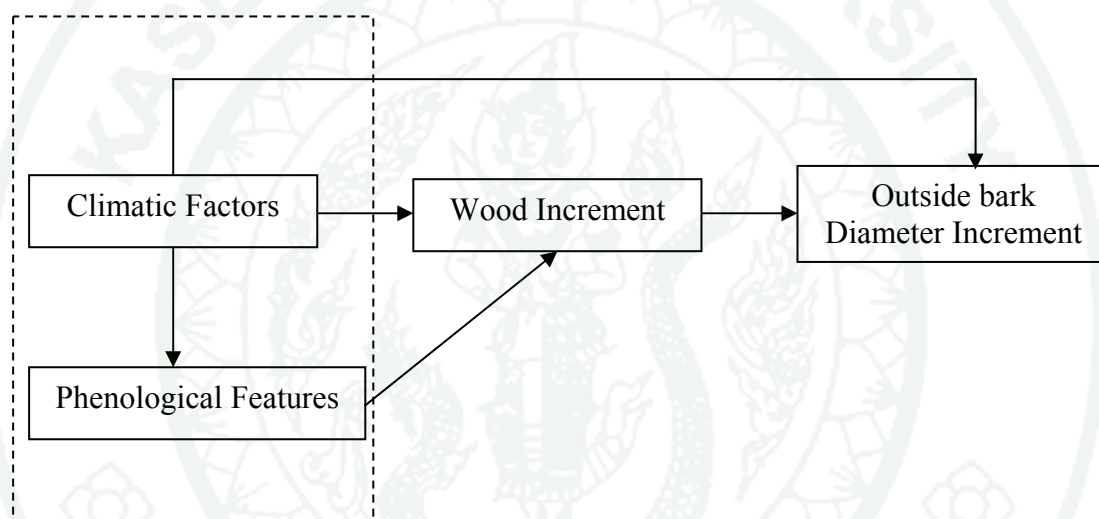
**Figure 48** Conceptual model of climate-growth response. Climatic and phenological factors induced wood increment in both direct and indirect pathways.

From the model, phenological data merely showed the relationships with climatic data, while wood increment showed the correlation both phenological and climatic data. The fluctuations and increments of outside bark diameters were directly conducted by wood increments and climatic factors, while phenological features illustrated the indirect influences of outside bark diameter increment through wood increment. The relationship between phenology and climatic factors, wood increment and climatic factors, wood increment and phenology, climatic factors and outside bark diameter increment, and among these factors were respectively described.

### 7.3.1 The relationship of phenology with climate

From Figure 49, the adaptation of conceptual model of climate-growth response as shown in Figure 48, climatic factors and phenological features placed in dash box were analyzed their relationship. Monthly climatic factors including mean monthly maximum temperature ( $T_{max}$ ), mean monthly minimum temperature ( $T_{min}$ ), mean monthly mean temperature ( $T_{mean}$ ), mean monthly relative humidity (RH), total monthly rainfall (Rainfall), and soil moisture (SM) in each 5 cm depth of 30 cm were correlated with phenological factors of leaves,

flowers, and fruits. Pheno-phases of leaves were leaf flushing (LF), mature light green leaves (MLL), mature dark green leaves (MDL), and leaf abscission (LA). Flower pheno-phases were flower bud bursts (FB), flower maturation (FM) and flower fading (FF), while fruit pheno-phases were young fruit (YF), mature fruit (MF), and ripe fruit (RF). The phenological features in each tree species were related to monthly climatic data using simple correlation analysis. *T. grandis* was firstly explained followed by *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.



**Figure 49** Conceptual model of climate-growth response: focused on the relationship of climatic and phenological factors. Dash box indicated variables for the analysis of simple correlation of climatic and phenological factors.

#### 7.3.1.1 *Tectona grandis* L.f.

For leaf phenology of teak trees, the beginning of leaf flushing (LF) were firstly found on March 2010 and continuously founded until July 2010 (Figure 8a and Table 7). The analysis of simple correlation was conducted to examine the relationship between leaf flushing (LF) and various climatic data. The analysis indicated that leaf flushing (LF) was not significantly correlated with all climatic and soil moisture data, but the highest correlation was associated with Tmax ( $r = 0.554$ ,  $p = 0.062$ ; Table 26). It could explained that the increasing Tmax at the

transitional periods of summer and rainy seasons in March till the first half of rainy season in June was found associated with leaf flushing (LF). In case of mature light green leaf (MLL), it was rapidly increasing in April and May after leaf flushing (LF) emerged in March as shown in Figure 8a and Table 7, but could not be significantly correlated with all selected climatic data. However, it showed the highest correlation with Tmax ( $r = 0.459$ ,  $p = 0.133$ ; Table 26) and could be explained that the increased Tmax at the transitional periods of summer and rainy seasons in April and May was found associated with the abundances of mature light green leaf (MLL).

The phenology of mature dark green leaf (MDL) was abundantly found in June through the end of rainy season in October and rarely found in the dry periods at the beginning of the year (Figure 8a and Table 7). The analysis indicated the occurrences of mature dark green leaf (MDL) positively and significantly correlated with RH ( $r = 0.827$ ,  $p = 0.001$ ) and Tmax ( $r = -0.661$ ,  $p = 0.019$ ; Table 26). The increasing RH and declined Tmax in rainy season, especially in June till November, were commonly found associated with the abundance of mature dark green leaf (MDL). At the end of rainy season till the dry periods at the beginning of the year, the occurrences of leaf abscission (LA) were found associated with the declination of rainfall, SM25 and SM30. As shown in Table 26, the analysis of simple correlation indicated the significantly correlation of leaf abscission (LA) with rainfall for  $r = -0.635$  ( $p = 0.026$ ), SM25 for  $r = -0.592$  ( $p = 0.042$ ) and SM30 for  $r = -0.618$  ( $p = 0.032$ ).

The occurrences of flower bud burst (FB), flower maturation (FM) and flower fading (FF) had a significant and positive correlation with rainfall for  $r = 0.578$  ( $p = 0.049$ ),  $0.624$  ( $p = 0.030$ ) and  $0.793$  ( $p = 0.002$ ), respectively. Not only the positive correlation with rainfall, flower fading (FF) was significantly correlated with Tmin ( $r = 0.636$ ,  $p = 0.026$ ) and RH ( $r = 0.663$ ,  $p = 0.019$ ) (Table 26). These flower pheno-phases were found during rainy season in June till August after rainfall deficit occurred in May, while flower fading (FF) was also found in the late of rainy season in September and October when Tmin dropped and RH increased (Figure 8b and Table 7).

**Table 26** Simple correlation analysis of *Tectona grandis* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
LF	1									
MLL	.489	1								
MDL	-.232	-.265	1							
LA	-.243	<b>-.672*</b>	-.141	1						
FB	.192	-.094	.537	-.140	1					
FM	.000	-.073	.572	-.217	<b>.775**</b>	1				
FF	.000	<b>.597*</b>	.349	-.728**	.192	.447	1			
YF	-.447	-.073	.572	-.542	.258	.400	.447	1		
MF	.000	<b>.658*</b>	-.343	-.408	.158	.000	<b>.632*</b>	1	1	
RF	-.192	.094	-.537	.140	<b>-1.000**</b>	<b>-.775**</b>	-.192	-.258	-.408	1
Tmax										
Tmin										
Tmean										
RH										
Rain										
SM5										
SM10										
SM15										
SM20										
SM25										
SM30										

Table 26 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	.554	.404	.540	-.181	-.005	.005	.035	.036	.008	-.118	-.085
MLL	.459	.339	.446	.088	.249	.052	.038	.086	.164	.243	.254
MDL	<b>-.661*</b>	.155	-.269	<b>.827**</b>	.563	.447	.397	.402	.437	.421	.551
LA	-.353	-.475	-.468	-.424	<b>-.636*</b>	-.485	-.451	-.413	-.490	<b>-.592*</b>	<b>-.618*</b>
FB	.063	.538	.347	.453	<b>.578*</b>	.508	.469	.502	.492	.383	.415
FM	.038	.572	.355	.405	<b>.624*</b>	.270	.150	.102	.150	.216	.273
FF	.154	<b>.636*</b>	.453	<b>.663*</b>	<b>.793**</b>	.372	.267	.252	.369	.555	.551
YF	-.268	.048	-.119	.566	<b>.588*</b>	<b>.682*</b>	<b>.631*</b>	.527	.550	<b>.655*</b>	<b>.675*</b>
MF	-.454	-.136	-.327	.512	.295	<b>.621*</b>	<b>.664*</b>	<b>.666*</b>	<b>.635*</b>	.511	<b>.638*</b>
RF	-.063	-.538	-.347	-.453	<b>-.578*</b>	-.508	-.469	-.502	-.492	-.383	-.415
Tmax	1	.573	<b>.878**</b>	-.392	.084	.007	-.007	-.060	-.075	-.055	-.183
Tmin		1	<b>.895**</b>	.421	<b>.630*</b>	.282	.201	.182	.209	.227	.183
Tmean			1	.031	.412	.168	.113	.072	.079	.101	.005
RH				1	<b>.752**</b>	<b>.601*</b>	.553	<b>.576*</b>	<b>.620*</b>	<b>.631*</b>	<b>.676*</b>
Rain					1	<b>.738**</b>	<b>.649*</b>	<b>.630*</b>	<b>.714**</b>	<b>.812**</b>	<b>.794**</b>
SM5						1	<b>.987**</b>	<b>.941**</b>	<b>.918**</b>	<b>.889**</b>	<b>.835**</b>
SM10							1	<b>.967**</b>	<b>.932**</b>	<b>.867**</b>	<b>.813**</b>
SM15								1	<b>.981**</b>	<b>.892**</b>	<b>.857**</b>
SM20									1	<b>.951**</b>	<b>.930**</b>
SM25										1	<b>.968**</b>
SM30											1

**Remark:** \* Correlation is significant at the 0.05 level (2-tailed).

\*\* Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 7, the occurrences of young fruit (YF), mature fruit (MF) and ripe fruit (RF) were significantly correlated with rainfall and soil moisture. The occurrence of young fruit (YF) was significantly correlated with rainfall, SM5, SM10, SM25 and SM30 for  $r = 0.588$  ( $p = 0.044$ ),  $0.682$  ( $p = 0.015$ ),  $0.631$  ( $p = 0.028$ ),  $0.655$  ( $p = 0.021$ ) and  $0.675$  ( $p = 0.016$ ), respectively. Mature fruit (MF) illustrated significantly correlated with SM5, SM10, SM15, SM20 and SM30 for  $r = 0.621$  ( $p = 0.031$ ),  $0.664$  ( $p = 0.018$ ),  $0.666$  ( $p = 0.018$ ),  $0.635$  ( $p = 0.026$ ) and  $0.638$  ( $p = 0.026$ ), respectively. Ripe fruit (RF) was only significantly correlated with rainfall for  $r = -0.578$  ( $p = 0.049$ ). It could be interpretation that young fruit (YF) and mature fruit (MF) were commonly found in the mid till the end of rainy season, while ripe fruit (RF) was found later in the dry period at the end of the year (Figure 8c and Table 7).

#### 7.3.1.2 *Afzelia xylocarpa* (Kurz) Craib.

The analysis of simple correlation was conducted to examine the relationship between phenological characteristics and climatic data. As shown in Table 27, the analysis indicated that leaf flushing (LF), mature light green leaf (MLL), leaf abscission (LA) and all flower pheno-phases were not significantly related to climatic data, while young fruit (YF) could not be analyzed the correlation with climatic data due to disappear during the investigated periods.

Mature dark green leaf (MDL) was abundantly found all the year except the declination and absent in December and January, respectively (Figure 9a and Table 8). Simple correlation indicated that the occurrences of mature dark green leaf (MDL) were positively and significantly correlated with  $T_{min}$ ,  $T_{mean}$ , rainfall, and SM in all depths of 0-30 cm.  $T_{min}$ ,  $T_{mean}$ , and Rainfall showed the correlation with mature dark green leaf (MDL) for  $r = 0.650$  ( $p = 0.022$ ),  $0.605$  ( $p = 0.037$ ) and  $0.667$  ( $p = 0.018$ ), respectively. Correlation coefficients of mature dark green leaf (MDL) with SM5, SM10, SM15, SM20, SM25 and SM30 were  $0.609$  ( $p = 0.036$ ),  $0.586$  ( $p = 0.045$ ),  $0.609$  ( $p = 0.035$ ),  $0.602$  ( $p = 0.038$ ),  $0.605$  ( $p = 0.037$ ) and  $0.614$  ( $p = 0.034$ ), respectively (Table 27). It could indicate that mature dark green

**Table 27** Simple correlation analysis of *Afzelia xylocarpa* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
LF	1									
MLL	.460	1								
MDL	-.502	.130	1							
LA	-.130	-0	.061	1						
FB	-.196	.213	-.055	-.302	1					
FM	-.196	.213	-.055	-.302	<b>1.000**</b>	1				
FF	-.196	.213	.166	-.091	-.091	1				
YF	.a	.a	.a	.a	.a	.a	1			
MF	-.291	.316	0.246	.000	-.135	-.135	.674*	1		
RF	.460	.250	-.389	.354	0.2132	0.2132	-.426	.a	1	
Tmax										
Tmin										
Tmean										
RH										
Rain										
SM5										
SM10										
SM15										
SM20										
SM25										
SM30										

Table 27 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	-.208	-.383	-.334	-.149	-.367	-.314	-.232	-.271	-.285	-.277	-.328
MLL	.224	.131	.202	-.213	-.145	-.196	-.227	-.248	-.295	-.290	-.318
MDL	0.416	<b>.650*</b>	<b>.605*</b>	0.424	<b>.667*</b>	<b>.609*</b>	<b>.586*</b>	<b>.609*</b>	<b>.602*</b>	<b>.605*</b>	<b>.614*</b>
LA	-.548	.034	-.279	.422	0.197	.086	.064	.101	.109	0.156	0.186
FB	.202	-.015	.099	-.345	-.036	-.342	-.351	-.344	-.327	-.348	-.356
FM	.202	-.015	.099	-.345	-.036	-.342	-.351	-.344	-.327	-.348	-.356
FF	.398	-0.02	.211	-.042	-.011	-.051	-.092	-.104	-.122	-.154	-.182
YF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
MF	.475	.544	<b>.580*</b>	-.135	.125	-0.05	-0.12	-0.13	-0.17	-0.130	-0.13
RF	-.521	-.541	<b>-.601*</b>	-.043	-.036	-.383	-.366	-.350	-.334	-.367	-.355
Tmax	1	.573	<b>.878**</b>	-.392	.084	-.002	-.019	.012	-.028	-.025	-.067
Tmin		1	<b>.895**</b>	.421	<b>.630*</b>	.305	.280	.300	.284	.335	.347
Tmean			1	.031	.412	.176	.152	.180	.149	.180	.164
RH				1	<b>.752**</b>	<b>.587*</b>	<b>.619*</b>	<b>.597*</b>	<b>.632*</b>	<b>.654*</b>	<b>.705*</b>
Rain					1	<b>.838**</b>	<b>.781**</b>	<b>.808**</b>	<b>.792**</b>	<b>.790**</b>	<b>.827**</b>
SM5						1	<b>.976**</b>	<b>.978**</b>	<b>.962**</b>	<b>.945**</b>	<b>.959**</b>
SM10							1	<b>.991**</b>	<b>.989**</b>	<b>.981**</b>	<b>.980**</b>
SM15								1	<b>.995**</b>	<b>.987**</b>	<b>.984**</b>
SM20									1	<b>.993**</b>	<b>.989**</b>
SM25										1	<b>.992**</b>
SM30											1

**Remark:** \* Correlation is significant at the 0.05 level (2-tailed); \*\* Correlation is significant at the 0.01 level (2-tailed).

a. Cannot be computed because at least one of the variables is constant.

leaf (MDL) commonly occurred in rainy season when rainfall and soil moisture were higher than other seasons.

The occurrences of mature fruit (MF) had a positive and significant correlation with  $T_{\text{mean}}$  ( $r = 0.580$ ,  $p = 0.048$ ), while ripe fruit (RF) had a negative and significant correlation with this climatic factor ( $r = 0.601$ ,  $p = 0.039$ ). In March and June which was the beginning of rainy season and  $T_{\text{mean}}$  was increase, mature fruit (MF) was found followed by ripe fruit (RF) in dry and cold period at the end of the year (Figure 9c). Therefore, the abundances of mature fruit (MF) and ripe fruit (RF) could be explained by the increasing and declined temperatures which respectively occurred at the mid and the end of each year.

#### 7.3.1.3 *Melia azedarach* L.

The beginning of leaf flushing (LF) was firstly found on January 2010 and continuously founded until July 2010, while mature light green leaf (MLL) and mature dark green leaf (MDL) were commonly found all the year except in the dry and cold period at the end of the year. A small amount of leaf abscission (LA) continuously found from May to the end of the year. The analysis of simple correlation was conducted to examine the relationship between these phenological stages and various climatic data including percent of soil moisture. The analysis showed insignificant correlation of leaf abscission (LA), flower bud burst (FB) and flower maturation (FM) on climatic data, while flower fading (FF) and young fruit (YF) could not be analyzed due to disappear during the investigated periods (Table 28).

Although climate in January was dry and cold, the increase temperature in this month till June was found associated with leaf flushing (LF). Using simple correlation analysis, the occurrence of this pheno-phase was significantly correlated with  $T_{\text{max}}$  and  $T_{\text{mean}}$  for 0.814 ( $p = 0.001$ ) and 0.678 ( $p = 0.015$ ), respectively. Mature light green leaf (MLL) was another leaf pheno-phase which was found associated with leaf flushing (LF) in January through the end of

rainy season and abundantly found in June (Figure 10a). The relationship between mature light green leaf (MLL) and climatic data examined using simple correlation analysis indicated that the occurrences of mature light green leaf (MLL) were positively and significantly correlated with  $T_{min}$  ( $r = 0.746$ ,  $p = 0.005$ ) and  $T_{mean}$  ( $r = 0.676$ ,  $p = 0.016$ ). It was also found that mature light green leaf (MLL) abundantly occurred in June when  $T_{min}$  and  $T_{mean}$  were higher than other months.

Simple correlation of mature dark green leaf (MDL) which was abundantly found in February to November, declined in December, and absent in January (Figure 10a) indicated the correlation with rainfall ( $r = 0.630$ ,  $p = 0.028$ ). The abundances of mature dark green leaf (MDL) could be explained by the increasing rainfall at the transition of dry and rainy season in February till the transition of rainy and dry seasons in November.

As described above, the occurrences of flower and fruit pheno-phases were not significantly related to climatic factors, except the phase of mature fruit (MF) and ripe fruit (RF). These two phases had significant correlations with soil moisture contents in all soil depths between 0-30 cm. Mature fruit (MF) could be found during rainy season, while ripe fruit (RF) generally found at the end of rainy season to the dry period at the end and the beginning of the year (Figure 10c). Soil moisture contents in these intervals illustrated the significant correlation with rainfall data due to the absorption of rainfall into soil particles increased soil moisture contents as shown in Table 28. The occurrence of mature fruit (MF) was significantly correlated with SM5, SM10, SM15, SM20, SM25 and SM30 for  $r = 0.668$  ( $p = 0.018$ ),  $0.689$  ( $p = 0.013$ ),  $0.666$  ( $p = 0.018$ ),  $0.636$  ( $p = 0.026$ ),  $0.588$  ( $p = 0.044$ ) and  $0.577$  ( $p = 0.050$ ), respectively. It could be explained that mature fruit (MF) was generally found in rainy season which soil moisture was increasing. The occurrence of ripe fruit (RF) was significantly correlated with SM5, SM10, SM15, SM20, SM25 and SM30 for  $r = -0.598$  ( $p = 0.040$ ),  $-0.608$  ( $p = 0.036$ ),  $-0.708$  ( $p = 0.010$ ),  $-0.768$  ( $p = 0.004$ ),  $-0.734$  ( $p = 0.007$ ) and  $-0.748$  ( $p = 0.005$ ), respectively. Due to the negative correlation with soil moisture contents, ripe fruit (RF) commonly found when rainfall

**Table 28** Simple correlation analysis of *Melia azedarach* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
LF	1									
MLL	.478	1								
MDL	-.140	.084	1							
LA	-.507	0	.237	1						
FB	.378	.000	-.053	-.447	1					
FM	.378	.000	-.053	-.447	<b>1.000**</b>	1				
FF	.a	.a	.a	.a	.a	.a	1			
YF	.a	.a	.a	.a	.a	.a	.a	1		
MF	-.120	.000	0.545	.000	-.316	-.316	.a	.a	1	
RF	-.098	.000	-.343	.192	0.2582	0.2582	.a	.a	-.408	1
Tmax										
Tmin										
Tmean										
RH										
Rain										
SM5										
SM10										
SM15										
SM20										
SM25										
SM30										

Table 28 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	<b>.814**</b>	.401	<b>.678*</b>	-.459	-.136	-.083	-.076	-.076	-.146	-.225	-.348
MLL	.436	<b>.746**</b>	<b>.676*</b>	.142	.292	.162	.082	.015	-.030	-.078	-.059
MDL	0.264	.509	.439	0.494	<b>.630*</b>	.333	.306	.294	.390	.474	.519
LA	-.377	.077	-.161	.302	0.105	-.342	-.398	-.367	-.279	-.021	-0.07
FB	.445	-.022	.230	-.566	-.035	-.313	-.281	-.375	-.426	-.433	-.516
FM	.445	-.022	.230	-.566	-.035	-.313	-.281	-.375	-.426	-.433	-.516
FF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
YF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
MF	.024	.166	.107	.512	.443	<b>.668*</b>	<b>.689*</b>	<b>.666*</b>	<b>.636*</b>	<b>.588*</b>	<b>.577*</b>
RF	-.175	-.154	-.183	-.174	-.054	<b>-.598*</b>	<b>-.608*</b>	<b>-.708**</b>	<b>-.768**</b>	<b>-.734**</b>	<b>-.748**</b>
Tmax	1	.573	<b>.878**</b>	-.392	.084	.007	-.007	-.060	-.075	-.055	-.183
Tmin	1	1	<b>.895**</b>	.421	<b>.630*</b>	.282	.201	.182	.209	.227	.183
Tmean	1	1	1	.031	.412	.168	.113	.072	.079	.101	.005
RH	1	1	1	1	<b>.752**</b>	<b>.601*</b>	.553	<b>.576*</b>	<b>.620*</b>	<b>.631*</b>	<b>.676*</b>
Rain	1	1	1	1	1	<b>.738**</b>	<b>.649*</b>	<b>.630*</b>	<b>.714**</b>	<b>.812**</b>	<b>.794**</b>
SM5	1	1	1	1	1	1	<b>.987**</b>	<b>.941**</b>	<b>.918**</b>	<b>.889**</b>	<b>.835**</b>
SM10	1	1	1	1	1	1	1	<b>.967**</b>	<b>.932**</b>	<b>.867**</b>	<b>.813**</b>
SM15	1	1	1	1	1	1	1	1	<b>.981**</b>	<b>.892**</b>	<b>.857**</b>
SM20	1	1	1	1	1	1	1	1	1	<b>.951**</b>	<b>.930**</b>
SM25	1	1	1	1	1	1	1	1	1	1	<b>.968**</b>
SM30	1	1	1	1	1	1	1	1	1	1	1

**Remark:** \* Correlation is significant at the 0.05 level (2-tailed); \*\* Correlation is significant at the 0.01 level (2-tailed).

a. Cannot be computed because at least one of the variables is constant.

amount was declined at the end of rainy season till the dry periods at the end and the beginning of the year.

#### 7.3.1.4 *Lagerstroemia duperreana* Pierre ex Gagnep

In case of leaf, flower, and fruit phenology conducted to examine the relationship with various climatic data using the analysis of simple correlation, the phenology of leaf flushing (LF), mature light green leaf (MLL) and leaf abscission (LA) were not significantly correlated with any climatic data at  $p < 0.5$  and mature fruit (MF) could not analyze the correlation with climatic data due to disappear during the investigated periods (Table 29).

During the rainy season, mature dark green leaf (MDL) was firstly found in April and abundantly found in May throughout the end of the year (Figure 11a). Using the simple correlation analysis, the occurrence of this phenophase was significantly correlated with the increment of RH ( $r = 0.796$ ,  $p = 0.002$ ), SM25 ( $r = 0.593$ ,  $p = 0.042$ ) and SM30 ( $r = 0.688$ ,  $p = 0.013$ ). The relationship of these variables indicated the occurrences of mature dark green leaf (MDL) in months which RH and soil moisture content were higher than other months. These conditions were generally found in rainy season.

In Figure 11b, flower bud burst (FB) was found in June and July and was significantly correlated with  $T_{min}$ . The occurrences of flower bud burst (FB) and increased  $T_{min}$  produced the correlation coefficient ( $r = 0.608$ ,  $p = 0.036$ ). It was similar to the phenophases of flower maturation (FM), flower fading (FF) and young fruit (YF) which were merely found in June as shown in Figure 11b-11c. Both of them were rarely found and significantly related to the fluctuation of  $T_{min}$  for  $r = 0.749$  ( $p = 0.005$ ). Therefore, the abundances of flower bud burst (FB), flower maturation (FM), flower fading (FF) and young fruit (YF) in *L. duperreana* could be explained by the increased  $T_{min}$  which was found in June. Ripe fruit (RF) could be found in dry period of January till March as shown in Figure 11c. Using the analysis of simple correlation, this phenophase showed the significantly correlation with RH,

**Table 29** Simple correlation analysis of *Lagerstroemia duperreana* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF	
LF	1										
MLL	.239	1									
MDL	.302	<b>.626*</b>	1								
LA	-426	.051	.172	1							
FB	-.316	.378	.127	.135	1						
FM	-.213	.255	.086	.091	<b>.674*</b>	1					
FF	-.213	0.2548	.086	0.0909	<b>.674*</b>	<b>1.000**</b>	1				
YF	-.213	.255	.086	.091	<b>.674*</b>	<b>1.000**</b>	<b>1.000**</b>	1			
MF									1		
RF										1	
Tmax											.a
Tmin											.a
Tmean											.a
RH											.a
Rain											.a
SM5											.a
SM10											.a
SM15											.a
SM20											.a
SM25											.a
SM30											.a

Table 29 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	.085	-.019	.035	.085	-.008	.106	.196	.253	.186	.047	.192
MLL	.020	.454	.276	.479	.513	.362	.321	.318	.346	.330	.475
MDL	-.044	.199	-.124	<b>.796**</b>	.514	.524	.560	.556	.528	<b>.593*</b>	<b>.688*</b>
LA	-.450	-.314	-.430	-.091	-.039	-.310	-.325	-.361	-.307	-.017	-.019
FB	.215	<b>.608*</b>	.472	.297	0.253	.085	.128	.136	.164	.167	.013
FM	.243	<b>.749**</b>	.570	.236	0.277	-.078	-.116	-.148	-.148	-.157	-.192
FF	.243	<b>.749**</b>	.570	0.236	0.277	-.078	-.116	-.148	-.148	-.157	-.192
YF	.243	<b>.749**</b>	.570	.236	0.277	-.008	-.012	-.148	-.148	-.016	-.019
MF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
RF	.247	-.254	-.011	<b>-.615*</b>	-.044	-.499	-.560	-.572	-.562	-.551	-.641*
Tmax	1	.573	<b>.878**</b>	-.392	.084	-.153	-.211	-.195	-.205	-.338	-.318
Tmin	1	1	<b>.895**</b>	.421	<b>.630*</b>	.240	.188	.199	.173	.113	.146
Tmean	1	1	1	.031	.412	.054	-.007	.008	-.013	-.120	-.091
RH	1	1	1	1	<b>.752**</b>	<b>.678*</b>	<b>.723**</b>	<b>.735**</b>	<b>.697*</b>	<b>.751**</b>	<b>.777**</b>
Rain	1	1	1	1	1	<b>.855**</b>	<b>.789**</b>	<b>.754**</b>	<b>.755**</b>	<b>.745**</b>	<b>.794**</b>
SM5	1	1	1	1	1	1	<b>.969**</b>	<b>.939**</b>	<b>.959**</b>	<b>.947**</b>	<b>.943**</b>
SM10	1	1	1	1	1	1	1	<b>.988**</b>	<b>.990**</b>	<b>.973**</b>	<b>.946**</b>
SM15	1	1	1	1	1	1	1	1	<b>.991**</b>	<b>.963**</b>	<b>.938**</b>
SM20	1	1	1	1	1	1	1	1	1	<b>.978**</b>	<b>.942**</b>
SM25	1	1	1	1	1	1	1	1	1	1	<b>.954**</b>
SM30	1	1	1	1	1	1	1	1	1	1	1

**Remark:** \* Correlation is significant at the 0.05 level (2-tailed); \*\* Correlation is significant at the 0.01 level (2-tailed).

a. Cannot be computed because at least one of the variables is constant.

which produced the correlation coefficient ( $r$ ) = -0.615,  $p$  = 0.033. It was indicated the occurrences of ripe fruit (RF) in months which RH was lower than other months. These conditions were generally found in dry period at the beginning of the year (Figure 45a).

#### 7.3.1.5 *Aglaia odoratissima* Blume

To study the correlation of phenology and climatic factors, flower and fruit phenology could not be analyzed due to the non-appearance of these pheno-phases during the investigated periods. Small amounts of leaf flushing (LF) were found in August till November, the second half of rainy season, and had a significant and negative correlation with  $T_{max}$  for  $r$  = -0.643 ( $p$  = 0.024) as shown in table 30. It was indicated that the declined temperature at the second half of rainy season was found associated with *A. odoratissima* leaf flushing.

The pheno-phase of mature dark green leaf (MDL) was abundantly found all the year, except in April and May which mature light green leaf (MLL) was plentiful in place of mature dark green leaf (MDL) (Figure 12). The relationship between mature dark green leaf (MDL) and climatic data were examined using simple correlation analysis. The analysis indicated that the occurrences of mature dark green leaf (MDL) were negatively and significantly correlated to  $T_{max}$  and  $T_{mean}$ . Correlation coefficients ( $r$ ) of these 2 predictors on mature dark green leaf (MDL) were -0.653 ( $p$  = 0.021) and -0.582 ( $p$  = 0.047), respectively (Table 30). It could explain that the abundance of mature dark green leaf (MDL) occurred when temperature gently declined, especially in the second half of rainy season and dry periods.

Leaf abscission (LA) generally occurred in the dry periods of November till March (Figure 12). Simple correlation analysis in Table 30 indicated the significant correlation of leaf abscission (LA) with  $T_{min}$  ( $r$  = -0.589,  $p$  = 0.044), RH ( $r$  = -0.622,  $p$  = 0.031), rainfall ( $r$  = -0.581,  $p$  = 0.048), SM15 ( $r$  = -0.614,  $p$  =

**Table 30** Simple correlation analysis of *Aglaia odoratissima* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
LF	1									
MLL	-.084	1								
MDL			1							
LA				1						
FB					1					
FM						1				
FF							1			
YF								1		
MF									1	
RF										1
Tmax										
Tmin										
Tmean										
RH										
Rain										
SM5										
SM10										
SM15										
SM20										
SM25										
SM30										

Table 30 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	<b>-.643*</b>	-.181	-.455	.545	.080	.132	.241	.307	.233	.257	.336
MLL	.540	.381	.515	.044	.357	.269	.260	.283	.264	.109	.294
MDL	<b>-.653*</b>	-.391	<b>-.582*</b>	0.157	-.027	.096	.057	.013	.035	.186	.064
LA	-.090	<b>-.589*</b>	-.391	<b>-.622*</b>	<b>-.581*</b>	-.469	-.552	<b>-.614*</b>	<b>-.584*</b>	-.051	-.049
FB	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
FM	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
FF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
YF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
MF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
RF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
Tmax	1	.573	<b>.878**</b>	-.392	.084	-.153	-.211	-.195	-.205	-.338	-.318
Tmin	1	1	<b>.895**</b>	.421	<b>.630*</b>	.240	.188	.199	.173	.113	.146
Tmean	1	1	1	.031	.412	.054	-.007	.008	-.013	-.120	-.091
RH	1	1	1	1	<b>.752**</b>	<b>.678*</b>	<b>.723**</b>	<b>.735**</b>	<b>.697*</b>	<b>.751**</b>	<b>.777**</b>
Rain	1	1	1	1	1	<b>.855**</b>	<b>.789**</b>	<b>.754**</b>	<b>.755**</b>	<b>.745**</b>	<b>.794**</b>
SM5	1	1	1	1	1	1	<b>.969**</b>	<b>.939**</b>	<b>.959**</b>	<b>.947**</b>	<b>.943**</b>
SM10	1	1	1	1	1	1	1	<b>.988**</b>	<b>.990**</b>	<b>.973**</b>	<b>.946**</b>
SM15	1	1	1	1	1	1	1	1	<b>.991**</b>	<b>.963**</b>	<b>.938**</b>
SM20	1	1	1	1	1	1	1	1	1	<b>.978**</b>	<b>.942**</b>
SM25	1	1	1	1	1	1	1	1	1	1	<b>.954**</b>
SM30	1	1	1	1	1	1	1	1	1	1	1

**Remark:** \* Correlation is significant at the 0.05 level (2-tailed); \*\* Correlation is significant at the 0.01 level (2-tailed).

a. Cannot be computed because at least one of the variables is constant.

0.033) and SM20 ( $r = -0.584$ ,  $p = 0.046$ ). It could be explained that the occurrences of leaf abscission (LA) were associated with declined temperature, RH, rainfall and soil moisture contents which were commonly found in the dry period at the end of the year.

#### 7.3.1.6 *Hydnocarpus ilicifolia* King

For the study of climate response on *H. ilicifolia*, the phenology of leaf flushing (LF), flowers, and fruits were not found during the investigated periods, while mature light green leaf (MLL) and mature dark green leaf (MDL) were not significantly correlated with any climatic factors at  $p < 0.05$ . It was only leaf abscission (LA) that was significantly correlated with selected climatic data. Leaf abscission (LA) generally found all the year, except in July and September (Figure 13). The occurrence of this pheno-phase was associated with declined SM15 and SM25 which correlation coefficients ( $r$ ) were  $-0.578$  ( $p = 0.049$ ) and  $-0.612$  ( $p = 0.034$ ), respectively (Table 31). As similar as *A. odoratissima*, it could be explained that the occurrence of leaf abscission (LA) was associated with declined soil moisture contents which was commonly found in the dry period at the end of the year.

The relationship of phenology with climate could be pointed out that each species significantly related to different climatic factors. Rainfall, RH and soil moisture contents were closely related to the phenology of mature dark green leaf (MDL), leaf abscission (LA) and all flower and fruit phenological variations of *T. grandis* (Table 26), while  $T_{mean}$  illustrated the significant correlation with the phenology of MDL, mature fruit (MF) and ripe fruit (RF) of *A. xylocarpa*.  $T_{min}$ , rainfall, and soil moisture contents also showed the significantly correlation with MDL of *A. xylocarpa* (Table 27). Young leaf phenology including leaf flushing (LF) and mature light green leaf (MLL) of *M. azedarach* were significantly related to temperature factors, while MDL significantly related to rainfall data. MF and RF of *M. azedarach* closely and significantly related to soil moisture contents in all collected soil depths (Table 28). MDL and RF of *L. duperreana* were significantly correlated with RH and soil moisture contents, while flower and fruit phenology

**Table 31** Simple correlation analysis of *Hydnocarpus ilicifolia* phenology and some climatic data.

	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF	
LF	.a										
MLL		1	.143	.a	.a	.a	.a	.a	.a	.a	
MDL			1	.378	.a	.a	.a	.a	.a	.a	
LA				1	.a	.a	.a	.a	.a	.a	
FB					1	.a	.a	.a	.a	.a	
FM						1	.a	.a	.a	.a	
FF							1	.a	.a	.a	
YF								1	.a	.a	
MF									1	.a	
RF										1	
Tmax											.a
Tmin											.a
Tmean											.a
RH											.a
Rain											.a
SM5											.a
SM10											.a
SM15											.a
SM20											.a
SM25											.a
SM30											.a

Table 31 (Continued)

	Tmax	Tmin	Tmean	RH	Rain	SM5	SM10	SM15	SM20	SM25	SM30
LF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
MLL	-.003	.348	.202	.336	.252	.101	.123	.044	.133	.155	.170
MDL	-0.37	-.109	-.263	0.194	.160	-.009	.122	-.088	-.048	-.008	-.080
LA	.092	-.084	.003	-.458	-.022	-.569	-.502	-.578*	-.535	-.612*	-.557
FB	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
FM	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
FF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
YF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
MF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
RF	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a
Tmax	1	.573	.878**	-.392	.084	-.232	-.291	-.191	-.198	-.227	-.196
Tmin		1	.895**	.421	.630*	.181	.128	.175	.172	.170	.191
Tmean			1	.031	.412	-.023	-.086	-.004	-.010	-.027	.002
RH				1	.752***	.709***	.708*	.676*	.678*	.723**	.701*
Rain					1	.797***	.792***	.764**	.777**	.764**	.771**
SM5						1	.990**	.985**	.984**	.983**	.979**
SM10							1	.967**	.975**	.977**	.965**
SM15								1	.993**	.987**	.988**
SM20									1	.991**	.997**
SM25										1	.992**
SM30											1

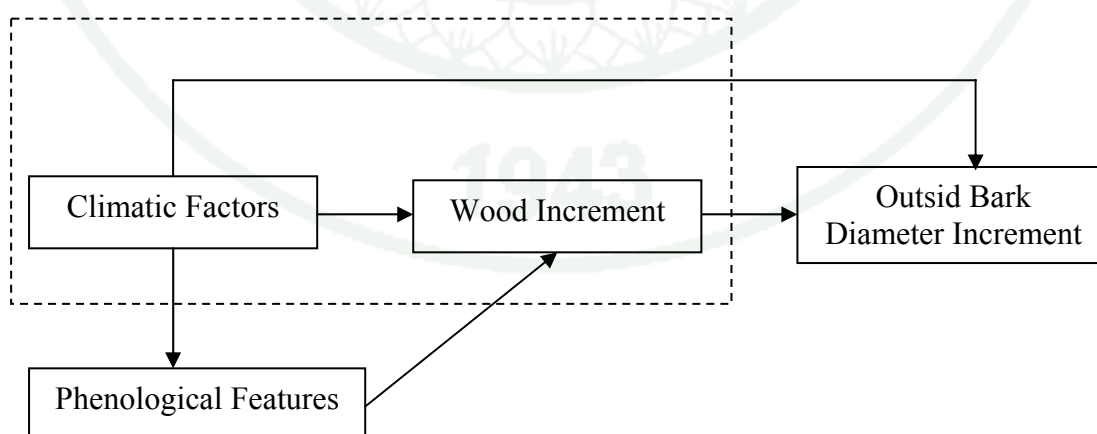
**Remark:** \* Correlation is significant at the 0.05 level (2-tailed); \*\* Correlation is significant at the 0.01 level (2-tailed).

a. Cannot be computed because at least one of the variables is constant.

mainly and significantly correlated with T<sub>min</sub> (Table 29). Leaf phenology of *A. odoratissima* including LF, MDL, and LA were significantly related to temperature, while LA was also significantly related to RH, rainfall and soil moisture contents (Table 30). It was only one pheno-phase of LA in *H. illicifolia* that significantly related to soil moisture contents, while flower and fruit pheno-phases of *A. odoratissima* and *H. illicifolia* were not found during the investigated periods (Table 31).

### 7.3.2 The relationship of wood increment with climate

From Figure 50, variables of climatic and wood increment placed in dash box were analyzed their relationship. Climatic variables were similar as variables using in the previous section, while wood increment data were received from the study of monthly wood increment using cambial marked method. For the analysis in this section, monthly wood increments in each species were divided to 2 types of direct measuring monthly wood increment (MWI) and relative monthly wood increment (RMWI). *Tectona grandis* was firstly explained followed by *Afzelia xylocarpa*, *Melia azedarach*, *Lagerstroemia duperreana*, *Aglaia odoratissima* and *Hydnocarpus ilicifolia*, respectively.



**Figure 50** Conceptual model of climate-growth response: focused on the relationship of climatic factors and wood increments. Dash box indicated variables for the analysis of simple correlation of climatic factors and wood increment.

### 7.3.2.1 *Tectona grandis* L.f.

Both of MWI and RMWI of teak woods were significantly correlated with RH, Rainfall and SM in all soil depths at 0-30 cm at  $p < 0.05$ , while 3 types of temperature (Tmax, Tmin and Tmean) were not found the significant correlation with teak wood increments at  $p < 0.05$ . Declined RH, rainfall, and SM in November 2009 till February 2010 were found associated with the declination of teak wood increment, while increased values of these climatic factors were also found associated with the rapid wood increment, especially in rainy season. The analysis of simple correlation indicated the correlation coefficients (r) of RH, rainfall, SM5, SM10, SM15, SM20, SM25, and SM30 on MWI for 0.715 ( $p = 0.009$ ), 0.693 ( $p = 0.013$ ), 0.609 ( $p = 0.035$ ), 0.581 ( $p = 0.048$ ), 0.603 ( $p = 0.038$ ), 0.630 ( $p = 0.028$ ), 0.585 ( $p = 0.046$ ) and 0.651 ( $p = 0.022$ ), respectively. These 8 climatic data were also significantly correlated with RMWI for  $r = 0.721$  ( $p = 0.008$ ), 0.733 ( $p = 0.007$ ), 0.642 ( $p = 0.024$ ), 0.605 ( $p = 0.037$ ), 0.613 ( $p = 0.034$ ), 0.640 ( $p = 0.025$ ), 0.606 ( $p = 0.037$ ) and 0.658 ( $p = 0.020$ ), respectively (Table 32).

### 7.3.2.2 *Afzelia xylocarpa* (Kurz) Craib.

Monthly wood increments of *A. xylocarpa* (MWI and RMWI) were significantly and positively correlated with rainfall and SM in all soil depths at 0-30 cm, while RH, Tmax, Tmin and Tmean were not significantly correlated with tree growth (at  $p < 0.5$ ). Rapid wood increments were found associated with the increasing rainfall and soil moisture in rainy season, whereas declined growth rates occurred in the dry periods at the end and the beginning of the year. The analysis of simple correlation indicated the correlation coefficients (r) of rainfall, SM5, SM10, SM15, SM20, SM25, and SM30 on MWI for 0.686 ( $p = 0.014$ ), 0.645 ( $p = 0.024$ ), 0.669 ( $p = 0.017$ ), 0.732 ( $p = 0.007$ ), 0.719 ( $p = 0.008$ ), 0.732 ( $p = 0.007$ ) and 0.711 ( $p = 0.010$ ), respectively. These climatic data were also significantly correlated with RMWI for  $r = 0.683$  ( $p = 0.014$ ), 0.629 ( $p = 0.028$ ), 0.651 ( $p = 0.022$ ), 0.713 ( $p = 0.009$ ), 0.699 ( $p = 0.011$ ), 0.716 ( $p = 0.009$ ) and 0.696 ( $p = 0.012$ ), respectively (Table 32).

**Table 32** Simple correlation analysis of measured and relative monthly wood increments and some climatic data.

Species	MWI	RMWI	Tmax	Tmin	Tmean	RH	Rainfall	SM5	SM10	SM15	SM20	SM25	SM30
<i>Tectona</i>	MWI	1	.991**	-.077	.442	.214	.715**	.609*	.581*	.603*	.630*	.585*	.651*
<i>grandis</i>	RMWI	1	-.076	.464	.228	.721**	.733**	.642*	.605*	.613*	.640*	.606*	.658*
<i>Azelia</i>	MWI	1	.996**	.329	.528	.484	.686*	.645*	.669*	.732**	.719**	.732**	.711**
<i>xylocarpa</i>	RMWI	1	.365	.579*	.534	.432	.683*	.629*	.651*	.713**	.699*	.716**	.696*
<i>Melia</i>	MWI	1	.982**	.187	.638*	.472	.823**	.685*	.661*	.717**	.769**	.747**	.750**
<i>azedarach</i>	RMWI	1	.129	.666*	.456	.746**	.833**	.670*	.639*	.696*	.743**	.703*	.718**
<i>Lagerstroemia</i>	MWI	1	.999**	-.421	.177	-.127	.618*	.639*	.562	.511	.530	.620*	.673*
<i>duperreana</i>	RMWI	1	-.393	.185	-.107	.671*	.615*	.638*	.560	.508	.529	.617*	.667*
<i>Aglaia</i>	MWI	1	.968**	-.180	-.035	-.120	.269	.462	.403	.357	.447	.527	.424
<i>odoratissima</i>	RMWI	1	-.137	.016	-.067	.182	.213	.394	.371	.335	.426	.487	.351
<i>Hydnocarpus</i>	MWI	1	.994**	-.143	.013	-.073	.471	.567	.633*	.482	.555	.547	.541
<i>ilicifolia</i>	RMWI	1	-.136	.051	-.046	.300	.504	.609*	.665*	.521	.592*	.584*	.582*

**Remark:** \*\* Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed).

### 7.3.2.3 *Melia azedarach* L.

As similar as *T. grandis*, wood increments of *M. azedarach* in both of MWI and RMWI were significantly correlated with RH, rainfall and SM in all soil depths at 0-30 cm ( $p < 0.05$ ). Tmin was another climatic data illustrating significant correlation with *M. azedarach* wood increment at  $p < 0.05$ . The declination of these climatic data at the end of the year were found associated with diminutive wood increment, while wet conditions generating in the rainy season were found associated with rapid increment of wood until the end of investigated periods. The analysis of simple correlation indicated the correlation coefficients ( $r$ ) of Tmin, RH, rainfall, SM5, SM10, SM15, SM20, SM25, and SM30 on MWI for 0.638 ( $p = 0.025$ ), 0.719 ( $p = 0.008$ ), 0.823 ( $p = 0.001$ ), 0.685 ( $p = 0.014$ ), 0.661 ( $p = 0.019$ ), 0.717 ( $p = 0.009$ ), 0.769 ( $p = 0.003$ ), 0.747 ( $p = 0.005$ ) and 0.750 ( $p = 0.005$ ), respectively. These climatic data were also significantly correlated with RMWI for  $r = 0.666$  ( $p = 0.018$ ), 0.746 ( $p = 0.005$ ), 0.833 ( $p = 0.001$ ), 0.670 ( $p = 0.017$ ), 0.639 ( $p = 0.025$ ), 0.696 ( $p = 0.012$ ), 0.743 ( $p = 0.006$ ), 0.703 ( $p = 0.011$ ) and 0.718 ( $p = 0.009$ ), respectively (Table 32).

### 7.3.2.4 *Lagerstroemia duperreana* Pierre ex Gagnep

Monthly wood increments of *L. duperreana* were significantly correlated with RH, rainfall and soil moisture in some soil depths, while 3 types of temperature and were not shown the significant relationship as similar as *T. grandis* and *A. xylocarpa*. These climatic data which increased in rainy season were found associated with rapid wood increment, while the declinations of these climatic data at the end of the year were found together with diminutive wood increments. The analysis of simple correlation indicated the correlation coefficients ( $r$ ) of RH, rainfall, SM5, SM25, and SM30 on MWI for 0.686 ( $p = 0.014$ ), 0.618 ( $p = 0.032$ ), 0.639 ( $p = 0.025$ ), 0.620 ( $p = 0.031$ ) and 0.673 ( $p = 0.016$ ), respectively. These climatic data were also significantly correlated with RMWI for  $r = 0.671$  ( $p = 0.017$ ), 0.615 ( $p = 0.033$ ), 0.638 ( $p = 0.026$ ), 0.617 ( $p = 0.033$ ) and 0.667 ( $p = 0.018$ ), respectively (Table 32).

#### 7.3.2.5 *Aglaia odoratissima* Blume

Monthly wood increments of *A. odoratissima* were not significantly related to all climatic data of RH, rainfall, 3 types of temperature and soil moisture in 6 soil depths at  $p < 0.05$ . However, monthly wood increments in term of MWI and RMWI illustrated the highest correlation with SM25, which the correlation coefficients ( $r$ ) were 0.527 ( $p = 0.078$ ) and 0.487 ( $p = 0.109$ ), respectively (Table 32).

#### 7.3.2.6 *Hydnocarpus ilicifolia* King

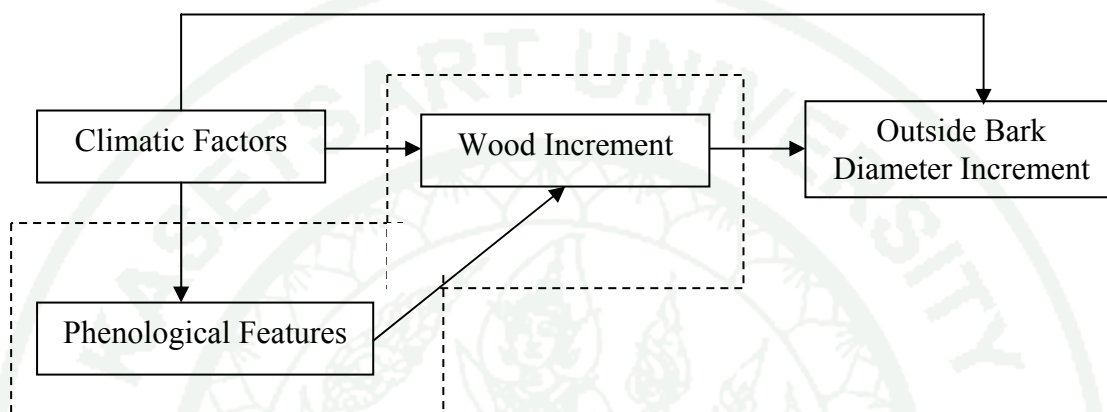
Monthly wood increment (MWI) of *H. ilicifolia* was significant correlation with soil moisture content at 5-10 cm soil depth (SM10) for  $r = 0.633$  ( $p = 0.027$ ). In case of relative monthly wood increment (RMWI), monthly increment was significantly correlated with soil moisture contents as similar as MWI, but expanded in several soil depths. Soil moistures in SM5, SM10, SM20, SM25 and SM30 were positive and significant correlation with RMWI for  $r = 0.609$  ( $p = 0.036$ ), 0.665 ( $p = 0.018$ ), 0.592 ( $p = 0.043$ ), 0.584 ( $p = 0.046$ ) and 0.582 ( $p = 0.047$ ), respectively (Table 32).

The relationship of monthly wood increment with climate as shown in Table 32 could be pointed out that RH, rainfall and soil moisture contents in all collected soil depths were significantly related to monthly wood increment of all deciduous tree species (*T. grandis*, *A. xylocarpa*, *M. azedarach*, *L. duperreana*). In case of evergreen species, soil moisture contents were also significantly correlated to monthly wood increment of *H. ilicifolia*, but all climatic factors and soil moisture contents were not significantly related to monthly wood increment of *A. odoratissima*.

### 7.3.3 The relationship of wood increment with phenology

Not only climatic data, but the changing of leaf, flower and fruit pheno-phases in each month were also tried to correlate with monthly wood increment (Figure 51). Monthly wood increments in each species were divided to 2 types of

direct measured monthly wood increment (MWI) and relative monthly wood increment (RMWI). *Tectona grandis* was firstly explained followed by *Afzelia xylocarpa*, *Melia azedarach*, *Lagerstroemia duperreana*, *Aglaia odoratissima* and *Hydnocarpus ilicifolia*, respectively.



**Figure 51** Conceptual model of climate-growth response: focused on the relationship of phenological factors and wood increment. Dash box indicated variables for simple correlation analysis between phenological data and wood increment.

### 7.3.3.1 *Tectona grandis* L.f.

Simple correlation analysis was conducted to examine the relationship between wood increment and all leaf phenological features. The analysis indicated that monthly wood increments in both of MWI and RMWI were significantly and positively correlated with the abundances of mature dark green leaf (MDL), flower bud burst (FB), flower maturation (FM) and mature fruit (MF) and negatively correlated with ripe fruit (RF) (Table 33). The analysis indicated the correlation coefficients ( $r$ ) of MWI with mature dark green leaf (MDL), flower bud burst (FB), flower maturation (FM), mature fruit (MF) and ripe fruit (RF) for 0.635 ( $p = 0.026$ ), 0.771 ( $p = 0.003$ ), 0.601 ( $p = 0.039$ ), 0.616 ( $p = 0.033$ ) and -0.771 ( $p = 0.003$ ), respectively. RMWI showed correlation coefficients ( $r$ ) with mature dark green leaf (MDL), flower bud burst (FB), flower maturation (FM), mature fruit (MF)

and ripe fruit (RF) for 0.664 ( $p = 0.019$ ), 0.806 ( $p = 0.002$ ), 0.658 ( $p = 0.020$ ), 0.600 ( $p = 0.039$ ) and -0.806 ( $p = 0.002$ ), respectively. The results indicated rapid wood increment when mature dark green leaf (MDL), flower bud burst (FB), flower maturation (FM) and mature fruit (MF) abundantly occurred and ripe fruit (RF) was rarely found. These characteristics commonly found in rainy season, especially at the second half of the season in June till August.

#### 7.3.3.2 *Afzelia xylocarpa* (Kurz) Craib.

The analysis of simple correlation analysis indicated that monthly wood increments (MWI and RMWI) were positively and significantly correlated with the abundances of mature dark green leaf (MDL), while other phenophases explored insignificant correlations at  $p < 0.05$  (Table 33). The correlation coefficients of MWI and RMWI on mature dark green leaf (MDL) were 0.664 ( $p = 0.019$ ) and 0.673 ( $p = 0.016$ ), respectively. The result indicated monthly wood increment occurring associated with the plentiful mature dark green leaf (MDL), especially in the rainy season.

#### 7.3.3.3 *Melia azedarach* L.

The analysis of simple correlation indicated that all leaf and flower phenology were not significantly correlated to monthly wood increments (MWI and RMWI) of *M. azedarach*, excepted mature dark green leaf (MDL). Mature fruit (MF) and ripe fruit (RF) were other phenophases which were significantly correlated with MWI and RMWI. As shown in table 33, correlation coefficients of MWI on mature dark green leaf (MDL), mature fruit (MF) and ripe fruit (RF) were 0.738 ( $p = 0.006$ ), 0.712 ( $p = 0.009$ ) and -0.645 ( $p = 0.023$ ), respectively. RMWI showed correlation coefficients ( $r$ ) with mature dark green leaf (MDL), mature fruit (MF) and ripe fruit (RF) for 0.681 ( $p = 0.015$ ), 0.655 ( $p = 0.021$ ) and -0.628 ( $p = 0.029$ ), respectively. It could be interpreted that rapid wood increment, especially in rainy season, commonly occurred with plentiful mature dark green leaf (MDL) and mature fruit (MF) and rare ripe fruit (RF).

**Table 33** Simple correlation analysis of direct measured (MWI) and relative (RMWI) monthly wood increments with tree phenological data.

Species	MWI	RMWI	LF	MLL	MDL	LA	FB	FM	FF	YF	MF	RF
<i>Tectona grandis</i>	MWI	1	.991**	.300	.635*	-.549	.771**	.601*	.524	.534	.616*	-.771**
	RMWI		1	.219	.664*	-.519	.806**	.658*	.527	.573	.600*	-.806**
<i>Afzelia xylocarpa</i>	MWI	1	.996**	-.062	.664*	.137	-.138	-.138	-.346	. <sup>a</sup>	-.217	-.101
	RMWI		1	-.043	.673*	.126	-.083	-.083	-.356	. <sup>a</sup>	-.179	-.131
<i>Melia azedarach</i>	MWI	1	.982**	.253	.738**	.120	-.405	-.405	. <sup>a</sup>	. <sup>a</sup>	.712**	-.645*
	RMWI		1	.320	.681*	.158	-.369	-.369	. <sup>a</sup>	. <sup>a</sup>	.655*	-.628*
<i>Lagerstroemia duperreana</i>	MWI	1	.999**	.530	.820**	.121	.077	.096	.096	.096	. <sup>a</sup>	-.504
	RMWI		1	.542	.818**	.125	.097	.098	.098	.098	. <sup>a</sup>	-.505
<i>Aglaia odoratissima</i>	MWI	1	.968**	-.310	.236	.082	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>
	RMWI		1	-.328	.137	-.045	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>
<i>Hydnocarpus ilicifolia</i>	MWI	1	.994**	.507	.358	-.089	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>
	RMWI		1	.517	.304	-.152	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>	. <sup>a</sup>

**Remark:** \*\*. Correlation is significant at the 0.01 level (2-tailed).

\*. Correlation is significant at the 0.05 level (2-tailed).

a. Can not be computed because at least one of the variables is constant

#### 7.3.3.4 *Lagerstroemia duperreana* Pierre ex Gagnep

As similar as *A. xylocarpa*, monthly wood increments of *L. duperreana* (MWI and RMWI) were positively and significantly related to the abundances of mature dark green leaf (MDL) (Table 33). The correlation coefficients of MWI and RMWI on mature dark green leaf (MDL) were 0.820 ( $p= 0.001$ ) and 0.818 ( $p = 0.001$ ), respectively. The result indicated monthly wood increment occurring associated with the plentiful mature dark green leaf (MDL), especially in the rainy season.

#### 7.3.3.5 *Aglaia odoratissima* Blume

The analysis of simple correlation indicated that all leaf phenology were not significantly correlated to monthly wood increment of *A. odoratissima* at  $p<0.05$  (Table 33). In addition, all flower and fruit pheno-phases were not found during the investigated periods.

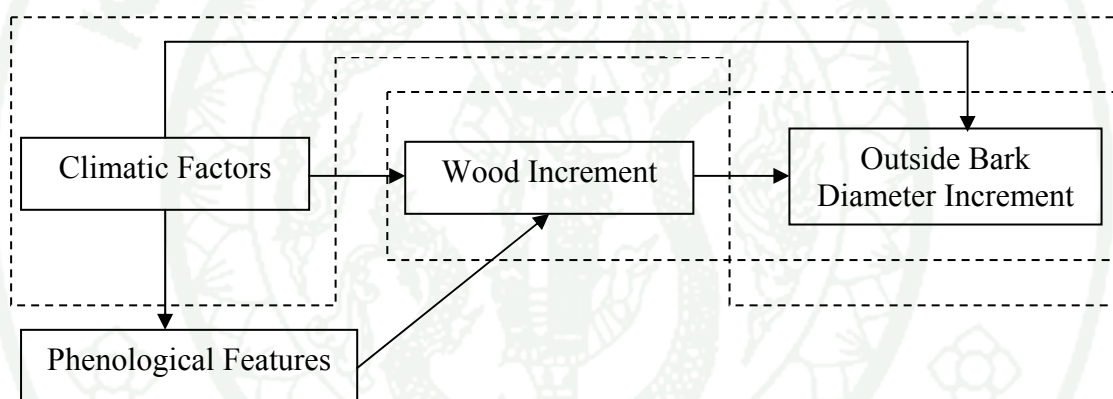
#### 7.3.3.6 *Hydnocarpus ilicifolia* King

As similar as *A. odoratissima*, *H. ilicifolia* was another species had insignificantly correlation between monthly wood increment and all leaf phenology at  $p<0.05$ . All flower and fruit pheno-phases were also disappeared and could not calculated the correlation coefficient with monthly wood increment (Table 33).

The relationship of monthly wood increment with phenology as shown in Table 33 could be pointed out that mature dark green leaf (MDL) was mainly significantly correlated with monthly wood increment of all deciduous tree species (*T. grandis*, *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima*, and *H. ilicifolia*). All evergreen species (*A. odoratissima* and *H. ilicifolia*) were not shown the significant correlation with all tree pheno-phases.

### 7.3.4 The relationship of outside bark diameter increment with climatic factors and wood increment

The fluctuations of outside bark diameter increments recorded from manual band dendrometers could be explained by net wood increments (xylem cells) and effects of bark shrinkage/swelling. Therefore, variables selected for studying factors relating outside bark diameter movement were divided to 2 groups of climatic factors and monthly wood increment (Figure 52). Outside bark diameters of *T. grandis* was firstly explained followed by *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.



**Figure 52** Conceptual model of climate-growth response: focused on the relationship of climatic factors and wood increment on outside bark diameter increment. Two dash boxes indicated climatic factors and wood increment related to outside bark diameter increment.

#### 7.3.4.1 *Tectona grandis* L.f.

By using the simple correlation analysis, the movement of band dendrometer scales reflecting outside bark diameter increments showed the significant relationship with monthly wood increments in both of direct measured (MWI) and relative (RMWI) monthly wood increment, climatic data of RH and rainfall, and soil moisture contents (SM) in all soil depths in 0-30 cm (Table 34).

Cumulative outside bark diameter increment (CSDI) illustrated correlation coefficient ( $r$ ) with MWI, RH, rainfall, SM5, SM10, SM15, SM20, SM25 and SM30 for 0.830 ( $p = 0.001$ ), 0.769 ( $p = 0.003$ ), 0.690 ( $p = 0.013$ ), 0.706 ( $p = 0.010$ ), 0.692 ( $p = 0.013$ ), 0.724 ( $p = 0.008$ ), 0.757 ( $p = 0.004$ ), 0.712 ( $p = 0.009$ ) and 0.794 ( $p = 0.002$ ), respectively. In case of standardized outside bark diameter increment (SSDI), factors significantly correlated with SSDI were similar as factors affecting CSDI, but correlation coefficients were different and RMWI was used instead of MWI. SSDI was significantly correlated with RMWI, RH, rainfall, SM5, SM10, SM15, SM20, SM25 and SM30 for 0.818 ( $p = 0.001$ ), 0.804 ( $p = 0.002$ ), 0.690 ( $p = 0.013$ ), 0.705 ( $p = 0.011$ ), 0.692 ( $p = 0.013$ ), 0.722 ( $p = 0.008$ ), 0.757 ( $p = 0.004$ ), 0.717 ( $p = 0.009$ ) and 0.803 ( $p = 0.002$ ), respectively. From these results, the increments of outside bark diameters were found when monthly wood increment and available water from RH, rainfall and SM were increased.

#### 7.3.4.2 *Afzelia xylocarpa* (Kurz) Craib.

The fluctuation of band dendrometer scales installed on *A. xylocarpa* trees showed the significant relationship with monthly wood increments, rainfall and soil moisture contents in some soil depths (Table 34). The simple correlation analysis of cumulative outside bark diameter increment (CSDI) on direct measured monthly wood increment (MWI), rainfall, SM5 and SM15 exhibited correlation coefficients ( $r$ ) for 0.725 ( $p = 0.008$ ), 0.622 ( $p = 0.031$ ), 0.590 ( $p = 0.043$ ), 0.588 ( $p = 0.044$ ), respectively. Standardized outside bark diameter increment (SSDI) was significantly correlated with relative monthly wood increment (RMWI), rainfall, SM5, SM10, SM15, SM25 and SM30 and exhibited correlation coefficients ( $r$ ) for 0.682 ( $p = 0.015$ ), 0.626 ( $p = 0.030$ ), 0.613 ( $p = 0.034$ ), 0.581 ( $p = 0.048$ ), 0.609 ( $p = 0.036$ ), 0.577 ( $p = 0.050$ ) and 0.588 ( $p = 0.044$ ), respectively. Outside bark diameter increments of *A. xylocarpa* were also increased when monthly wood increment and available water from rainfall and soil moisture contents were increased as similar as *T. grandis*.

**Table 34** Simple correlation analysis of outside bark diameter increment with monthly wood increment and climatic data.

Species	CSDI	SSDI	MWI	RMWI	Tmax	Tmin	Tmean	RH
<i>Tectona grandis</i>	CSDI	<b>.996<sup>**</sup></b>	<b>.830<sup>**</sup></b>	<b>.840<sup>**</sup></b>	-.458	.107	-.187	<b>.769<sup>**</sup></b>
	SSDI	1	<b>.810<sup>**</sup></b>	<b>.818<sup>**</sup></b>	-.493	.098	-.211	<b>.804<sup>**</sup></b>
<i>Azela xylocarpa</i>	CSDI	<b>.995<sup>**</sup></b>	<b>.725<sup>**</sup></b>	<b>.719<sup>**</sup></b>	.063	.397	.264	.445
	SSDI	1	<b>.692<sup>*</sup></b>	<b>.682<sup>*</sup></b>	-.027	.340	.182	.484
<i>Melia azedarach</i>	CSDI	<b>.996<sup>**</sup></b>	<b>.774<sup>**</sup></b>	<b>.823<sup>**</sup></b>	.076	.390	.268	.430
	SSDI	1	<b>.793<sup>**</sup></b>	<b>.831<sup>**</sup></b>	.120	.405	.300	.413
<i>Lagerstroemia duperreana</i>	CSDI	<b>.899<sup>**</sup></b>	<b>.820<sup>**</sup></b>	<b>.827<sup>**</sup></b>	-.506	.005	-.274	<b>.648<sup>*</sup></b>
	SSDI	1	<b>.713<sup>**</sup></b>	<b>.702<sup>*</sup></b>	<b>-.815<sup>**</sup></b>	-.309	<b>-.625<sup>*</sup></b>	<b>.617<sup>*</sup></b>
<i>Aglaia odoratissima</i>	CSDI	<b>.991<sup>**</sup></b>	.169	.182	<b>-.844<sup>**</sup></b>	-.408	<b>-.698<sup>*</sup></b>	.505
	SSDI	1	.074	.085	<b>-.876<sup>**</sup></b>	-.468	<b>-.750<sup>**</sup></b>	.459
<i>Hydnocarpus ilicifolia</i>	CSDI	<b>1.000<sup>**</sup></b>	-.125	-.141	<b>-.860<sup>**</sup></b>	-.532	<b>-.778<sup>**</sup></b>	.353
	SSDI	1	-.111	-.128	<b>-.862<sup>**</sup></b>	-.535	<b>-.781<sup>**</sup></b>	.356

Table 34 (Continued)

Species	Rainfall	SM5	SM10	SM15	SM20	SM25	SM30
<i>Tectona grandis</i>	CSDI	.706*	.692*	.724**	.757**	.712**	.794**
	SSDI	.705*	.692*	.722**	.757**	.717**	.803**
<i>Azizelia xylocarpa</i>	CSDI	.590*	.556	.588*	.547	.555	.563
	SSDI	.613*	.581*	.609*	.570	.577*	.588*
<i>Melia azedarach</i>	CSDI	.576	.551	.596*	.612*	.537	.573
	SSDI	.580*	.555	.607*	.633*	.568	.602*
<i>Lagerstroemia dupperreana</i>	CSDI	.719**	.713**	.653*	.703*	.803**	.753**
	SSDI	.603*	.637*	.592*	.625*	.746**	.695*
<i>Aglaia odoratissima</i>	CSDI	.360	.462	.427	.434	.516	.507
	SSDI	.281	.391	.362	.361	.445	.437
<i>Hydnocarpus ilicifolia</i>	CSDI	.215	.234	.218	.192	.211	.181
	SSDI	.225	.245	.228	.203	.221	.191

**Remark:** \*\* Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed).

#### 7.3.4.3 *Melia azedarach* L.

By using the analysis of simple correlation, the fluctuation of band dendrometer scales installed on *M. azedarach* trees showed the significant relationship of outside bark diameter increment with monthly wood increment, rainfall and soil moisture contents in some soil depths (Table 34). The analysis of simple correlation produced the correlation coefficients ( $r$ ) of cumulative outside bark diameter increment (CDSI) on direct measured wood increment (MWI), rainfall, SM15 and SM20 for 0.774 ( $p = 0.003$ ), 0.620 ( $p = 0.032$ ), 0.596 ( $p = 0.041$ ), 0.612 ( $p = 0.034$ ), respectively. Standardized outside bark diameter increment (SSDI) was significantly correlated with relative monthly wood increment (RMWI), rainfall, SM5, SM15, SM20 and SM30 and exhibited correlation coefficients ( $r$ ) for 0.831 ( $p = 0.001$ ), 0.637 ( $p = 0.026$ ), 0.580 ( $p = 0.048$ ), 0.607 ( $p = 0.036$ ), 0.633 ( $p = 0.027$ ) and 0.602 ( $p = 0.038$ ), respectively. It could be explained that outside bark diameters enhanced on the similar periods with the increase of monthly wood increment, rainfall, and soil moisture content.

#### 7.3.4.4 *Lagerstroemia duperreana* Pierre ex Gagnep

The scale movements of manual band dendrometers installed on *L. duperreana* indicated the significant relationship of outside bark diameter increment with monthly wood increment, RH and soil moisture contents in all soil depths of 0-30 cm (Table 34). Cumulative outside bark diameter increment (CSDI) explored correlation coefficient ( $r$ ) with direct measured monthly wood increment (MWI), RH, SM5, SM10, SM15, SM20, SM25 and SM30 for 0.820 ( $p = 0.001$ ), 0.648 ( $p = 0.023$ ), 0.719 ( $p = 0.008$ ), 0.713 ( $p = 0.009$ ), 0.653 ( $p = 0.021$ ), 0.703 ( $p = 0.011$ ), 0.803 ( $p = 0.002$ ) and 0.753 ( $p = 0.005$ ), respectively. In case of standardized outside bark diameter increment (SSDI), it was significantly correlated with relative monthly wood increment (RMWI), Tmax, Tmean, RH, SM5, SM10, SM15, SM20, SM25 and SM30 for 0.702 ( $p = 0.011$ ), -0.815 ( $p = 0.001$ ), -0.625 ( $p = 0.030$ ), 0.617 ( $p = 0.033$ ), 0.603 ( $p = 0.038$ ), 0.637 ( $p = 0.026$ ), 0.592 ( $p = 0.043$ ), 0.625 ( $p = 0.030$ ), 0.746 ( $p = 0.005$ ) and 0.695 ( $p = 0.012$ ), respectively. From these results, the

increments of outside bark diameters were found when monthly wood increment and available water from RH, rainfall and soil moisture contents were increased, while  $T_{max}$  and  $T_{mean}$  were declined.

#### 7.3.4.5 *Aglaia odoratissima* Blume

By using the analysis of simple correlation as shown in Table 34, the fluctuation of outside bark diameter showed the significant relationship with  $T_{max}$  and  $T_{mean}$ , while other climatic factors had insignificant relationship at  $p < 0.05$ . The simple correlation indicated correlation coefficients ( $r$ ) of cumulative outside bark diameter increment (CSDI) on  $T_{max}$  and  $T_{mean}$  for -0.844 ( $p = 0.001$ ) and -0.698 ( $p = 0.012$ ), respectively. Standardized outside bark diameter increment (SSDI) was significantly correlated with  $T_{max}$  and  $T_{mean}$  for -0.876 ( $p = 0.000$ ) and -0.750 ( $p = 0.005$ ), respectively. From these results, the fluctuation of outside bark diameters occurred when temperature changed. Bark swelling and shrinkage were found when temperature decreased and increased, respectively.

#### 7.3.4.6 *Hydnocarpus ilicifolia* King

The fluctuations of band dendrometer scales installed on *H. ilicifolia* trees showed the significant relationship with  $T_{max}$  and  $T_{mean}$  (Table 34). The simple correlation indicated correlation coefficients ( $r$ ) of cumulative outside bark diameter increment (CSDI) on  $T_{max}$  and  $T_{mean}$  for -0.860 ( $p = 0.000$ ) and -0.778 ( $p = 0.003$ ), respectively. Standardized outside bark diameter increment (SSDI) was significantly correlated with  $T_{max}$  and  $T_{mean}$  for -0.862 ( $p = 0.000$ ) and -0.781 ( $p = 0.003$ ), respectively. From these results, the fluctuation of outside bark diameters occurred when temperature changed as similar as *A. odoratissima*. Bark swelling and shrinkage were found when temperature decreased and increased, respectively.

The relationship of outside bark diameter increment with climatic factors and wood increment as shown in Table 34 could be pointed out that outside

bark diameter increments of all deciduous tree species (*T. grandis*, *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima*, and *H. ilicifolia*) were mainly significantly correlated with their monthly wood increments, while outside bark diameter increments of all evergreen species (*A. odoratissima* and *H. ilicifolia*) were significantly correlated with temperature factors.

### 7.3.5 Path Analysis of factors affecting tree growth

Multiple regressions were firstly selected to analyze factors affecting tree growth. All climatic data and soil moisture contents including RH, rainfall, Tmax, Tmin, Tmean, SM5, SM10, SM15, SM20, SM25 and SM30 were defined as independent variables. These factors illustrating linear relationship were called multicollinearity which was not suitable for regression analysis. The tolerance (TR) and/or the variance inflation factor (VIF) were suggested to detect multicollinearity. O'Brien (2007) suggested that the tolerance (TR) of less than 0.20 and/or the VIF of 5 and above indicates a multicollinearity problem. For this problem, it could be solved by using the technique of principle component analysis (PCA) to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components (PCs). The number of principal components must less than or equal to the number of original variables.

All climatic and soil moisture data collected from Wang Nam Khiao Forestry Student Practice Station (WKNFSPS) and 3 sites at Sakaerat Environmental Research Station (SERS1, SERS2 and SERS3) were calculated TR and VIF to check the effect of multicollinearity. Tmax was set as dependent variable and was correlated with other climatic data of RH, rainfall, Tmin, Tmean, SM5, SM10, SM15, SM20, SM25 and SM30. The results illustrated multicollinearity which tolerance was less than 0.20 and VIF was greater than 5 (Table 35). In case of WKNFSPS, these variables were converted to 3 components of climatic data based on the criteria of Eigen values  $\geq 1$  (Table 36). Varimax rotation was used to obtain a clear pattern of factor loadings which were somehow clearly marked by high loadings for some variables and low loadings for others. In Table 37, it was illustrated the rotated

component matrix of factor loadings which grouped the related factors in the same component. In this case, it was divided to 3 components. The first component was related to soil moisture contents in all soil depths and was re-named as “Soil moisture”. The second component related to temperature in both of Tmax, Tmin and Tmean and was re-named as “Temperature”. The last component related to rainfall and RH data which was re-named as “Precipitation”. These 3 components were finally used as independent factors in regression analysis (Table 38 and Figure 53). Each component was closely related to selected climatic factors, was not significantly correlated with other components and could explain the cumulative variance of all climatic factors for 95.145%.

**Table 35** Multicollinearity test on all independent variables from WNKFSPS.

Variable	WNKFSPS		SERS1		SERS2		SERS3	
	TR	VIF	TR	VIF	TR	VIF	TR	VIF
Tmin	.003	322.34	.008	122.77	.010	100.38	.003	324.00
Tmean	.004	238.75	.012	85.40	.007	145.62	.004	269.50
RH	.010	97.34	.012	84.53	.012	83.42	.006	154.29
Rainfall	.006	163.91	.029	34.39	.014	71.64	.011	88.10
SM5	.000	3171.31	.011	92.47	.002	405.95	.001	876.81
SM10	.001	1556.68	.006	170.02	.002	663.35	.001	977.34
SM15	.000	6143.72	.003	335.15	.002	417.15	.001	906.07
SM20	.000	9790.15	.002	496.92	.000	2090.61	.002	567.99
SM25	.002	629.29	.010	98.49	.001	787.44	.001	1527.09
SM30	.005	212.81	.026	37.95	.001	1160.88	.002	612.32

**Remark:** Dependent Variable: Tmax.

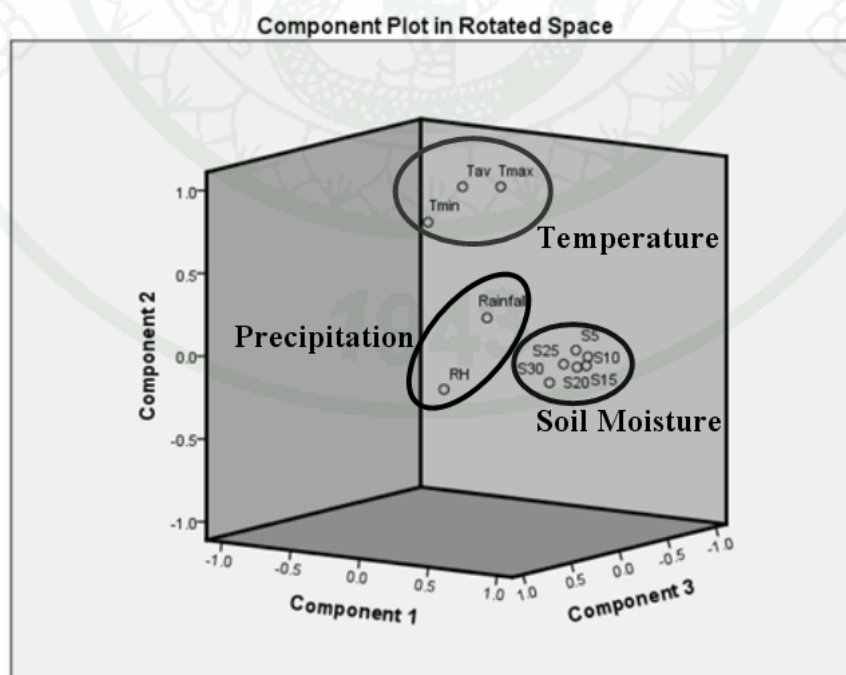
**Table 36** Total variance explained from 11 climatic and soil moisture variables from WNKFSPS.

Components	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
	1	6.815	61.959	61.959	6.815	61.959	61.959	5.837	53.068
2	2.633	23.935	85.894	2.633	23.935	85.894	2.690	24.458	77.526
3	1.018	9.251	95.145	1.018	9.251	95.145	1.938	17.619	95.145
4	.323	2.938	98.083						
5	.130	1.185	99.268						
6	.042	.386	99.654						
7	.026	.233	99.887						
8	.011	.099	99.986						
9	.001	.013	99.999						
10	4.686E-5	.000	100.000						
11	1.214E-5	.000	100.000						

**Remark:** Extraction Method: Principal Component Analysis.

**Table 37** Rotated component matrix of factor loadings from 11 climatic and soil moisture variables from WNKFSPS.

Variables	Components		
	1	2	3
SM15	.968	.012	.138
SM10	.962	.062	.114
SM20	.960	.014	.224
SM5	.940	.113	.206
SM25	.917	.040	.302
SM30	.870	-.065	.382
Tmean	.040	.993	.098
Tmax	-.006	.922	-.364
Tmin	.077	.843	.509
RH	.442	-.079	.865
Rainfall	.607	.339	.654



**Figure 53** Grouping of WNKFSPS climatic and soil moisture variables.

**Table 38** Factor scores calculated from factor loading of 11 climatic and soil moisture variables from WNKFSPS.

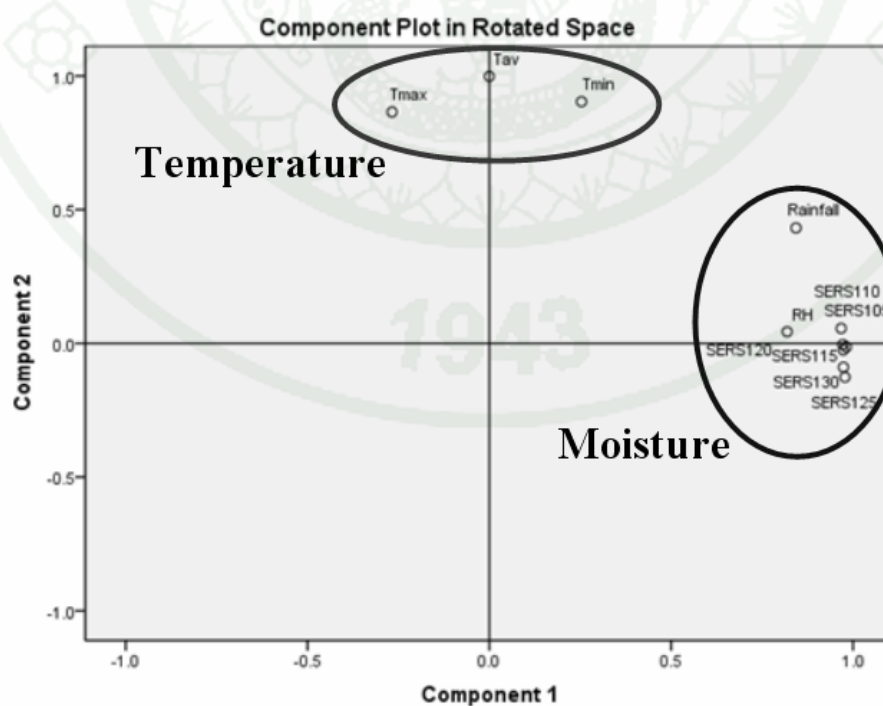
Month	Factor scores		
	Soil moisture	Temperature	Precipitation
SEP	1.34	-0.36	0.58
OCT	-0.4	-0.73	1.78
NOV	-0.79	-1.5	0.07
DEC	-0.84	-1.17	-0.83
JAN	-0.1	-0.94	-0.73
FEB	-1.18	0.41	-0.67
MAR	-0.14	0.88	-1.34
APR	0.88	1.04	-0.68
MAY	-0.71	0.91	-0.1
JUN	-0.9	1.69	1.53
JUL	1.68	0.12	-0.56
AUG	1.16	-0.35	0.94

For SERS1, multicollinearity problem was also eliminated using principle component analysis (PCA). Climatic and soil moisture variables were converted to 2 components of climatic data based on the criteria of Eigen values  $\geq 1$  (Table 39). In Table 40 and Figure 54, based on varimax rotation, it illustrated the rotated component matrix of 2 non-significantly correlated components. The first component was related to RH, rainfall and soil moisture contents in all soil depths and was re-named as “Moisture”. The second factor related to temperature in both of Tmax, Tmin and Tmean and was re-named as “Temperature”. These 2 components (Table 41) were finally used as independent factors in regression analysis and could explain all selected climatic data for 90.831%.



**Table 40** Rotated component matrix of factor loadings from 11 climatic and soil moisture variables from SERS1.

Variables	Components	
	1	2
SERS110	.982	-.014
SERS125	.978	-.126
SERS130	.974	-.089
SERS120	.973	-.025
SERS115	.972	-.004
SERS105	.967	.056
Rainfall	.843	.432
RH	.819	.044
Tmean	.000	.998
Tmin	.253	.904
Tmax	-.268	.865



**Figure 54** Grouping of SERS1 climatic and soil moisture variables.

**Table 41** Factor scores calculated from factor loading of 11 climatic and soil moisture variables from SERS1.

Month	Factor scores	
	Moisture	Temperature
SEP	1.44	-0.27
OCT	0.65	-0.49
NOV	-0.58	-1.47
DEC	-0.80	-1.33
JAN	-0.60	-1.00
FEB	-1.28	0.29
MAR	-1.09	0.71
APR	0.52	0.95
MAY	-0.64	0.86
JUN	-0.17	1.87
JUL	0.84	0.09
AUG	1.70	-0.22

At SERS2, using PCA, climatic and soil moisture variables were also converted to 2 components of climatic data based on the criteria of Eigen values  $\geq 1$  (Table 42). In Table 43 and Figure 55, based on varimax rotation, it illustrated the rotated component matrix of 2 non-significantly correlated components. The first components was related to RH, rainfall and soil moisture contents in all soil depths and was re-named as “Moisture”. The second factor related to temperature in both of Tmax, Tmin and Tmean and was re-named as “Temperature”. These 2 components (Table 44) were finally used as independent factors in regression analysis and could explain all selected climatic data for 90.993%.

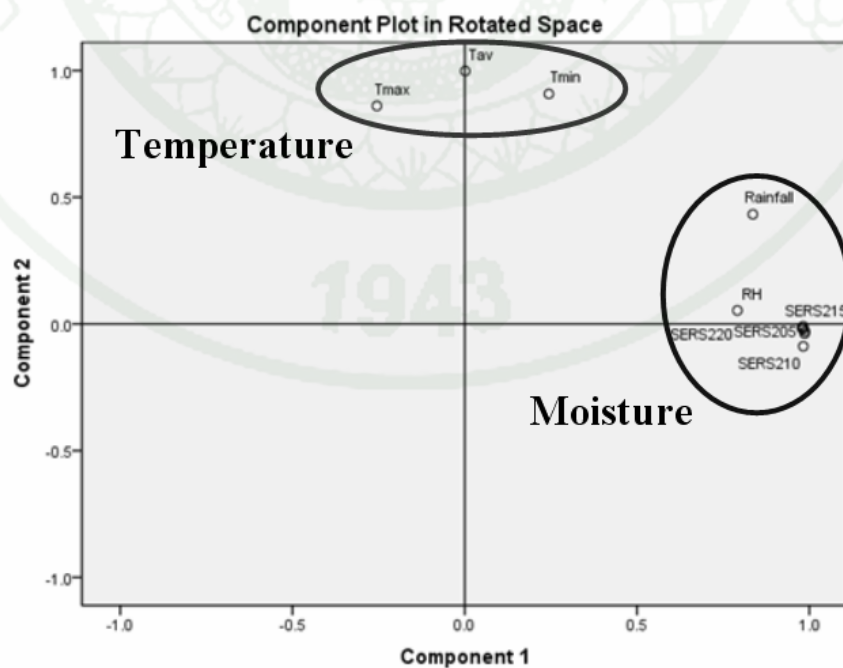
**Table 42** Total variance explained from 11 climatic and soil moisture variables from SERS2.

Components	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
	1	7.258	65.983	65.983	7.258	65.983	65.983	7.248	65.893
2	2.751	25.011	90.993	2.751	25.011	90.993	2.761	25.100	90.993
3	.771	7.006	98.000						
4	.132	1.203	99.203						
5	.043	.388	99.591						
6	.025	.223	99.814						
7	.014	.127	99.941						
8	.005	.049	99.991						
9	.001	.007	99.998						
10	.000	.002	100.000						
11	.000	.000	100.000						

**Remark:** Extraction Method: Principal Component Analysis.

**Table 43** Rotated component matrix of factor loadings from 11 climatic and soil moisture variables from SERS2

Variables	Components	
	1	2
SERS110	.988	-.029
SERS125	.986	-.038
SERS130	.982	-.020
SERS120	.982	-.088
SERS115	.982	-.009
SERS105	.978	-.016
Rainfall	.836	.433
RH	.791	.053
Tmean	.001	.998
Tmin	.244	.908
Tmax	-.255	.861



**Figure 55** Grouping of SERS2 climatic and soil moisture variables.

**Table 44** Factor scores calculated from factor loading of 11 climatic and soil moisture variables from SERS2.

Month	Factor scores	
	Moisture	Temperature
SEP	-0.86	-1.32
OCT	-0.63	-1.01
NOV	-1.12	0.26
DEC	-1.03	0.69
JAN	0.62	0.92
FEB	-0.82	0.90
MAR	-0.22	1.88
APR	0.85	0.11
MAY	1.71	-0.23
JUN	-0.86	-1.32
JUL	-0.63	-1.01
AUG	-1.12	0.26

Climatic and soil moisture variables at SERS3 were converted to 2 components of climatic data based on the criteria of Eigen values  $\geq 1$  by using PCA analysis (Table 45). In Table 46 and Figure 56, based on varimax rotation, it illustrated the rotated component matrix of 2 non-significantly correlated components. The first factor was related to RH, rainfall and soil moisture contents in all soil depths and was re-named as “Moisture”. The second factor related to temperature in both of Tmax, Tmin and Tmean and was re-named as “Temperature”. These 2 components (Table 47) were finally used as independent factors in regression analysis and could explain all selected climatic data for 89.393%.

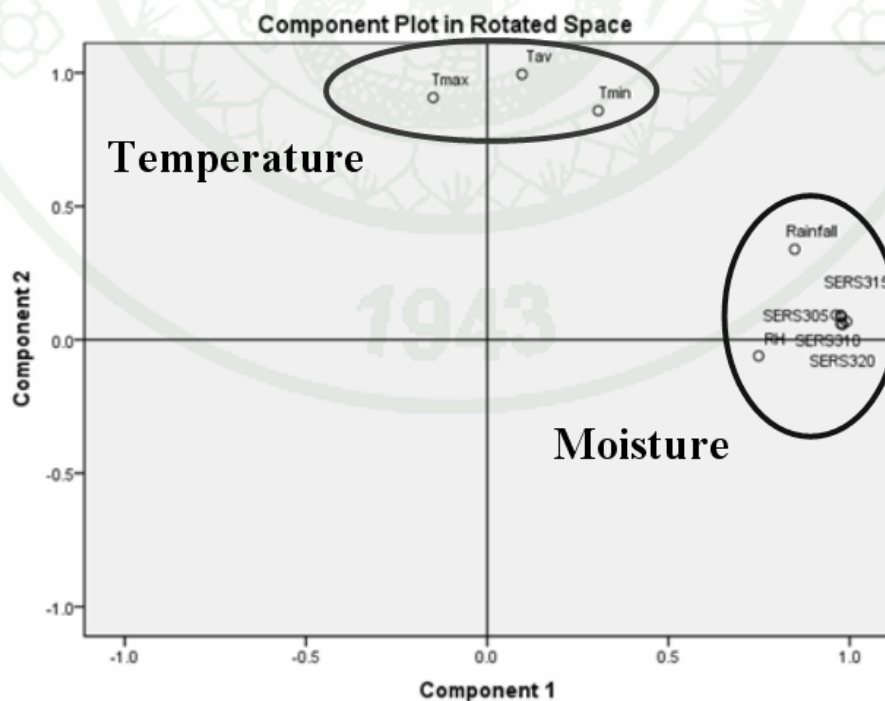
**Table 45** Total variance explained from 11 climatic and soil moisture variables from SERS3.

Components	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
	1	7.311	66.461	66.461	7.311	66.461	66.461	7.132	64.832
2	2.523	22.933	89.393	2.523	22.933	89.393	2.702	24.561	89.393
3	.921	8.377	97.771						
4	.157	1.427	99.197						
5	.049	.442	99.639						
6	.032	.287	99.927						
7	.005	.050	99.976						
8	.001	.012	99.989						
9	.001	.009	99.998						
10	.000	.002	100.000						
11	.000	.000	100.000						

**Remark:** Extraction Method: Principal Component Analysis.

**Table 46** Rotated component matrix of factor loadings from 11 climatic and soil moisture variables from SERS3

Variables	Components	
	1	2
SERS110	.991	.068
SERS125	.980	.057
SERS130	.977	.085
SERS120	.975	.060
SERS115	.975	.092
SERS105	.962	.092
Rainfall	.848	.339
RH	.749	-.061
Tmean	.096	.994
Tmin	-.149	.907
Tmax	.306	.858



**Figure 56** Grouping of SERS3 climatic and soil moisture variables.

**Table 47** Factor scores calculated from factor loading of 11 climatic and soil moisture variables from SERS3.

Month	Factor scores	
	Moisture	Temperature
SEP	1.57	-0.43
OCT	0.29	-0.61
NOV	-0.56	-1.46
DEC	-1.00	-1.18
JAN	-0.73	-0.94
FEB	-1.22	0.42
MAR	-0.61	0.79
APR	0.67	0.99
MAY	-0.90	0.97
JUN	-0.06	1.77
JUL	0.95	0.07
AUG	1.61	-0.37

From the analysis of factors affecting tree growth using multiple regressions, some variables were eliminated from the model of factors affecting tree growths due to exhibit the insignificant and/or lower significant correlation. In addition, multiple regressions did not illustrate the hierarchical process of factors affecting tree growths as shown in Figure 48. Some independent variables performed as endogenous variables and showed indirect influences on dependent variables. The relationship of each phenological feature and climatic factors could directly analyze and explain using the ordinary linear and multiple regressions. Monthly wood increments, which were directly influenced by climatic and phenological data and were indirectly influenced by climatic data through phenological data, could not be analyzed using the ordinary linear regression. Therefore, path analysis was applied to analyze both direct and indirect effects of all selected variables on tree growths. Path Analysis of *T. grandis* was firstly performed and described. It was followed by the

analysis of *A. xylocarpa*, *M. azedarach*, *L. duperreana*, *A. odoratissima* and *H. ilicifolia*, respectively.

#### 7.3.5.1 *Tectona grandis* L.f.

From the conceptual model of climatic and phenological factors inducing tree growth illustrated in Figure 48, all predictors were added to the model, while non-significant predictors were latterly removed (Figure 57). Overall model fit was examined in 3 groups of absolute fit indices, comparative fit indices and miscellaneous measures. The testing indicated that the default model was fit and passed the overall model fit examination ( $\chi^2 = 4.796$ ,  $df = 6$ ,  $p = 0.570$ ; Root Mean Square Error of Approximation (RMSEA) = 0.000 and Comparative Fit Index (CFI) = 1.00).

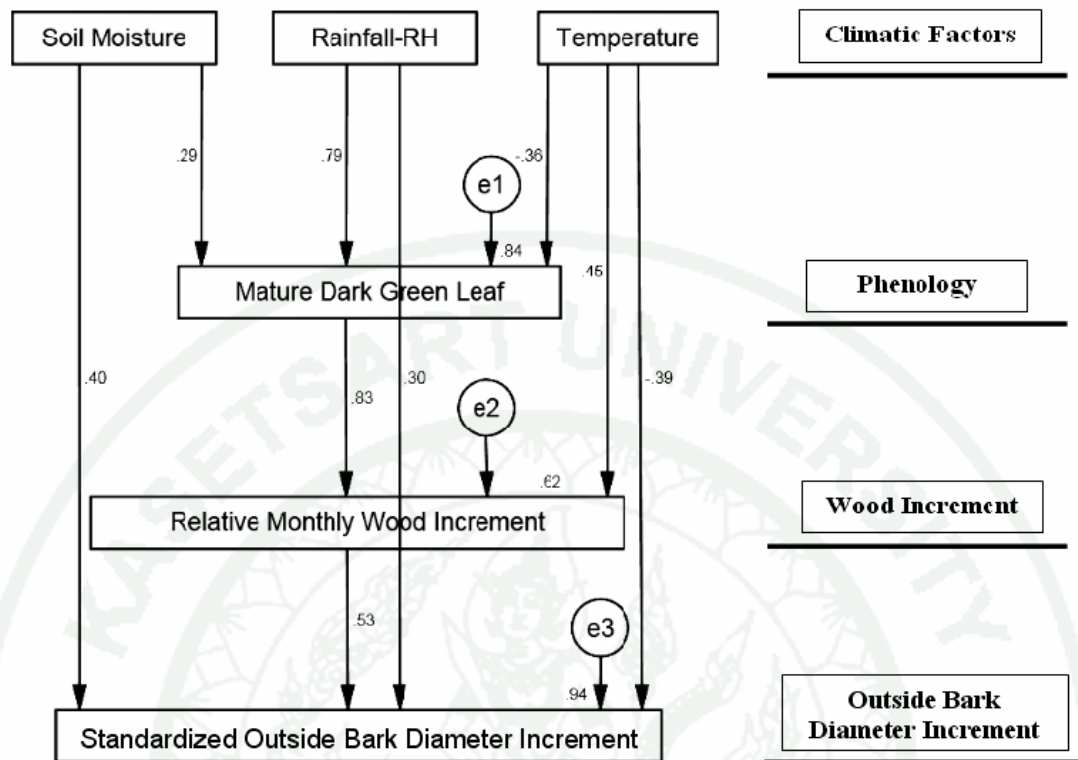
All path coefficients in Figure 57 were analyzed and were statistically significant ( $p < 0.05$ ). Path diagrams of teak growth predicted that soil moisture, rainfall with RH and temperature induced the occurrences of mature dark green leaves ( $r = 0.29$ ,  $0.79$  and  $-0.36$ , respectively). These 3 variables could totally be explained the occurrences of mature dark green leaf (MDL) for 84%. The occurrences of mature dark green leaf (MDL) and fluctuation of temperature directly generated tree growths which were detected by monthly wood increment for  $r = 0.83$ ,  $0.45$ , respectively. Rainfall-RH and soil moisture was not shown the directly significant relationship with monthly wood increment, but these variables were significantly related with the occurrences of mature dark green leaf (MDL), a potential factor for inducing wood increment. Therefore, Rainfall-RH and soil moisture illustrated as the indirect factor influencing wood formation for  $r = 0.65$  and  $0.24$ , respectively. Both of mature dark green leaf (MDL), temperature, soil moisture and Rainfall-RH could be explained the occurrences of monthly wood increment for 62%. Monthly wood increment directly influenced outside bark diameter changes detected by manual band dendrometers ( $r = 0.53$ ). Additionally, the swelling/shrinkage of barks inducing the movement of dendrometer scales also directly related to Rainfall-RH ( $r = 0.30$ ), temperature ( $r = -0.39$ ) and soil moisture ( $r = 0.40$ ). Outside

bark diameter increment was also indirectly influenced by Rainfall-RH, temperature and soil moisture through mature dark green leaf (MDL) and monthly wood increment for  $r = 0.35$ ,  $0.08$  and  $0.13$ , respectively. Both of Rainfall-RH, temperature, soil moisture, mature dark green leaf (MDL) and monthly wood increment could be used to explain the variation of outside bark diameter increment for 94%. Direct, indirect, and total effects of each variable on monthly wood and outside bark diameter increments were calculated and shown in Table 48 and 49. The total effect calculations illustrated that mature dark green leaf (MDL) was the most important factor affecting monthly wood increment for  $r = 0.83$  followed by Rainfall-RH ( $r = 0.65$ ), soil moisture ( $r = 0.24$ ) and temperature ( $r = 0.15$ ), respectively. Rainfall-RH was the major factor inducing outside bark diameter increment for  $r = 0.63$  followed by monthly wood increment ( $r = 0.53$ ), soil moisture ( $r = 0.53$ ), mature dark green leaf ( $r = 0.44$ ) and temperature ( $r = -0.31$ ), respectively.

**Table 48** Path coefficients of factors affecting monthly wood increments of *Tectona grandis*

Variable	Direct effect	Indirect effect	Total effect
Temperature	0.45	-0.30	0.15
Rainfall-RH	0.00	0.65	0.65
Soil Moisture	0.00	0.24	0.24
Mature Dark Green Leaf	0.83	0.00	0.83

From the path diagram in Figure 57, it could be hierarchically interpreted that the increased available moisture from Rainfall-RH and soil moisture content associated with declined temperature stimulated the abundances of mature dark green leaves. Monthly wood rapidly increased when mature dark green leaves were plentiful. Finally, outside bark diameter increments were explored due to teak wood increment from above explanation associating with the direct effect from increased soil moisture and rainfall-RH and decreased temperature.



**Figure 57** Path diagrams: factors affecting monthly tree growth of *Tectona grandis*.

**Table 49** Path coefficients of factors affecting outside bark diameter increments of *Tectona grandis*

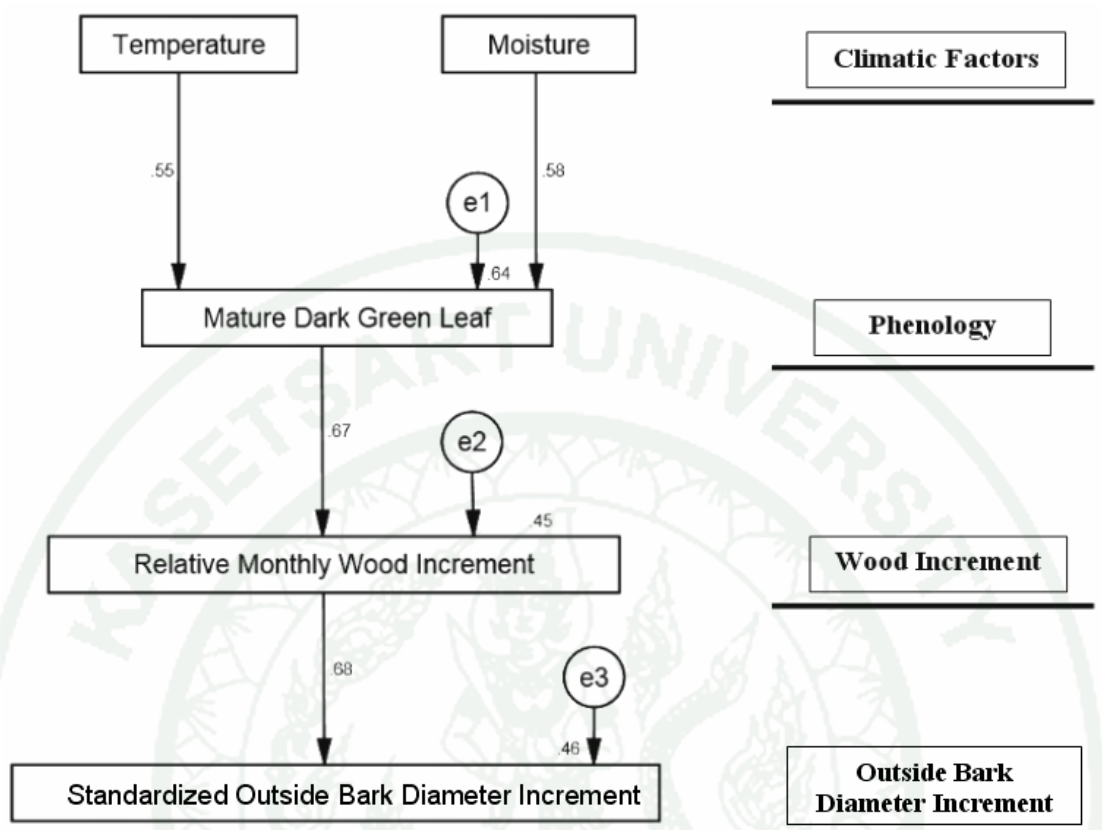
Variable	Direct effect	Indirect effect	Total effect
Temperature	-0.39	0.08	-0.31
Rainfall-RH	0.30	0.35	0.65
Soil Moisture	0.40	0.13	0.53
Mature Dark Green Leaf	0.00	0.44	0.44
Monthly Wood Increment	0.53	0.00	0.53

#### 7.3.5.2 *Azelia xylocarpa* (Kurz) Craib.

From the general model of climatic and phenological factors inducing tree growth (Figure 48), all predictors were added to the model and non-

significant predictors were latterly removed (Figure 58). The testing of overall model fit indicated that the default model was fit and suited for factor affecting tree growth explanation ( $\chi^2 = 6.632$ ,  $df = 6$ ,  $p = 0.356$ ; Root Mean Square Error of Approximation (RMSEA) = 0.098 and Comparative Fit Index (CFI) = 0.970).

All path coefficients in sequential model of *A. xylocarpa* growth (Figure 58) were statistically significant ( $p < 0.05$ ) and predicted that suitable temperature (derived from  $T_{max}$ ,  $T_{min}$  and  $T_{mean}$ ) and moisture (derived from soil moisture content, rainfall and RH) directly induced the occurrences of mature dark green leaves ( $r = 0.55$  and  $0.58$ , respectively). These 2 variables could explain the occurrences of mature dark green leaf (MDL) for 64%. The occurrences of mature dark green leaf (MDL) directly generated monthly wood increment for  $r = 0.67$ , while temperature and moisture indirectly induced wood increment through mature dark green leaf (MDL) for  $r = 0.37$  and  $0.39$ , respectively. Both of direct effects from mature dark green leaf (MDL) and indirect effects from temperature and moisture could be explained the occurrences of monthly wood increment for 45%. Monthly wood increment directly influenced the increments of outside bark diameters detected by manual band dendrometers ( $r = 0.68$ ). Temperature, moisture and mature dark green leaf (MDL) also illustrated the indirect influence on outside bark diameter increments through monthly wood increments as described above and could be explained the occurrences of outside bark diameter increment for 46%. Direct, indirect, and total effects of each variable on monthly wood and outside bark diameter increments of *A. xylocarpa* were calculated and shown in Table 50 and 51. The total effect calculations illustrated that mature dark green leaf (MDL) was the most important factor affecting monthly wood increment for  $r = 0.67$  followed by moisture ( $r = 0.39$ ) and temperature ( $r = 0.37$ ), respectively. Monthly wood increment was the major factor inducing outside bark diameter increment for  $r = 0.68$  followed by mature dark green leaf ( $r = 0.46$ ), moisture ( $r = 0.27$ ) and temperature ( $r = 0.25$ ), respectively.



**Figure 58** Path diagrams: factors affecting monthly tree growth of *Afzelia xylocarpa*.

**Table 50** Path coefficients of factors affecting monthly wood increments of *Afzelia xylocarpa*.

Variable	Direct effect	Indirect effect	Total effect
Moisture	0.00	0.39	0.39
Temperature	0.00	0.37	0.37
Mature Dark Green Leaf	0.67	0.00	0.67

From the path diagram in Figure 58, it could be hierarchically explained that the increased available moisture (from rainfall-RH and soil moisture contents) and temperature stimulated the abundances of mature dark green leaves. Monthly wood rapidly increased when mature dark green leaves were plentiful as similar as *T. grandis*. Outside bark diameter increments were directly affected by

monthly wood increment of *A. xylocarpa* associating with the indirect of moisture and temperature through mature dark green leaves and monthly wood increment as describe above.

**Table 51** Path coefficients of factors affecting outside bark diameter increments of *Afzelia xylocarpa*.

Variable	Direct effect	Indirect effect	Total effect
Moisture	0.00	0.27	0.27
Temperature	0.00	0.25	0.25
Mature Dark Green Leaf	0.00	0.46	0.46
Monthly Wood Increment	0.68	0.00	0.68

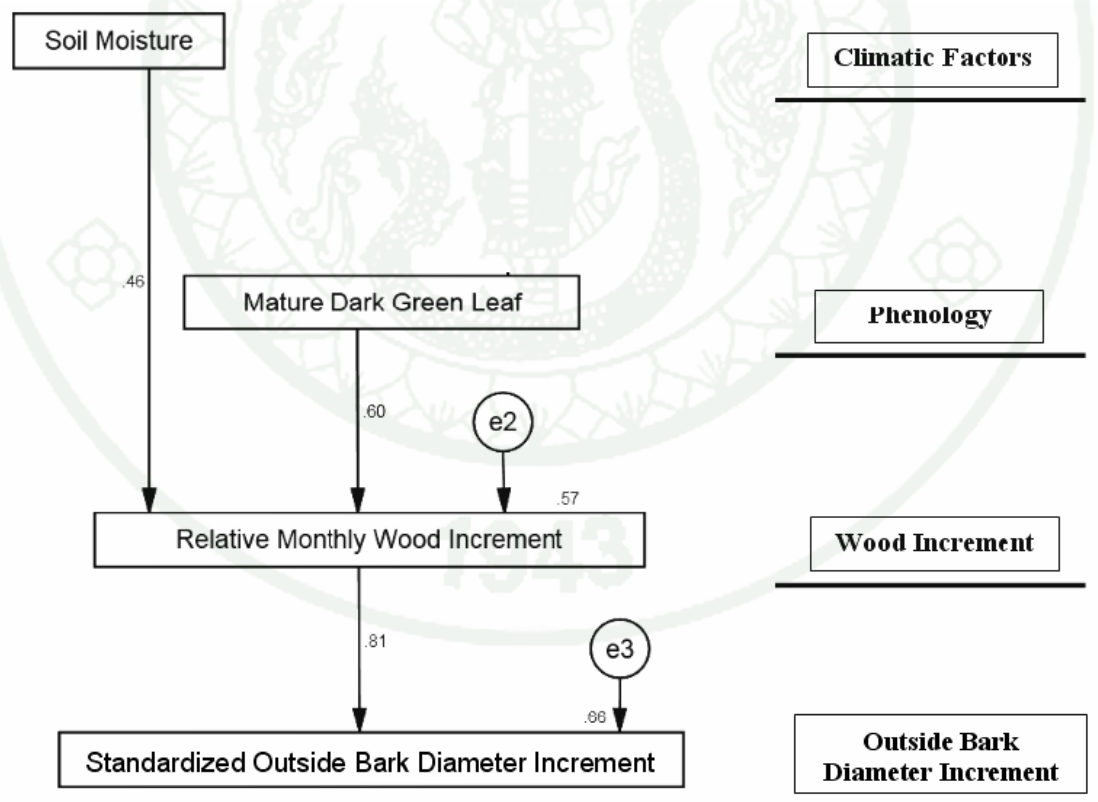
#### 7.3.5.3 *Melia azedarach* L.

The testing indicated that the trimmed model of factor affecting *M. azedarach* growth as shown in Figure 59 was fit and passed the overall model fit examination ( $\chi^2 = 2.647$ ,  $df = 3$ ,  $p = 0.449$ ; Root Mean Square Error of Approximation (RMSEA) = 0.00 and Comparative Fit Index (CFI) = 1.00).

The standardized path coefficients in Figure 59 were analyzed from trimmed model which all path coefficients were statistically significant ( $p < 0.05$ ). Sequential model of *M. azedarach* growth predicted that soil moisture and mature dark green leaf (MDL) directly induced monthly wood increment ( $r = 0.46$  and  $0.60$ , respectively), while the occurrences of mature dark green leaf (MDL) were not significantly related to all climatic data. Soil moisture and mature dark green leaf (MDL) could explain the increment of wood for 57%. Outside bark diameter increment detected by manual band dendrometers was directly influenced by monthly wood increment ( $p = 0.81$ ) and indirectly influenced by soil moisture and mature dark green leaf (MDL) through monthly wood increment. These direct and indirect influences could explain the changing of outside bark diameter for 66%. Direct, indirect, and total effects of each variable on monthly wood and outside bark diameter

increments of *M. azedarach* were calculated and shown in Table 52 and 53. The total effect calculations illustrated that mature dark green leaf (MDL) was the most important factor affecting monthly wood increment for  $r = 0.60$  followed by soil moisture for  $r = 0.46$ . Monthly wood increment was the major factor inducing outside bark diameter increment for  $r = 0.81$  followed by mature dark green leaf ( $r = 0.49$ ) and soil moisture ( $r = 0.37$ ), respectively.

From the path diagram in Figure 59, it could be hierarchically explained that the increased soil moisture content associated with the abundances of mature dark green leaves stimulated monthly wood increments. Outside bark diameter of *M. azedarach* was increased due to monthly wood increment which was stimulated from soil moisture and mature dark green leaf (MDL) as described above.



**Figure 59** Path diagrams: factors affecting monthly tree growth of *Melia azedarach*.

**Table 52** Path coefficients of factors affecting monthly wood increments of *Melia azedarach*.

Variable	Direct effect	Indirect effect	Total effect
Soil Moisture	0.46	0.00	0.46
Mature Dark Green Leaf	0.60	0.00	0.60

**Table 53** Path coefficients of factors affecting outside bark diameter increments of *Melia azedarach*.

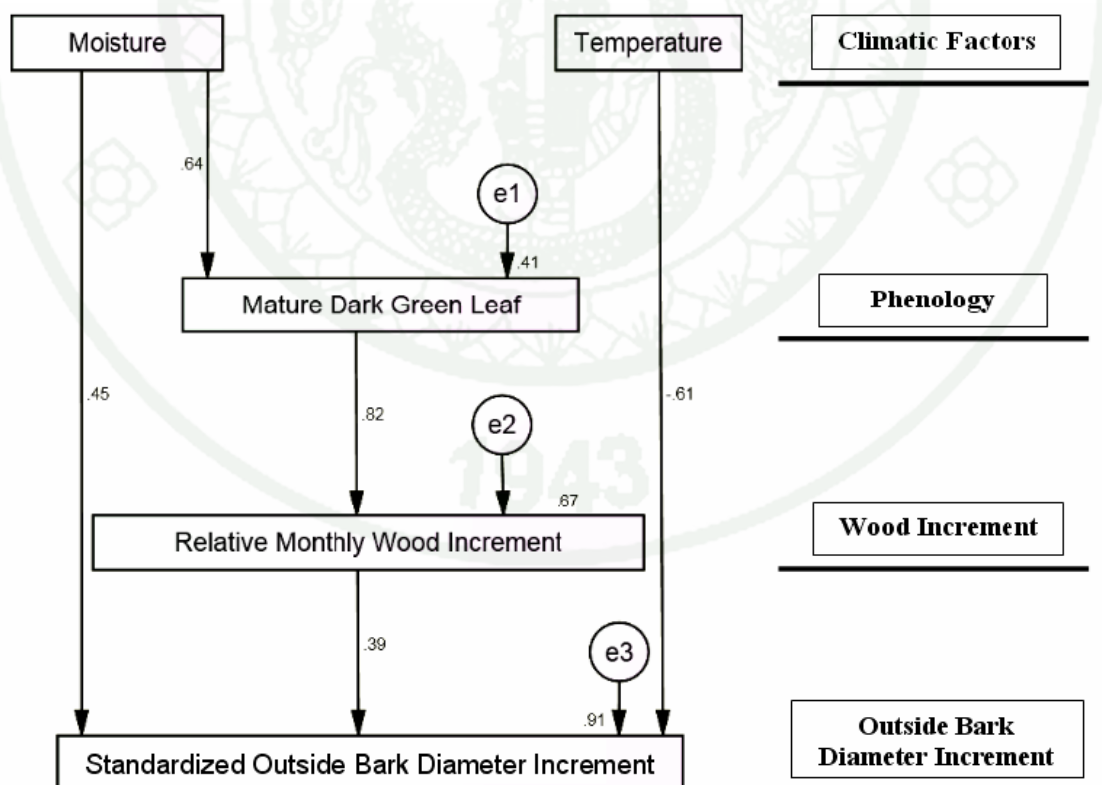
Variable	Direct effect	Indirect effect	Total effect
Soil Moisture	0.00	0.37	0.37
Mature Dark Green Leaf	0.00	0.49	0.49
Monthly Wood Increment	0.81	0.00	0.81

#### 7.3.5.4 *Lagerstroemia duperreana* Pierre ex Gagnep

From the conceptual model of climatic and phenological factors inducing tree growth of *L. duperreana* in Figure 48, all predictors were added to the model, while non-significant predictors were latterly removed as shown in Figure 60. The testing indicated that the model was fit and passed the overall model fit examination ( $\chi^2 = 1.238$ ,  $df = 5$ ,  $p = 0.941$ ; Root Mean Square Error of Approximation (RMSEA) = 0.00 and Comparative Fit Index (CFI) = 1.000).

The path coefficients in Figure 60 were analyzed and all path coefficients were statistically significant ( $p < 0.05$ ). Sequential model of *L. duperreana* growth predicted that moisture derived from rainfall and RH directly induced the occurrences of mature dark green leaf (MDL) for  $r = 0.64$  and could explain the occurrence of mature dark green leaf (MDL) for 41%. The abundances of mature dark green leaf (MDL) generated wood increment for  $r = 0.82$ . Moisture indirectly influenced monthly wood increment through mature dark green leaf (MDL) for  $r = 0.52$ . Both of mature dark green leaf (MDL) and moisture could explain monthly

wood increment of *L. duperreana* for 67%. Monthly wood increment directly influenced outside bark diameter increment detected by manual band dendrometers ( $r = 0.39$ ). Additionally, the changing of outside bark diameter increment also directly influenced by temperature and moisture ( $r = -0.61$  and  $0.45$ , respectively) and indirectly influenced by moisture through mature dark green leaf (MDL) and monthly wood increment for  $r = 0.20$ . Moisture, temperature, mature dark green leaf (MDL) and monthly wood increment generated outside bark diameter increment and could explain the changing for 91%. Direct, indirect, and total effects of each variable on monthly wood and outside bark diameter increments were calculated and shown in table 54 and 55. The total effect calculations illustrated that mature dark green leaf (MDL) was the most important factor affecting monthly wood increment for  $r = 0.82$  followed by moisture for  $r = 0.53$ . Moisture was the major factor inducing outside bark diameter increment for  $r = 0.66$  followed by temperature ( $r = -0.61$ ), monthly wood increment ( $r = 0.39$ ) and mature dark green leaf ( $r = 0.32$ ), respectively.



**Figure 60** Path diagrams: factors affecting monthly tree growth of *Lagerstroemia duperreana*.

From the path diagram in Figure 60, it could be hierarchically explained that the increased available moisture (from rainfall-RH and soil moisture content) stimulated the abundances of mature dark green leaves. Monthly wood rapidly increased when mature dark green leaves were plentiful. Outside bark diameter increment occurred when moisture increased, temperature declined and monthly wood increased due to the stimulation of mature dark green leaf abundance and increased moisture.

**Table 54** Path coefficients of factors affecting monthly wood increments of *Lagerstroemia duperreana*.

Variable	Direct effect	Indirect effect	Total effect
Temperature	0.00	0.00	0.00
Moisture	0.00	0.53	0.53
Mature Dark Green Leaf	0.82	0.00	0.82

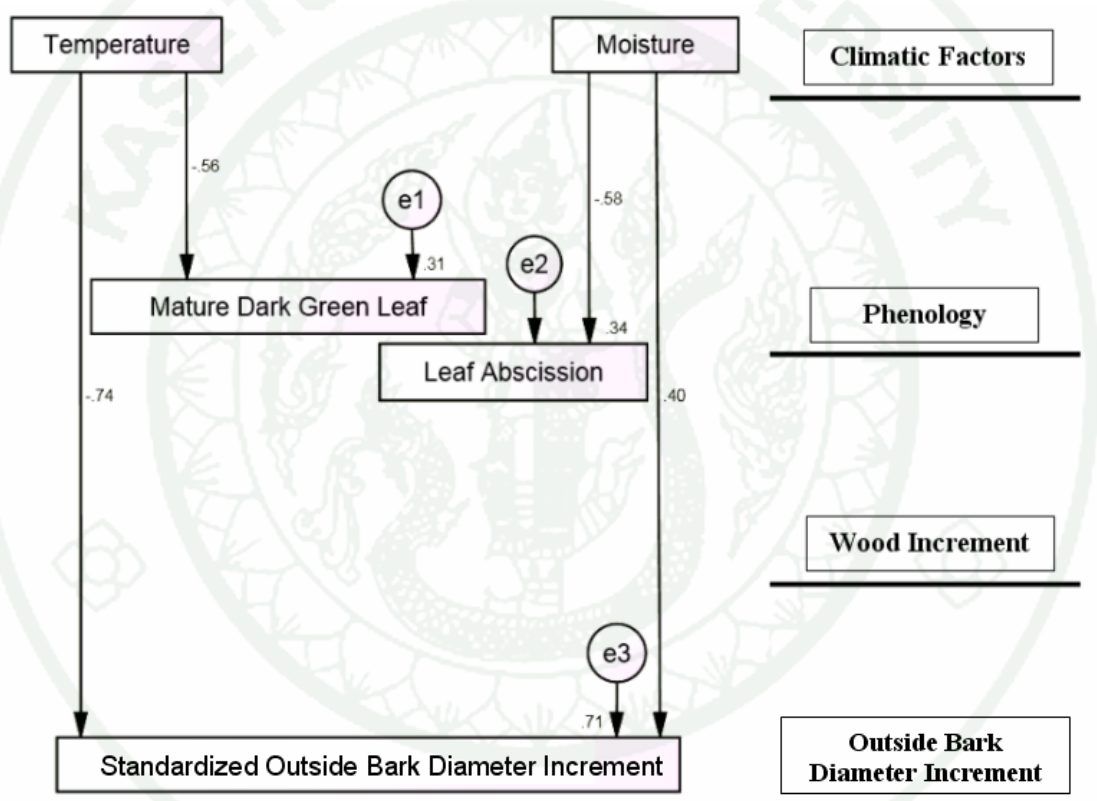
**Table 55** Path coefficients of factors affecting outside bark diameter increments of *Lagerstroemia duperreana*.

Variable	Direct effect	Indirect effect	Total effect
Temperature	-0.61	0.00	-0.61
Moisture	0.45	0.20	0.66
Mature Dark Green Leaf	0.00	0.32	0.32
Monthly Wood Increment	0.39	0.00	0.39

#### 7.3.5.5 *Aglaia odoratissima* Blume

As shown in Figure 61, temperature and moisture were the major climatic factors directly influencing mature dark green leaf (MDL) for  $r = -0.56$  and leaf abscission (LA) for  $r = -0.58$ , respectively. The occurrences of mature dark green leaf (MDL) and leaf abscission (LA) could be explained by the fluctuation of temperature and moisture for 31% and 34%, respectively. Outside bark diameter

increment detected by manual band dendrometers was induced by temperature ( $r = -0.74$ ) and moisture ( $r = 0.40$ ). The association of temperature and moisture could be explained the fluctuation of outside bark diameter for 71%. All climatic and phenological factors were not significantly related to monthly wood increment. The relationships of variables shown in Figure 61 were direct influences, while indirect influences inducing tree growth of these factors were not significantly found in this study.



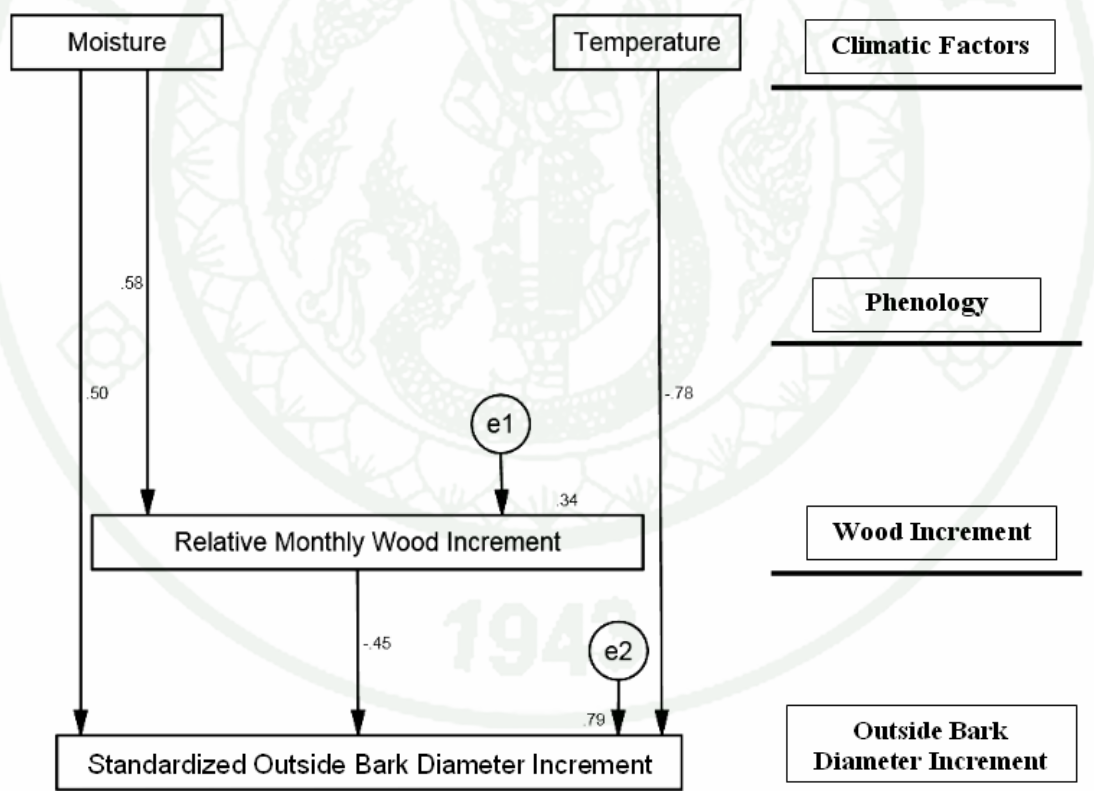
**Figure 61** Path diagrams: factors affecting tree growth of *Aglaia odoratissima*.

From the path diagram in Figure 61, it could be explained that the declined temperature stimulated the occurrences of mature dark green leaves, while the declined moisture available from rainfall-RH and soil moisture content induced leaf abscission. However, the increment of monthly wood did not relate to these climatic and phenological data. Outside bark diameter increment also related to the fluctuation of temperature and moisture. The increment of moisture caused bark

swelling and outside bark diameter increased, while declined temperature stimulated the shrinkage of outside bark diameters.

### 7.3.5.6 *Hydnocarpus ilicifolia* King

From the conceptual model of climatic and phenological factors inducing tree growth in Figure 48, all variables were added to the model, while non-significant predictors were latterly removed (Figure 62). The testing indicated that the model was fit and passed the overall model fit examination ( $\chi^2 = 0.036$ ,  $df = 2$ ,  $p = 0.982$ ; Root Mean Square Error of Approximation (RMSEA) = 0.00 and Comparative Fit Index (CFI) = 1.00).



**Figure 62** Path diagrams: factors affecting monthly tree growth of *Hydnocarpus ilicifolius*.

Path coefficients which were illustrated in Figure 62 were statistically significant ( $p < 0.05$ ). All climatic factors were not significantly related to

phenological data while wood increment of *H. ilicifolia* detected by cambial marked technique increased due to the fluctuation of moisture ( $r = 0.58$ ). Moisture could explain wood increment of *H. ilicifolia* for 34%. Outside bark diameter increment detected by manual band dendrometers was directly forced by monthly wood increment ( $r = -0.45$ ). Not only monthly wood increments, but moisture and temperature also directly influence wood increment ( $r = 0.50$  and  $-0.78$ , respectively). Moisture also illustrated the indirect effect on outside bark diameter increment through monthly wood increment ( $r = 0.26$ ). Both of moisture, temperature and monthly wood increment could explain the fluctuation of outside bark diameter increment for 79%. Direct, indirect, and total effects of each variable on monthly wood and outside bark diameter increments were calculated and shown in Table 56 and 57. The total effect calculations illustrated that moisture was the most important factor affecting monthly wood increment for  $r = 0.58$ . Temperature was the major factor inducing outside bark diameter increment for  $r = -0.78$  followed by monthly wood increment ( $r = -0.45$ ) and moisture ( $r = 0.24$ ), respectively.

**Table 56** Path coefficients of factors affecting monthly wood increments of *Hydnocarpus ilicifolius*.

Variable	Direct effect	Indirect effect	Total effect
Moisture	0.58	0.00	0.58
Temperature	0.00	0.00	0.00

**Table 57** Path coefficients of factors affecting the outside bark diameter increments of *Hydnocarpus ilicifolius*.

Variable	Direct effect	Indirect effect	Total effect
Moisture	0.50	-0.26	0.24
Temperature	-0.78	0.00	-0.78
Monthly Wood Increment	-0.45	0.00	-0.45

From the path diagram in Figure 62, it could be hierarchically explained that the increased available moisture (from rainfall-RH and soil moisture content) stimulated monthly wood increment. Outside bark diameter increment occurred when moisture increased and temperature declined. However, the convergent relationship of outside bark diameter and monthly wood increment was ambiguous.

Based on the occurrences and abundances of leaf phenology (mature dark green leaves), tree species in this study were divided into 2 groups of evergreen and deciduous tree species. The first group of evergreen species composed of *A. odoratissima* and *H. ilicifolia* which mature dark green leaves could be found all the year. The second group was deciduous species which leaf abscission and leafless occurred in some intervals at least 1 month during the investigated periods, including *T. grandis*, *A. xylocarpa*, *M. azedarach* and *L. duperreana*. The fluctuation of leaf phenology in deciduous species directly induced monthly wood increment while monthly wood increments of evergreen species did not significantly related to the occurrences of their leaves. The relationship between leaf phenology and wood increment were also studied by several researchers. Venugopal and Liangkuwang (2007) found that cambial activities and annual rhythm of xylem production of elephant apple trees (*Dillenia indica* Linn.) occurred after the sprouting of new leaves and buds for 15 days as similar as the study of Cufar *et al.* (2008) who illustrated leaf unfolding of beech (*Fagus sylvatica*) immediately followed by the reaction of cambium and wood increment from a humid continental site in SE central Europe, while Askeyev *et al.* (2005) did not found the relationship between leaf phenology and wood increment of pedunculate oak (*Quercus robur*) in the middle Volga region, Tatarstan, Russia. At La Selva Biological Station, Costa Rica, deciduous trees in old growth forest showed a significant relationship between stem increment and leaflessness, while evergreen trees found no relationship (O'Brien *et al.*, 2008).

The climatic data of moisture (rainfall-RH and soil moisture) and temperature (Tmax, Tmin and Tmean) illustrated both of direct and indirect relationship with monthly wood increment of all deciduous species through the

occurrences of mature dark green leaves. However, the major factor affecting monthly wood increments of the deciduous species was the abundances of mature dark green leaves. It was different with the evergreen species which the abundances of mature dark green leaves occurred throughout the year and the increment of monthly wood formation did not significantly related to leaf abundances. All climatic data did not showed the significant correlation with the monthly wood increment of *A. odoratissima* but moisture was significantly related to wood increment of *H. illicifolius*. Lamotte *et al.*, (1998) and Marod *et al.* (2003) explained that all selected species, except *A. odoratissima*, from Sakaerat Environmental Research Station (SERS) were dominant and co-dominant tree species with the upper layers of crown covers while *A. odoratissima* was the lower layers of crown covers and was suppressed by other trees. Microclimatic factors varied vertically within the forest stand and induced plant water status changing vertically. Response to increased air temperature, higher leaf temperature in the upper canopy caused a steeper gradient of vapor pressure from the leaf to the air greater than the observation from the shaded understory and ground vegetation (Thompson and Hinckley, 1977). Therefore, the fluctuation of climate could directly affect to these dominant and co-dominant tree species and illustrated insignificant correlation or the lower effects to the suppressed or understory trees. However, Borchert (1999) explained that seasonal rainfall drove leaf phenology, cambial growth and wood increment in deciduous trees, but were progressively uncoupled in evergreen trees. Lisi *et al.* (2008) also found trunk increment dynamics of 24 tree species from a seasonal semi-deciduous forest of southeast Brazil corresponded to seasonal changes in precipitation. Not only the increased temperature in a growing period inducing tree growth, but the study of *Pinus leucodermis* at a tree-line in southern Italy by Deslauriers *et al.* (2008) also suggested the increased temperature in an earlier onset of cambial activity and all differentiation phases about 20 days resulting in an increased duration of xylogenesis. Several researches suggested wood increment associated with environmental influences such as temperature influencing cambial activities of *Araucaria angustifolia* in southeastern South America (Oliveira *et al.*, 2009), *Picea abies* in the Paneveggio forest of Italy (Nocetti and Romagnoli, 2008), and *Pinus sylvestris* and *Betula* spp. in the Northern Boreal Forest in Finland (Schmitt *et al.*, 2004) and

duration of rainy season influencing initiate wood formation in several tree species of tropical mountain forest in Ethiopia (Krepkowski *et al.*, 2011). To confirm the effect of climate and phenology on tree growth, Heinrich and Banks (2006) constructed the restricted growth conditions of minimum water and nutrient, *Toona sinensis* and *T. ciliata* often illustrated longer leafless periods, shorter flushes of leaves, and decreased vessel sizes and diameter growth increments.

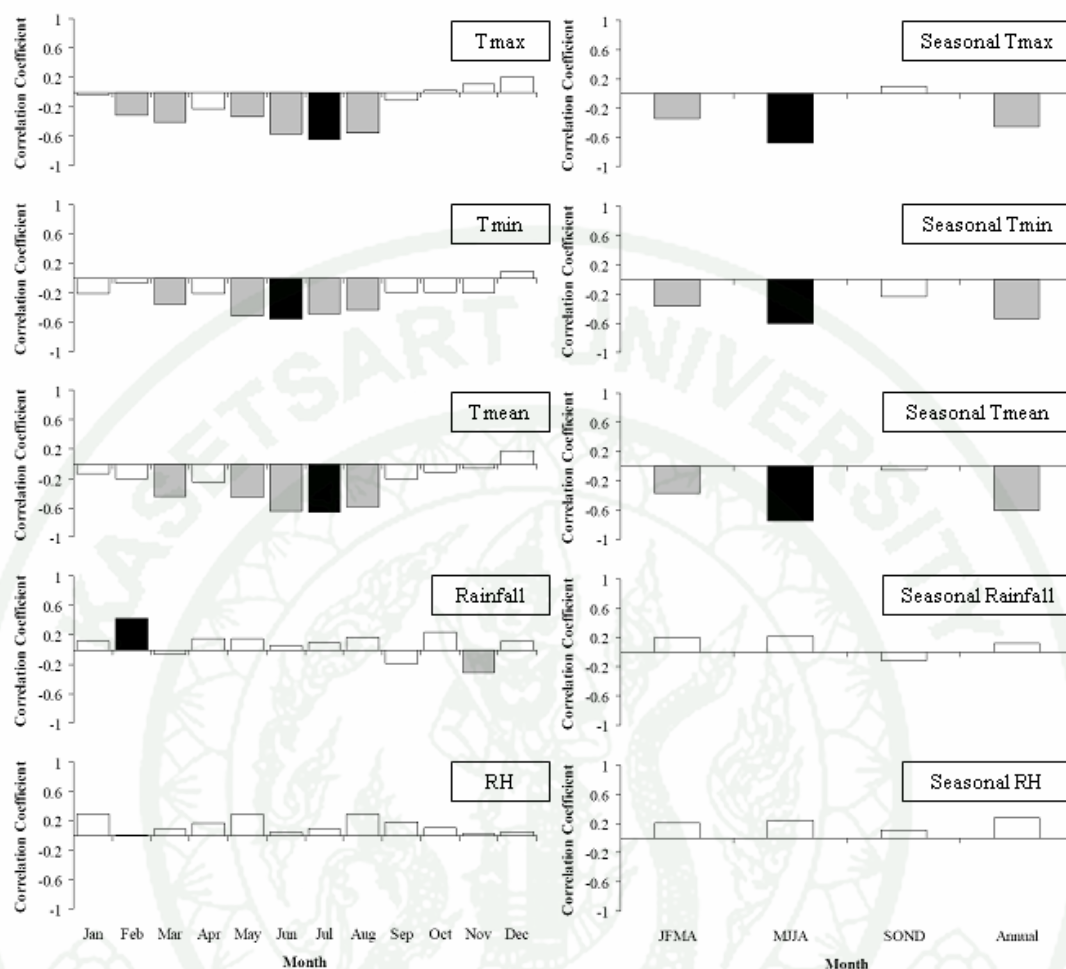
Outside bark diameter increments of the deciduous trees including *T. grandis*, *A. xylocarpa*, *M. azedarach* and *L. duperreana* directly and positively related to the increment of xylem elements, while the evergreen species including *A. odoratissima* and *H. illicifolia* were not shown the positive relationship of outside bark diameter increment with monthly wood increment. According to the stem shrink and swelling of *T. grandis*, *L. duperreana*, *A. odoratissima* and *H. illicifolia*, increased or decreased temperature induced shrinkage or swelling of outside bark diameter, respectively. Moisture showed direct and positive effects on outside bark diameter increments of *T. grandis*, *L. duperreana*, *A. odoratissima* and *H. illicifolia*. Although, temperature and moisture did not directly induced outside bark diameter increments in *A. xylocarpa* and *M. azedarach*, temperature and moisture still induced outside bark diameter increment through mature dark green leaves and monthly wood increments. Several studies explained outside bark diameter increments in rainy or wet season relating to new cell formation and development, while swelling and shrinkage in dormant period probably depended on the bark water content, rather than changes in xylem growth (Bräuning and Burchardt, 2005; Bräuning *et al.*, 2008; Jezik *et al.*, 2007; Deslauriers *et al.*, 2003; Gruber *et al.*, 2009). However, to avoid the effect of bark swelling and shrinkage, several studies recommended the cambial wounding technique to investigate the seasonal rhythms of xylem growth instead of dendrometer bands (Kuroda and Kiyono, 1997; Makinen *et al.*, 2008).

### 7.3.6 The relationship of ring width index with climate

To explore factors inducing teak tree growth, the reliable tree ring index from 1976 - 2008 was correlated with monthly and seasonal climatic data in

January till April (JFMA), May till August (MJJA) and September till December (SOND) by using the analysis of linear correlation and multiple regression at 95% confident level as mentioned in the section of the methodology to study the relationship of false ring formation and ring width index with climate, while tree ring index from 1962-1975 was rejected due to the EPS value was lower than the critical point of 0.85. In each climatic data, Tmax in July, Tmin in June, Tmean in July and rainfall in February illustrated the significant and highest correlation with annual ring width index of teak for  $r = -0.652, -0.556, -0.662$  and  $0.424$ , respectively. These climatic factors could be separately used to explain the fluctuation of teak annual ring width for 42.45%, 30.95%, 43.78% and 17.98%, respectively. The averages of Tmax, Tmin, and Tmean in May-August showed the highest significant correlation with tree growth for  $r = -0.674, -0.603$  and  $-0.760$ . The fluctuation of these climatic data could be used to explain annual tree growth variation for 45.42%, 36.35% and 57.74%, respectively. Annual Tmax, Tmin and Tmean also found the significant correlations with annual ring width of teak for  $r = -0.455, -0.537$  and  $-0.609$ , respectively. Annual Tmax, Tmin and Tmean could explain the variation of teak annual ring width for 20.73%, 28.80% and 37.15%, respectively. For the study, seasonal Tmean in May till August which was the beginning of rainy season illustrated the highest correlation with teak ring index in 1976-2008 for  $r = -0.760$  and could explained the fluctuation of teak ring index for 57.74%. Climatic data of RH, seasonal RH and grouped rainfall had no significant correlation with teak growth. The correlation of teak growth and climate during 1976-2008 was shown in Figure 63.

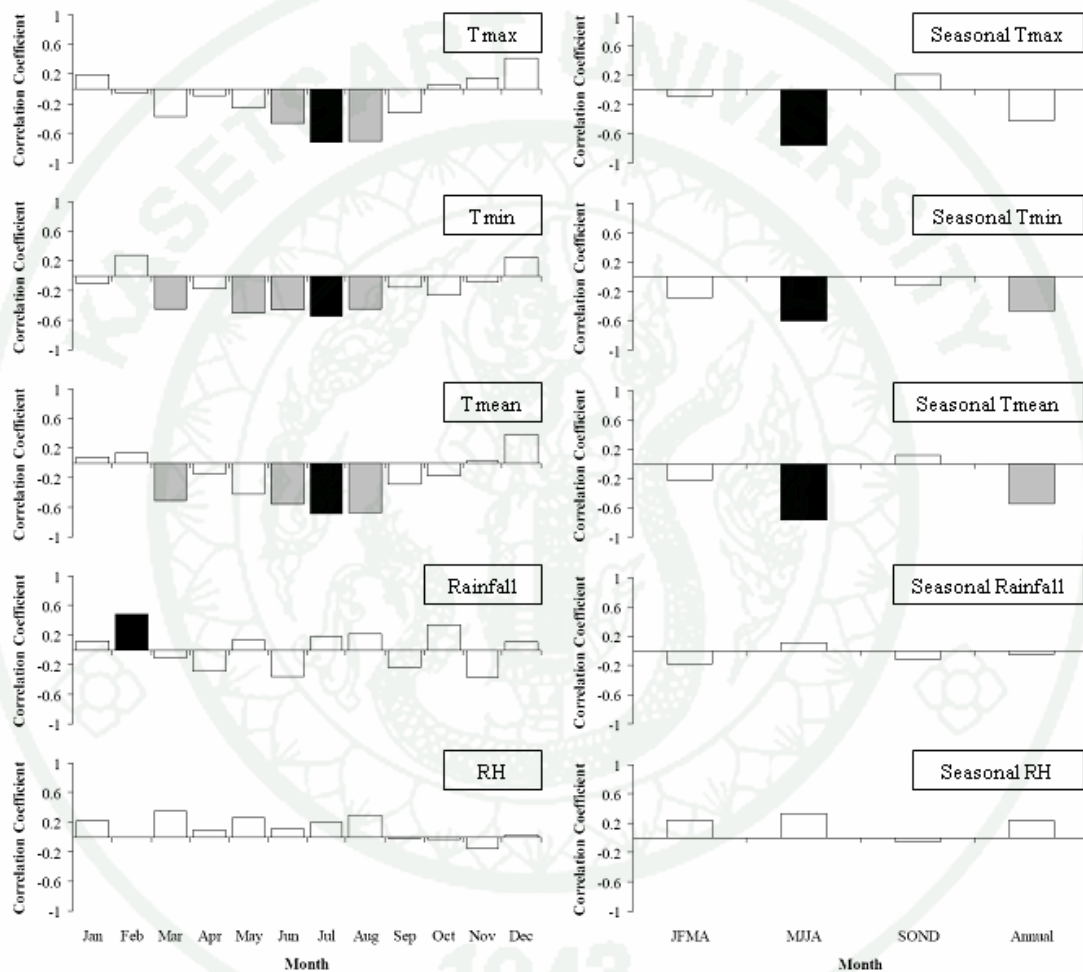
The reliable tree ring index (1976-2008) was also divided to 2 segments of 1976-1996 and 1997-2008 based on their growing trends in Figure 44b. These 2 segments were also correlated with monthly and seasonal climatic data by using the analysis of linear regression. For the chronological segment of 1976-1996, Tmax, Tmin and Tmean in July and rainfall in February illustrated the highest significant correlation with the tree ring index of teaks for  $r = -0.720, -0.552, -0.686$  and  $0.482$ , respectively. These factors could be separately explained annual ring width variations for 51.81%, 30.49%, 47.04% and 23.24%, respectively (Figure 64).



**Figure 63** Monthly, seasonal and annual climatic data of Tmax, Tmin, Tmean, rainfall and RH related to teak growth in 1976-2008. Each box indicated correlation coefficient of teak growth and selected climatic data in each period. Gray and black boxes indicated the significant and the highest significant correlation coefficient ( $p < 0.05$ ), respectively.

The seasonal climate of Tmax, Tmin and Tmean during May till August were negatively correlated with tree growth for  $r = -0.759$ ,  $-0.599$  and  $-0.767$ , respectively. These temperature data could explain teak annual ring width variations for 57.58%, 35.84% and 58.89%, respectively (Figure 64). Annual Tmin and Tmean also found the significant correlations with annual ring width of teak for  $r = -0.472$  and  $-0.547$ . Annual Tmin and Tmean could explain the variation of teak annual ring with for 22.26% and 29.94%, respectively. RH, seasonal RH and seasonal rainfall

were not found the significant correlation with teak growth. For the study, seasonal Tmean in May till August which was the beginning of rainy season illustrated the highest correlation with teak ring index in 1976-1996 for  $r = -0.767$  and could explained the fluctuation of teak ring index for 58.89%.

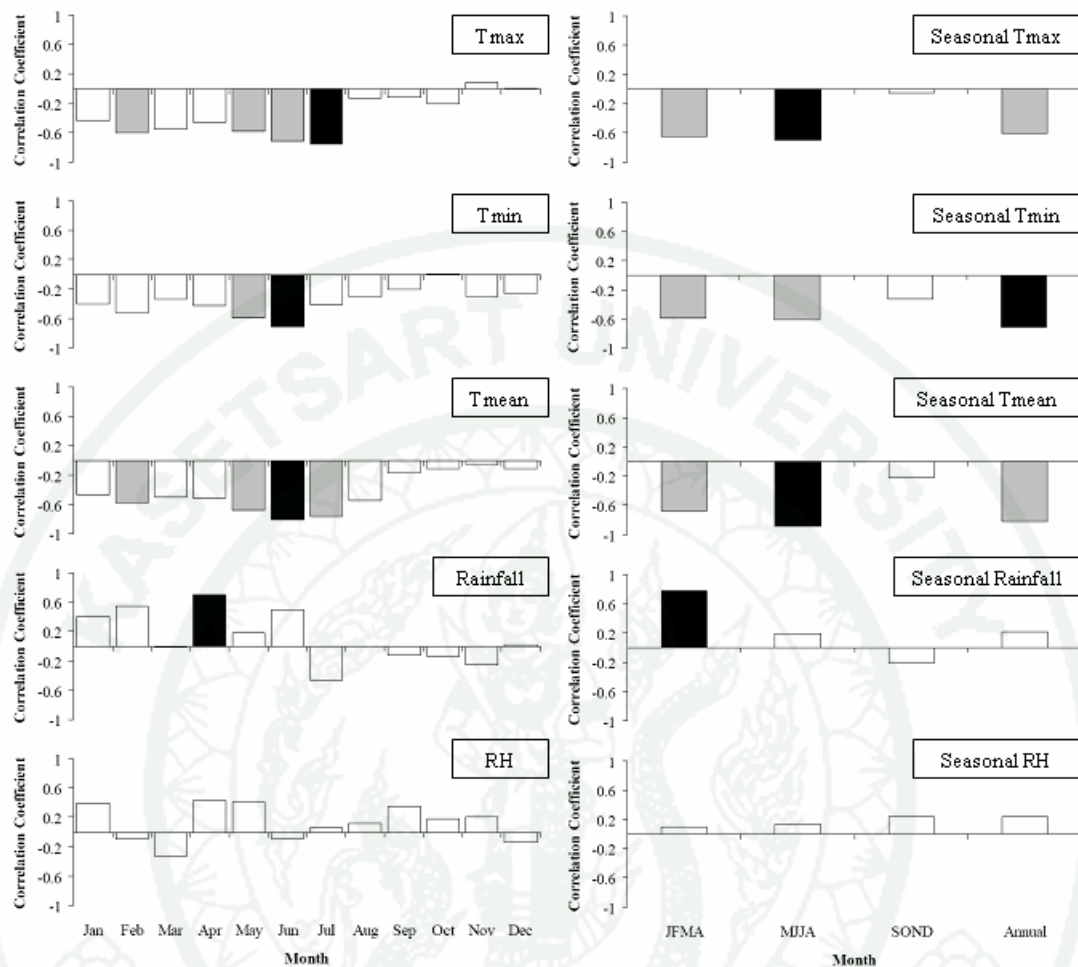


**Figure 64** Monthly, seasonal and annual climatic data of Tmax, Tmin, Tmean, rainfall and RH related to teak growth in 1976-1996. Each box indicated correlation coefficient of teak growth and selected climatic data in each period. Gray and black boxes indicated the significant and the highest significant correlation coefficient ( $p < 0.05$ ), respectively.

The last segment of teak ring chronology (1997-2008) also presented the similar trend of climate-growth relationship. Rainfall in April and total rainfall in

January to April was significantly correlated with tree ring index of this segment for  $r = 0.699$  and  $0.782$ , respectively, while the prior segment of 1976-1996 was not found rainfall-growth relationship. These rainfall factors could explain the variation of teak ring widths in this period for 48.79% and 61.09%, respectively.  $T_{max}$  in July,  $T_{min}$  and  $T_{mean}$  in June were significantly negative correlated with the tree ring index for  $r = -0.759$ ,  $-0.707$  and  $-0.815$  respectively. The seasonal climate of  $T_{max}$ ,  $T_{min}$  and  $T_{mean}$  during May to August illustrated the highest correlated with tree growth for  $r = -0.695$ ,  $-0.608$  and  $-0.889$ , respectively.  $T_{max}$  in July,  $T_{min}$  in June,  $T_{mean}$  in June and the seasonal climate of  $T_{max}$ ,  $T_{min}$  and  $T_{mean}$  in May till August could significantly explain the variations of teak ring widths for 57.65%, 50.03%, 66.50%, 48.26%, 37.02% and 79.02%, respectively. Annual  $T_{max}$ ,  $T_{min}$  and  $T_{mean}$  also found the significant correlations with annual ring width of teak for  $r = -0.616$ ,  $-0.707$  and  $-0.820$ , respectively. Annual  $T_{max}$ ,  $T_{min}$  and  $T_{mean}$  could explain the variation of teak annual ring with for 38.00%, 49.96% and 67.31%, respectively (Figure 65). RH and seasonal RH were not found the significant correlation with tree growth. For the study, seasonal  $T_{mean}$  in May till August which was the beginning of rainy season illustrated the highest correlation with teak ring index in 1997-2008 for  $r = -0.889$  and could explained the fluctuation of teak ring index for 79.02%.

From the result of climate-growth correlation in 1976-2008, 1976-1996 and 1997-2008, the variation of ring width indices illustrated the similar climate-growth response. The variation of teak ring width was mainly controlled by seasonal temperature in growing season (May-August) as similar as the study of factors affecting tree ring formation in teak (figure 57), which illustrated the direct effect of temperature on monthly wood increment, while other climatic data illustrated only indirect effects on teak wood increment.



**Figure 65** Monthly, seasonal and annual climatic data of Tmax, Tmin, Tmean, rainfall and RH related to teak growth in 1997-2008. Each box indicated correlation coefficient of teak growth and selected climatic data in each period. Gray and black boxes indicated the significant and the highest significant correlation coefficient ( $p < 0.05$ ), respectively.

The increased rainfall in dry periods at the beginning of the year combined with the decreased temperature in May till August decreased the water stress at the beginning and during the growing period. These conditions released the limitation of teak growth and induced wider ring widths in year which rainfall increased and temperature decreased greater than the average of each climatic factor. Compared with other climate-growth responses of teak in Thailand and other countries, teak growth was generally controlled by rainfall during monsoon season

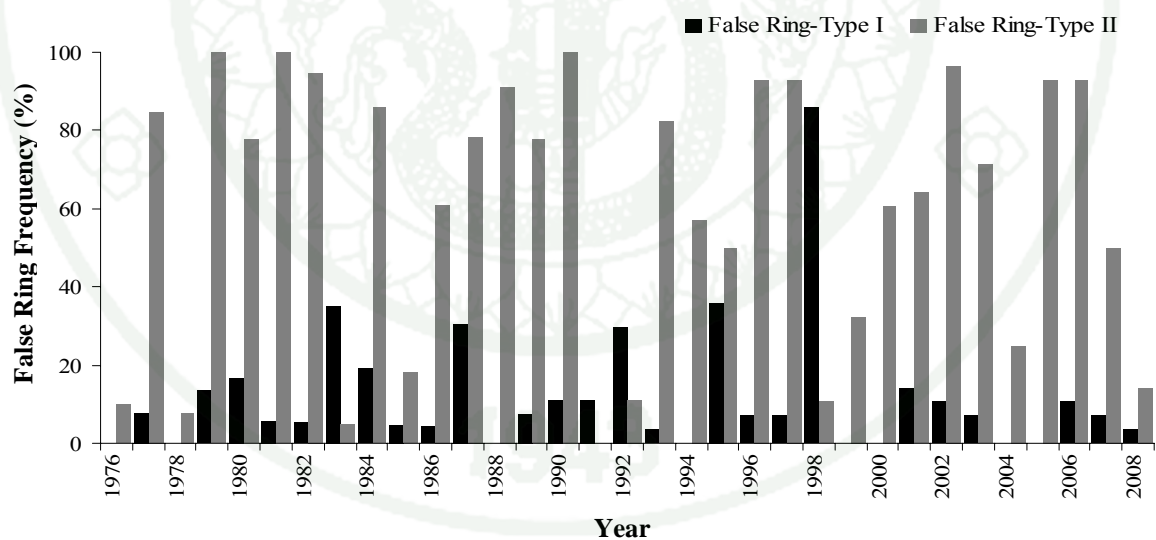
(Bhattacharyya *et al.*, 2007; Borgaonkar *et al.*, 2009; Buckley *et al.*, 2007; Pumijumnong *et al.*, 1995; Ram *et al.*, 2008; Shah *et al.*, 2007), while our studies found the response of rainfall on tree growth at the beginning of rainy season. Buckley *et al.* (2007) also suggested the positive response of pre-monsoon rainfall on teak ring width as similar as our studies. Priya and Bhat (1999) irrigated teak trees in pre-monsoon and also found the pre-monsoon shower breaking the cambial dormancy. The increasing of average temperature in May to August was significant correlation with declined teak ring width as similar as the study of Buckley *et al.* (2007). Fritts (1976) also suggested that the lower temperature in growing season may decrease evaporation and water stress in trees which large ring width was formed following this condition.

Although it was suggested that temperature in May till August mainly controlled teak growth during 1976-2008, mean temperature in July generally illustrated the highest correlation with teak growth during 1976-1996, and mean temperature in June mainly controlled teak growth during 1997-2008. It was demonstrated that the strength of temperature-growth correlation shifted from July in the prior couple decades to be June in recent decade. High temperature in July of the prior decades may increase the rate of evaporation and the stress of water used efficiency, while declined rainfall combined with high temperature in June may induce drought and increase the stress of water used efficiency in recent decade. Several tree-ring studies suggested the earlier shifting of tree growth relating to warming and seasonal changing (D'Arrigo *et al.* 2007; Moore *et al.*, 2007; Vaganov *et al.*, 1999). Not only tree-ring, but phenological studies in several studies were also explained the earlier shifting of pheno-phase such as flowering, leaf bud burst, and leafless (Bradley *et al.*, 1999; Chmielewski and Rotzer, 2001; Lesica and Kittelson, 2010).

### 7.3.7 The relationship of false ring formation with climate

The percentage frequency of occurrence of false rings type I and type II, which were previously identified as the occurrences of the zone resembling

earlywood with one or more rows of paratracheal parenchyma and large vessels at the beginning of the annual ring and the occurrences of the zone resembling annual ring in latewood zone, respectively, were determined for each growing year of all increment cores in reliable tree ring index. Based on the assumption of unusual climatic data might induce the occurrences of teak false rings, false ring frequencies in each year were calculated and the characteristics of climatic data in years which false rings were found in plenty were analyzed. The occurrence of false ring-type I was found for 85.71% of all sample cores in 1998 and were found less than 40% in the remaining growing years (1976-1997; 1999-2008) (Figure 66). In 1979, 1981 and 1990, false ring-type II were found in all wood cores, while between 80-100% false ring-type II occurred in 1977, 1982, 1984, 1988, 1993, 1996, 1997, 2002, 2005, and 2006. In the remaining growing years, false ring-type II occurrence varied within the range 0-80 % (Figure 66). Number of increment cores, false ring-type I and false ring-type II were shown in Table 58.



**Figure 66** Percent of false ring frequency in each growing year. Black and gray boxes referred to false ring-type I and false ring-type II, respectively.

**Table 58** Numbers of false ring occurrences in *Tectona grandis*.

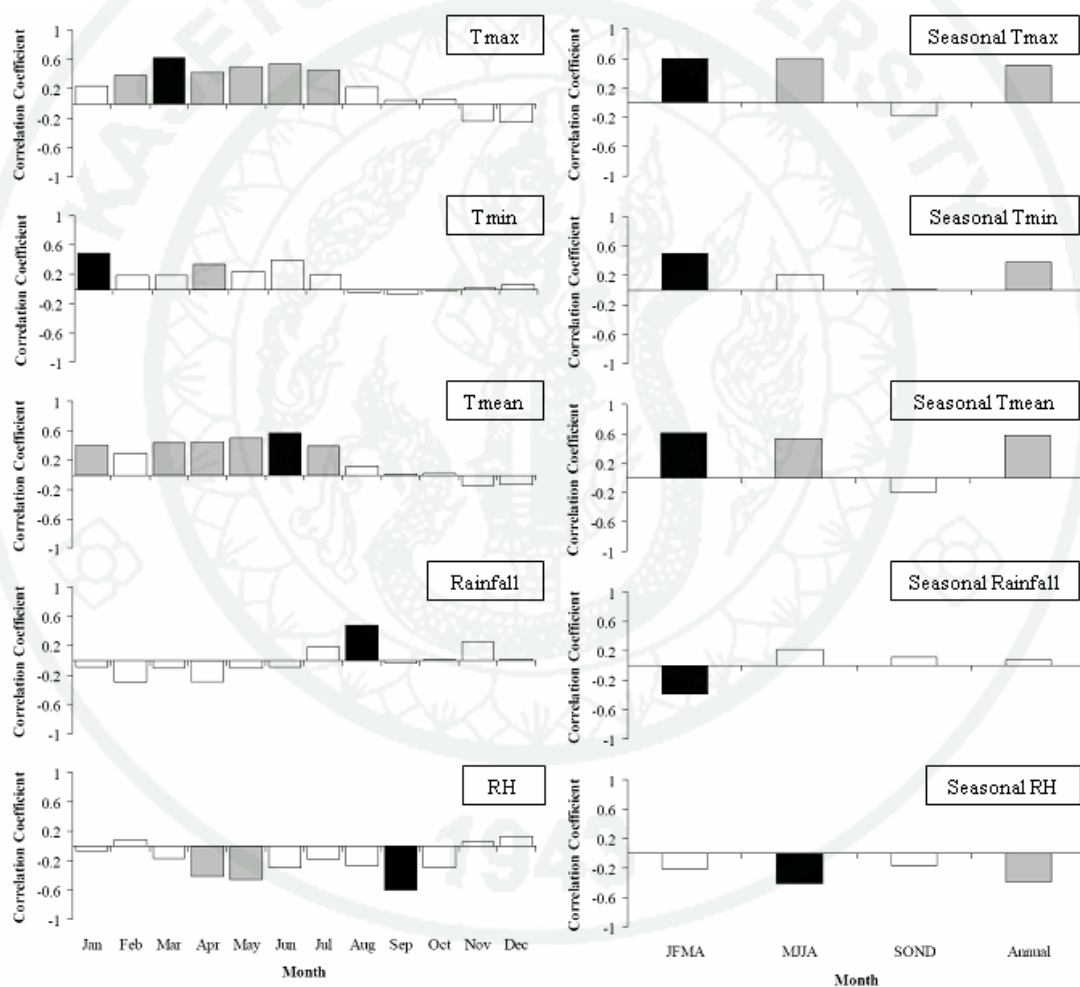
Year	No. Core	No. False Ring		False Ring (%)	
		Earlywood	Latewood	Earlywood	Latewood
1976	10	0	1	0.00	10.00
1977	13	1	11	7.69	84.62
1978	13	0	1	0.00	7.69
1979	15	2	15	13.33	100.00
1980	18	3	14	16.67	77.78
1981	18	1	18	5.56	100.00
1982	19	1	18	5.26	94.74
1983	20	7	1	35.00	5.00
1984	21	4	18	19.05	85.71
1985	22	1	4	4.55	18.18
1986	23	1	14	4.35	60.87
1987	23	7	18	30.43	78.26
1988	23	0	21	0.00	91.30
1989	27	2	21	7.41	77.78
1990	27	3	27	11.11	100.00
1991	27	3	0	11.11	0.00
1992	27	8	3	29.63	11.11
1993	28	1	23	3.57	82.14
1994	28	0	16	0.00	57.14
1995	28	10	14	35.71	50.00
1996	28	2	26	7.14	92.86
1997	28	2	26	7.14	92.86
1998	28	24	3	85.71	10.71
1999	28	0	9	0.00	32.14
2000	28	0	17	0.00	60.71
2001	28	4	18	14.29	64.29
2002	28	3	27	10.71	96.43
2003	28	2	20	7.14	71.43
2004	28	0	7	0.00	25.00
2005	28	0	26	0.00	92.86
2006	28	3	26	10.71	92.86
2007	28	2	14	7.14	50.00
2008	28	1	4	3.57	14.29

There were several climatic data exploring the significant correlation with false ring occurrences. Tmax in February till July was significantly correlated with the occurrence of false ring-type I, while March Tmax illustrated the highest correlation coefficient ( $r$ ) for 0.628 and could explain the occurrences of false ring-type I for 39.40%. Tmin and Tmean in January and June illustrated the highest

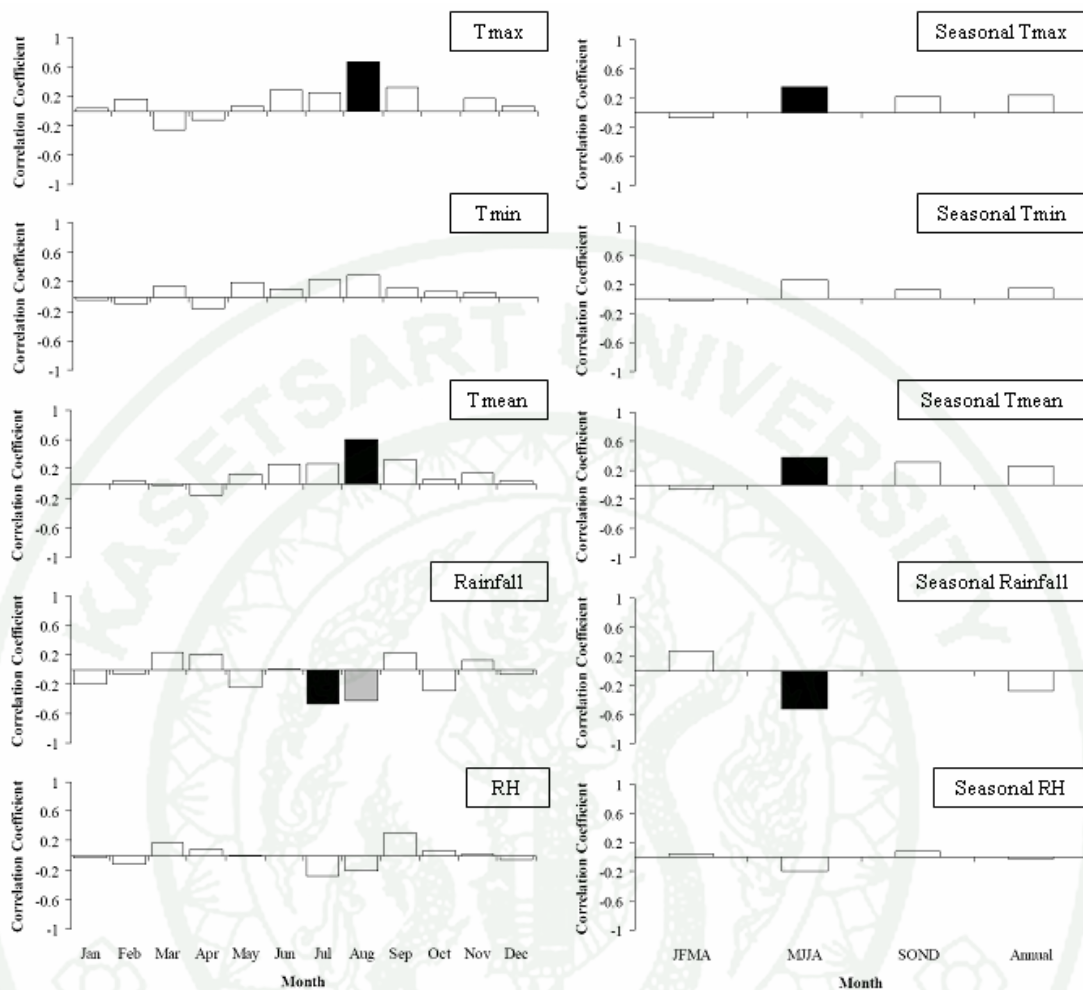
correlation with false ring type-I for  $r = 0.489$  and  $0.570$ , respectively. These 2 variables could explain the occurrences of false ring-type I for 23.86% and 32.49%, respectively. Rainfall and RH in August and September illustrated the highest correlation with false ring type-I for  $r = 0.482$  and  $-0.608$ , respectively. These 2 variables could explain the occurrences of false ring-type I for 23.26% and 36.91%, respectively. The average of Tmax, Tmin and Tmean and total rainfall in January to April and average RH in May to August were significantly correlated with the occurrence of false ring type I for  $r = 0.601$ ,  $0.502$ ,  $0.615$ ,  $-0.387$  and  $-0.406$ , respectively (Figure 67). These factors could explain the occurrences of false ring-type I for 36.13%, 25.23%, 37.83%, 14.94% and 16.46%, respectively. In case of annual climatic data, Tmax, Tmin, Tmean and RH showed the significant correlation with false ring-type I occurrences for  $r = 0.504$ ,  $0.383$ ,  $0.579$  and  $-0.390$ , respectively, and could explain the occurrence of false ring-type I for 25.43%, 14.66%, 33.49% and 15.19%, respectively. Annual rainfall did not found the significant correlation with the occurrences of false ring-type I. In this case, Tmax in March illustrated the highest correlation with false ring-type I for  $r = 0.628$  and could explain the occurrences of false ring-type I for 39.40%. It was interpreted that the increased Tmax in March which was the beginning of annual teak ring formation (Figure 22) generated teak growing stress and fiber cells were formed. Later, the increase rainfall re-stimulated the formation of the zone resembling earlywood with one or more rows of paratracheal parenchyma and large vessels before actual latewood cells were formed. The occurrence of the zone resembling earlywood with paratracheal parenchyma and large vessels was defined as false ring-type I.

The frequency of false ring-type II illustrated the highest significant correlation with Tmax and Tmean in August and rainfall in July for  $r = 0.673$ ,  $0.599$  and  $-0.471$ , respectively. These variables could explain the occurrences of false ring-type II for 45.25%, 35.84% and 22.14%, respectively. Additionally, the average of Tmax and Tmean in May till August and total rainfall in May till August were significantly correlated with the frequency of false ring-type II for  $r = 0.359$ ,  $0.383$  and  $-0.525$ . These variables could explain the occurrences of false ring-type II for 12.89%, 14.65% and 27.60%, respectively. Tmin, RH, grouped Tmin, grouped RH

and annual climatic data did not found the significant correlation with the occurrences of false ring-type II. The correlation among false ring-type II and climatic data were shown in Figure 68. In this case, Tmax in August illustrated the highest correlation with false ring-type II for  $r = 0.673$  and could explain the occurrences of false ring-type II for 45.25%. It was interpreted that the increased Tmax in August which was the mid-period of teak growing intervals (Figure 22) generated teak growing stress and formed false ring-type II.



**Figure 67** Monthly, seasonal and annual climatic data and false ring-type I relationship. Each box indicated correlation coefficient of false ring frequencies and selected climatic data in each period. Gray and black boxes indicated the significant and the highest significant correlation coefficient ( $p < 0.05$ ), respectively.



**Figure 68** Monthly, seasonal and annual climatic data and false ring-type II relationship. Each box indicated correlation coefficient of false ring frequencies and selected climatic data in each period. Gray and black boxes indicated the significant and the highest significant correlation coefficient ( $p < 0.05$ ), respectively.

For the relationship between tree growth and false ring occurrences, the narrow ring widths mostly associated with false ring occurrences as shown in Table 59. It was indicated that teaks may be disturbed by unusual characteristics of factors inducing tree growth during the growing season such as the increased Tmax in March and August as described above. From teak cambial marking results which initial banded parenchyma associated with large vessel occurred in March and April,

the increased temperature and declined rainfall at the beginning of the year as shown in the significant correlation between false ring-type I and all climatic data (Figure 67) might suddenly interfered teak growth and caused false ring-type I occurrences. In case of false ring-type II, false ring which occurred during the growing season until the end of December as shown in Figure 22 might be disturbed from increasing temperature and declined rainfall in May till August (Figure 68). In this case, increased temperature and declined rainfall were the major factors inducing drought and narrow ring widths coupled with false ring formation. While the study informed the suppressed growth that occurred together with false ring formation, Masiokas and Villalba (2004) found the significant correlation between the false ring occurrences in present year (t) and suppressed growth in the followed year (t+1) and Copenheaver *et al.* (2006) classified ring widths of the first ring (t-1) and fourth ring (t-4) before the formation of false ring to be statistically wider than others.

**Table 59** Simple correlation analysis of annual ring width index with false ring-type I and type II.

	<b>False Ring- Type I</b>	<b>False ring- Type II</b>	<b>Annual Ring Width Index</b>
<b>False Ring-Type I</b>	1	-.253	<b>-.506<sup>**</sup></b>
<b>False ring-Type II</b>		1	<b>-.375<sup>*</sup></b>
<b>Annual Ring Width Index</b>			1

**Remark:** \*\* Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed).

Climatic conditions were correlated with the frequency of false ring occurrences in order to indicate factors inducing false ring formation. By comparing with false ring studies in juvenile teaks (Priya and Bhat, 1998), their result showed drought during active growing season stimulating false ring formation as similar as the result of our studies. However, the procedures to study false ring formation were different. Priya and Bhat (1998) constructed the artificial drought to induce false ring

formation, while this study identified the major climatic factor inducing false ring formation in natural stand by using the climate-growth correlation based on dendrochronological technique.

It was suggested that the declination of the total rainfall in January till April combined with the increased temperature in the same periods were the main factor of false ring formation in earlywood zone. The results were related to the studies of Priya and Bhat (1998) who stated that the artificial drought in the early growing season was the causation of early wood false ring formation. The decreased rainfall and increased temperature in May till August were the main causes of false ring formation in latewood. Our studies also announced that the increased temperature, especially in August, combined with dropped rainfall (especially in July and August) were the causation of false ring formation in latewood zone.

At the study site, heavy rainfall normally occurred at the end of the growing period (September to October), which was similar to the resumption of watering after drought inducement by Priya and Bhat (1998). They found increased vessel sizes appearing as a false ring in the latewood zone of the annual growth increment similar to this study. Therefore, both of natural and artificial climates, drought following by wet periods during the growing season were the main characteristic that induced false ring appearances. Comparing with other species, false ring formation was generally caused by dry and followed by wet in growing season as similar as our studies (Campelo *et al.*, 2006; Copenheaver *et al.*, 2006; Masiokas and Villalba, 2004).

## CONCLUSION AND RECOMMENDATION

Wood samples of 92 species were collected from Sakaerat Environmental Research Station (SERS) and Wang Nam Khiao Forestry Student Practice Station of the Faculty of Forestry, Kasetsart University (WNKFSPS). They were divided into 3 groups of distinct, indistinct, and non-distinct rings for 32, 48 and 12 species, respectively. Distinct growth rings were visible due to one or both of the characteristics of 1) presenting marginal parenchyma; 2) showing distinct or abrupt anatomical changes at the growth ring boundary and 3) composing of ring porous or semi-ring porous vessel arrangement. In case of ring porous and semi-ring porous associated with continuous marginal parenchyma in *Tectona grandis* (Lamiaceae) and *Melia azedarach* and *Toona ciliata* (Meliaceae) enhanced the visibility of growth ring clearer than the investigation using the individual characteristic as described above.

Mean sensitivity (MS), a measurement of the relative change in ring-width from one year to the next reflecting the limitation of tree growth by some factors in a given site, was calculated using growth ring width series of 32 distinct ring species. For future studies, if these tree-ring formations are proved as annual rings, trees with high values of mean sensitivity ( $\geq 0.5$ ) will be 12 species and the highest mean sensitivity was 0.822 in *Murraya paniculata*, while the rest of 18 species illustrated the moderate mean sensitivity in range of 0.25-0.50. *Garuga pinnata* and *Sterblus ilicifolius* illustrated low mean sensitivity for 0.242 and 0.180, respectively. At WNKFSPS and SERS, *M. paniculata* which illustrated the distinct growth ring and high mean sensitivity shall be the first priority for annual ring formative studies to serve the opportunity of tropical tree species in tree ring analysis related to climatic fluctuation in present back to past (namely dendroclimatology).

Six tree species of *T. grandis*, *A. xylocarpa*, *L. duperreana*, and *M. azedarach*, *A. odoratissima* and *H. ilicifolia* were selected to study phenological fluctuation for 1 year. Deciduous tree species (*T. grandis*, *A. xylocarpa*, *M. azedarach*, and *L. duperreana*) illustrated leaf flushing at the beginning of rainy season following by

leaf maturation in rainy season and leaf abscission during the dry and cold season at the end of the year. Two species of the tropical evergreen species (*A. odoratissima* and *H. ilicifolia*) illustrated leaf maturation throughout the year, while young leaves were abundantly found in rainy season and leaf abscission rarely found throughout the year. Flowering shortly occurred either during or after leaf flushing or when trees were leafless. However, fruit pheno-phases of 4 deciduous species were rarely found, while 2 evergreen species were not found during the investigated periods.

The increments of outside bark diameters manually recorded by band dendrometers continuously declined from the installed period in the second half of rainy season to the end of dry season (September 2009 - February 2010). In rainy season, outside bark diameters rapidly increased until the end of the investigated period in September 2010 association with the abundances of leaf maturation in all selected species.

Among 4 selected deciduous species, *T. grandis* and *M. azedarach* were semi-ring porous species and *L. duperreana* was ring porous species, while *A. xylocarpa* was diffuse ring porous species as similar as 2 selected evergreen species of *A. odoratissima* and *H. ilicifolia*.

Axial parenchyma and/or vessel size variation were the marked points of annual ring boundaries of *T. grandis*, *A. xylocarpa*, *L. duperreana*, and *M. azedarach* while fiber cell wall thickness and flatted fiber were useful to identify the annual ring boundaries of *L. duperreana*, *A. odoratissima* and *H. ilicifolia*. In case of this study, four deciduous species were suitable and could be applied for tree-ring studies due to the clarity of annual ring boundaries investigated under the stereomicroscope. Although, the rest of two evergreen species were also proved as annual ring formed species and appropriated for tree-ring analysis, micro-sections of the transverse surfaces and higher magnifications of the stereomicroscope were needed for sample preparation and annual ring investigation.

Monthly wood increment of deciduous trees (*T. grandis*, *A. xylocarpa*, *M. azedarach* and *L. duperreana*) detected by cambial marking technique initiated on the same periods of leaf flushing or a month later while cessation occurred in the month of leaf abscission. Although wood increment of evergreen trees (*A. odoratissima* and *H. ilicifolia*) illustrated the dormant periods in the dry periods at the end and the beginning of the year, their leaf phenology (especially in mature dark green leaves: MDL) were abundantly found throughout the year. Therefore, the discovery of growth dormancy (in term of wood increment) in evergreen tree species could destroy the wide assumption of tree growth continuously throughout the year and confirm the possibility of tropical trees in tree-ring analysis when growth dormancy yielded the results of climate-growth relationship.

The climatic factors of monthly temperature, rainfall, relative humidity and soil moisture content in each study site were grouped using the technique of principle component analysis (PCA) to be 1) moisture and 2) temperature components. These two components illustrated both of direct and indirect relationship with monthly wood increment. The increased temperature directly induced wood increment of *T. grandis* and the increased moisture directly induced wood increment of *M. azedarach* and *H. ilicifolia*. Moreover, these 2 factors illustrated indirect effects on monthly wood increment through the increasing of mature dark green leaves of *T. grandis*, *A. xylocarpa* and *L. duperreana*. However, these climatic factors did not showed the significant correlation with monthly wood increment of *A. odoratissima*. Using the technique of path analysis (PA), the fluctuation of leaf phenology in deciduous species directly and mainly induced monthly wood increment while monthly wood increments of evergreen species did not significantly related to the occurrences of their leaves.

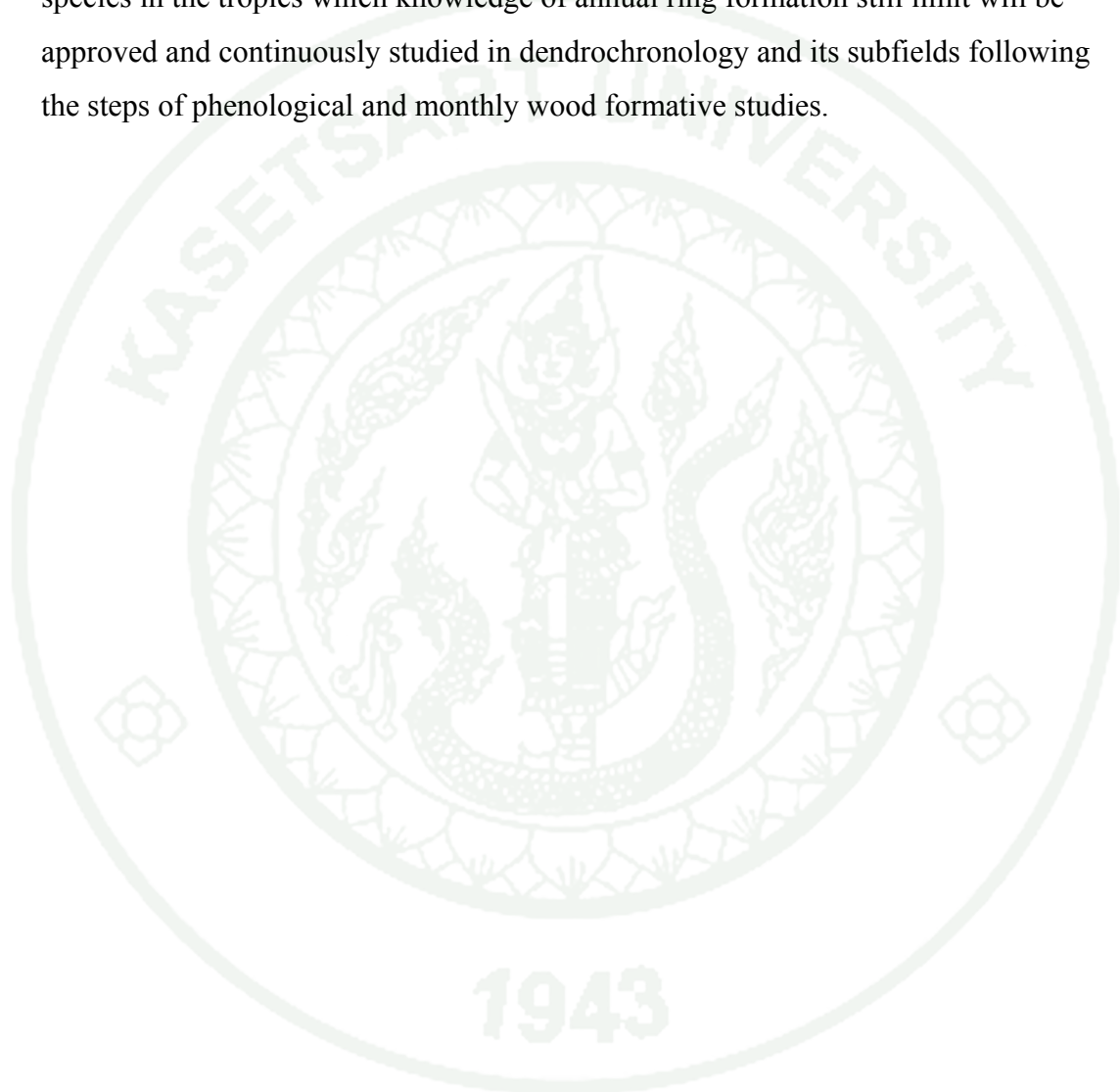
Outside bark diameter increments of *T. grandis*, *A. xylocarpa*, *M. azedarach*, *L. duperreana* and *H. ilicifolia* directly and positively related to the increment of xylem elements, except *A. odoratissima*. According to the shrink and swelling of stems, climatic data of moisture and temperature showed both of direct and indirect effects on outside bark diameter increments of all deciduous and evergreen species.

Teak was selected for tree-ring analysis. Vessel size variations of *T. grandis* were useful to define annual ring boundaries and identify false rings. The occurrences of false rings were important to explain the climatic variability. Instead of annual climatic explanation, wood anatomical features of false rings and their relative positions were used to explain some characteristics of monthly climatic data greater than upon the data of annual ring widths. Seasonal temperatures in May to August were significantly correlated to teak growth. Lower temperature during teak growing season reduced the stress of water consumption and increased available moisture for tree growth. The earlier shifting of tree growth from July in the past couple decades to be June in current decades was related to earlier drought occurrence.

The occurrences of teak false rings were significantly related to mean ring width variation. False rings mostly found associated with narrow ring widths. Seasonal rainfall and temperature in January to April and May to August were important to induce false ring formation. Heavy rainfall in January to April combined with low temperature in May to August stimulated fast growth, which could present as the wide ring width. Pre-monsoon drought from low rainfall and high temperature in January to April was the causation of false ring formation in earlywood zone (false ring-type I). High temperature and lower rainfall in May to August following with heavy rainfall in post monsoon stimulated false ring formation in latewood zone (false ring-type II).

For future studies, *A. xylocarpa*, *L. duperreana*, *M. azedarach*, *H. ilicifolia* and *A. odoratissima* which were confirmed as annual ring formative species and explored monthly growth-climate relationships shall be investigated annual growth-climate relationship following the standard method of dendrochronology. For annual ring identification and ring width measurement using tree-ring measuring system, the analysis of *A. xylocarpa*, *L. duperreana* and *M. azedarach* may be easier than *H. ilicifolia* and *A. odoratissima* due to the occurrences of ring porous and semi-ring porous characteristic. Although the changing of cell wall thickness which was the criteria for annual ring identification in *H. ilicifolia* and *A. odoratissima* were difficult to detect by using the stereomicroscope connected to tree-ring measuring system,

density of thick and thin wall fibers could be detected by densitometer and converted to annual ring width for dendrochronological researches. Therefore, based on this information, new palaeo-climatic information in several regions of Thailand will be derived from these annual ring formative tree species. On the other hand, several tree species in the tropics which knowledge of annual ring formation still limit will be approved and continuously studied in dendrochronology and its subfields following the steps of phenological and monthly wood formative studies.



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