DENDROCLIMATOLOGICAL INVESTIGATIONS ON TEAK (*Tectona grandis* L. F.) IN THRISSUR FOREST DIVISION OF KERALA

By

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THESIS

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Sreejith

DECLARATION

I hereby declare that this thesis entitled **"Dendroclimatological investigations on teak (*Tectona grandis* L. F.) IN Thrissur forest division of Kerala"** is a bonafide record of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society to me.

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Certified that this thesis entitled **"Dendroclimatological investigations on teak (*Tectona grandis* L. F.) in Thrissur forest division of Kerala"** is a record of research work done independently by **Mr. Sreejith Babu (2009-17-105)** under my guidance and supervision and has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society to him.

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To my Family

To my God

To Tectona

INTRODUCTION

INTRODUCTION

Growth rings in trees serve as a useful tool for the determination of age and growth rate of the trees of managed stands. The variability of annual radial increments is predominantly determined by the climate of the vegetation period. Because tree rings to a large degree reflect the annual changes of the regional climate, the tree-ring patterns in the same stand and climatic region are similar (Fritts, 1976).

Unlike trees of temperate regions, most of the tropical trees have been excluded from tree-ring studies because of lack of seasonality and the absence of a clear dormancy of the cambial activity failing to produce distinct growth rings and majority of them are diffuse porous. Gamble's (1902) studies on growth rings forms pioneer dendroclimatological work in tropical trees. It is estimated that about twenty five percent of the total number of tropical tree species produce growth rings (Chowdhury, 1939; 1940). Several dendroclimatological studies have been carried out on tree species from upper tree-line in different mountain regions. Many trees in the tropical forests of the Indian subcontinent are known to produce growth rings (Gamble, 1902). Among the trees with growth rings, *Tectona grandis* L. f. (Teak) exhibits datability of growth rings to the formative year. Teak tree is widely distributed in the peninsular and central India. Teak, being a ring porous species, shows distinct annual growth ring patterns useful for dendroclimatological studies. India is considered to be the only known centre for genetic diversity and variability of teak, having its natural distribution zone confined predominantly to the peninsular region below 24°N latitude. It is reported that the location factor contributed as much as 31.4 %, whereas seed origin contributed only 1.46% for variability in teak growth (Purkayastha and Satyamurthi, 1975). Pattern of radial growth in trees depends largely on the climatic conditions of different localities (Rao and Dave, 1981).

Dominated by monsoon climate, Kerala could form important site for understanding tree-growth responses to climate. Also the usefulness of teak for dendroclimatic reconstructions like rainfall and ENSO (El-Nino Southern Oscillation) index has already reported (Pant et al., 2000; Fujiwara et al., 2002; Yadav et al., 2006; Shah et al., 2007 and Ram et al., 2008). The size, number and distribution of vessels in a tree ring have been recognized as significant parameters in ecological and environmental studies. However, a large temporal and spatial network of tree-ring chronologies in this region is needed to understand past variations of rainfall and related parameters and how it influences the growth of teak.

The present investigation focuses on analysis of the tree-ring chronologies in teak grown as plantations at Thrissur forest division in comparison with tree-ring chronologies from Karikadam in Chalakudy forest division with the following objectives.

1. Analyse tree-ring chronologies of teak to find out their dendroclimatic potential and to assess the tree growth-climate relationship at the above sites.

2. Find out whether any significant relationship exists between climate and mean vessel area (MVA) of teak and its prospect for climatic reconstruction of the study area.

3. Assess the potential of MVA of teak as a proxy for reconstruction of precipitation data of south west and north east monsoons.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Basic methods and the underlying rationale for tree-ring analysis are well established and continue to be refined. The salient research findings of dendroclimatological studies conducted in temperate and tropical tree species are summarised hereunder.

2.1 Tree-ring research across the world

The beginning of scientific study of tree rings is generally credited to the early 1900s and to an astronomer named Andrew Ellicott Douglass. While working in Arizona, USA, Douglass noticed not only variation in tree-ring width but also that this variability was similar between multiple trees. Douglass refined the understanding of how climate affects tree rings, ultimately publishing 75 works in dendrochronology, many of which can be classified as dendroclimatology. From the humble beginning of Douglass working on tree rings as he related ring width to climatic factors such as temperature and rainfall in Arizona, the field of dendrochronological research expanded and became popular in various parts of the globe.

2.2 Dendroclimatological studies using ring width

2.2.1 Studies in temperate regions

A major portion of dendroclimatological studies take place in temperate regions of the world due to presence of easily datable species and occurrence of distinct seasons. The influence of climatic factors on the growth of *Pinus nigra* in western France was evaluated by Lebourgeois (2000). Analysis and climatic models showed that summer drought was a major limiting-growth factor.

Spurk (1997) carried out dendroclimatological investigations on *Pinus sylvestris* growing in Germany. A significant influence by precipitation, followed by saturation deficit and relative humidity was observed. Similarly, Xiong and Palmer (2000) reconstructed New Zealand temperatures back to AD 1720 using *Libocedrus bidwillii* tree-rings. Manrique and Cancio (2000) did climatic reconstructions of Spain from a network of about 1000 tree ring samples, mainly using *Pinus nigra, Pinus sylvestris, Pinus uncinata* and *Quercus* spp. The analysis of the series of climatic values for almost a millennium were obtained from these dendroclimatic investigations.

Panyushkina and Ovchinnikov (1999) investigated climate influence on the dynamics of radial increment of larch in the Altai Mountains in Siberia. They found that June temperature is the general climatic factor controlling the increment of larch (*Larix decidua*) in the Altai Mountains. The chronologies obtained were suitable for reconstructing the summer temperature for the last 350 years, and also for analysing the variation in global summer air temperature. Khantemirov et al. (1999) worked on the dendroclimatic potential of *Juniperus sibirica*. Analysis of the basal discs allowed a 636-year ring-width chronology to be produced, revealing the mean May/June/July temperature of the current year to be the main climatic factor affecting radial increment. Comparison of the juniper chronology with the chronologies for *Larix sibirica* and *Picea obovata* revealed similarities and differences between the bushes and the trees.

Dendroclimatic response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest was analyzed by Hofgaard et al. (1999). Correlation analyses and principal component analyses were used to identify common spatiotemporal growth patterns and site and species-specific patterns since 1825. A moist summer in the previous year and an early start of the current growing season favoured growth of both species.

Two independent reconstructions of maximum May-August temperatures were developed from a new network of Engelmann spruce (*Picea engelmannii*) tree-ring chronologies at treeline sites across Interior British Columbia, Canada by Wilson and Luckman (2003). Both models explained 53% of the regional temperature variance and correlated strongly over their common period. Significant changes were also noted in the relationships between summer mean, maximum and minimum temperatures in this region in the last few decades.

Piovesan et al. (2003) constructed a long-term tree ring chronology for beech (*Fagus sylvatica*) in a high-elevation, old-growth forest of Central Italy. The climatic signals of beech trees were investigated by means of pointer intervals and bootstrapped response functions for the period 1832-2000. Mid-summer precipitation (July-August) and May temperature were the prominent climatic signals.

Bednarz et al. (1998) studied dendrochronology of Norway spruce (*Picea abies*) in the Babia Gora National Park, Poland. They found that radial growth was positively correlated with June-July temperature and sunshine and negatively correlated with June-July precipitation. The influence of climate in the summer of the previous year was also significant. Nabais et al. (1998) studied tree-rings to climate relationships of *Quercus ilex* in North East Portugal. The synchronization of growth curves of different trees was made visually using event years, which often corresponded to years with unusual climatic events. Precipitation, especially in January and during late spring and summer, had a positive effect on stem diameter growth. High temperatures in summer had a negative effect on the growth whereas high minimum temperatures in winter had a positive effect.

Brauning (2001) developed a network of 15 *Juniperus* spp chronologies in eastern Tibet and created a climate history of the Tibetan plateau during the last 1000 years. Some chronologies showed both high correlation coefficients to rainfall deviations over India as well as to the Eurasian snow cover in winter, the latter being a crucial factor in controlling the strength of the monsoon circulation in the following summer.

Akkemik (2003) studied tree rings of *Cedrus libani* from three sites located in Turkey taking a total of 41 increment cores and three site chronologies were constructed. Low precipitation was an important limiting factor for growth. At the valley bottom site, neither precipitation, except for December, nor temperatures, except for February were a limiting factor.

The influence of precipitation, saturation deficit, relative humidity, and temperature on the growth of *Pinus sylvestris* growing on 21 different sites in stage in Germany, was investigated by Spurk (1997). A significant influence of precipitation, followed by saturation deficit and relative humidity was observed. The influence of climate partially increased from earlywood to latewood caused by drier soil condition in the course of the year.

Dendrochronological results using Austrian pine (*Pinus nigra*) sampled in the Pannonic region of Austria, south of Vienna, were presented by Strumia (1997). A response function analysis showed that Austrian pine is highly sensitive to summer rainfall with July rainfall being strongly related to the tree growth of the 20th century. In the previous century, no such relationship could be observed. Rainfall during May, on the other hand, used to have strong effects on growth but this relationship ceased during the last 40 years.

Villanueva and McPherson (1999) carried out dendroclimatic studies in the mountains of southwest USA and north Mexico. Chronologies were developed for climate reconstruction in the southwestern mountains of the USA (Animas Mountains, New Mexico) and northwestern Mexico (Sierra de Ajos, Sonora) with Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). Seasonal precipitation (October-January) and current July Palmer Drought Severity Index (PDSI) was reconstructed for Animas Mountains, and annual precipitation (July-July) and current July PDSI were reconstructed for Sierra los Ajos. However, not significant relationship was found between climatic variables and fire occurrence in Sierra los Ajos, apparently as a consequence of different land uses.

Tree-ring samples of *Picea schrenkiana* were studied along an altitudinal gradient in the central Tianshan Mountains by Ting et al. (2005). Ring-width chronologies were developed for three sites at different altitudes. The results showed that precipitation was the most important factor limiting tree radial growth in the arid central Tianshan Mountains, precipitation in August of the prior growth year played an important role on tree's radial growth across the entire altitudinal gradient even at the cold, high-elevation treeline site.

Koprowski and Zielski (2006) conducted dendrochronology of Norway spruce (*Picea abies*) from two range centres in lowland Poland. Spruce growth in northern Polish sites is positively correlated with rainfall from May to July. Tree-ring widths in southern sites are more correlated with March temperature.

Levanic (2005) conducted research on effect of climate on growth of European larch (*Larix decidua*) at the upper treeline in the Southeastern Alps. The response function analysis showed significant positive response (wide tree ring) of larch to above-average temperature in June and significant negative response to above-average temperature in March.

Pumijumnong and Wanyaphet (2006) aimed at characterizing the cambial dynamics and its dependence on climate of two pine species native to Thailand, *Pinus merkusii* and *Pinus kesiya*. The response function described the relationship between tree-ring widths indices and monthly rainfall and temperature and revealed that the growth of *Pinus merkusii* at one site depended positively from rainfall in May. *Pinus merkusii* at other site however, had a positive correlation with rainfall from previous November to current July, whereas temperature in the preceding autumn and winter should be above-average and in the current spring and summer should be below-average.

Tree-ring data from *Chamaecyparis lawsoniana* (Port Orford cedar) were used to create a standardized chronology by Carroll and Jules (2005). They produced a 580-year tree-ring chronology (A.D. 1420 to 2000) from a large number of cedars of southwestern Oregon and northern California. The radial growth was positively correlated with year-round soil moisture conditions, specifically with cool, wet conditions in summer and warm, wet conditions in winter.

Reasonable methods were developed for establishing tree-ring width chronologies of *Larix gmelinii* (larch) plantations in Northeast China by Zhao et al. (2007). The correlation analysis showed that the established chronology is more scientific and reasonable, which can be applied in dendroclimatic analysis. Results show that about 40% of the variance of growth ring width is caused by climate change, about 30% by inheritance, about 20% by silviculture, and about 10% by site conditions and other factors. Khorchani (2007) studied the impact of drought on the growth of three forest species in Tunisia (*Pinus halepensis, Pinus pinea* and *Pinus pinaster*). Dry and wet years have been determined using a model for studying the radial growth-water balance relationship. This model also permitted to predict the sensitivity of these three pine species as drought increases.

Case and Peterson (2007) investigated climate-growth relations of lodgepole pine in the North Cascades National Park, Washington. Multivariate analysis and correlation analysis were used to simplify growth patterns and identify climate-growth relations. Mid-elevation chronologies correlated negatively with growing season maximum temperature and positively with growing season precipitation. By contrast, high-elevation chronologies correlated positively with annual temperatures and winter Pacific Decadal Oscillation index.

Akkemik and Demir (2003) conducted tree ring analysis on eastern beech (*Fagus orientalis*) in the Belgrade Forest, Turkey and investigated the relationships between tree-ring width and mean monthly temperature and total monthly precipitation. The precipitation and temperature except extreme years did not affect tree ring width significantly. The forest had optimum growing conditions and was a low elevation site for the tree species, therefore the influence of climatic variables used in the response function was not significant except the precipitation in February.

Potential for dendrochronology of *Taxodium mucronatum* and its conservation in Mexico was studied by Diaz et al. (2007). Two precipitation reconstructions over 500 years long have been developed for northern Mexico. Radial growth of three tree species (*Tsuga canadensis, Acer saccharum* and *Fagus grandifolia*) from an old-growth forest, in southwestern Quebec, Canada, was compared by Tardif et al. (2001) using a dendroclimatic approach. Radial growth of all three species was positively correlated with precipitation and negatively correlated with temperatures during the early summer months of the year the annual ring was formed. Radial growth of the three species was also negatively correlated with temperatures during the late summer months of the year prior to ring formation. Of the three species, hemlock was most influenced by temperature and showed a positive correlation with winter temperatures.

The influence of minimum, maximum and mean monthly temperatures and precipitation on the radial growth of Scots pine (*Pinus sylvestris*) was studied by Tuovinen (2005) beyond the continuous forest line in northern Finland. Latewood density, annual ring width and earlywood width responded more strongly to climate than latewood width or earlywood density. Earlywood width is controlled by precipitation in June and temperatures in mid-winter (December/January) and March.

Wang et al. (2005) investigated seven tree-ring variables (maximum density, minimum density, mean earlywood density, mean latewood density, earlywood width, latewood width and annual ring width) of *Larix gmelinii* and *Pinus sylvestris* and compared with meteorological data from a weather station near the sampling site. The maximum temperature controlled the latewood density of both species in July and August. In addition, the latewood density of *Pinus sylvestris* was closely related to the length of the growing season. Correlation analysis also demonstrated that the annual ring widths of *Larix gmelinii* were sensitive to the temperature at the beginning of the growing season, but the ring widths of *Pinus sylvestris* did not have any significant climatic response.

Sano et al. (2005) reconstructed temperature variations since the mid-18th century for western Nepal from tree-ring width and density of *Abies spectabilis*. Response analysis of tree-ring parameters with climate records revealed that the ring width was correlated negatively with March-May (pre-monsoon) temperature and positively with March-May precipitation, while the minimum density was correlated positively with March-July temperature and negatively with March-May precipitation. On the other hand, the maximum and mean densities were positively correlated with August-September and March-September temperatures, respectively.

Zhao et al. (2007) developed reasonable methods for establishing tree-ring width chronologies of *Larix gmelinii* (larch) plantations in Northeast China. Results show that about 40% of the variance of growth ring width is caused by climate change, about 30% by inheritance, about 20% by silviculture, and about 10% by site conditions and other factors.

Yu et al. (2007) carried out dendroclimatic analysis of *Betula ermanii* forests at their upper limit of distribution in Changbai Mountain, Northeast China. Correlation and response function coefficients indicated that radial growth of Erman's birch was positively influenced by previous August, October and current February temperature, and previous winter, and current March, June and September precipitation. In addition, radial growth showed a negative relationship to previous August and current June sunshine ratio. Together, these results suggested that climate affected radial growth of Erman's birch through altering soil water availability.

Sensitivity of Scots pine trees to winter colds and summer droughts was assessed using a dendroclimatological investigation by Vitas (2006). Investigation revealed high heterogeneity among pine trees in respect to their response to low winter temperatures and summer droughts. It was found that trees characterised by similar response to contrasting climatic conditions mostly are located in smaller or bigger clusters.

Vitas and Erlickyte (2008) studied the influence of droughts to the radial growth of Scots pine (*Pinus sylvestris*) in Lithuania to estimate the differences of the impact of droughts on dry and wet growing sites. The impact of droughts on the radial growth of pine using pointer years was investigated. Winter colds and summer droughts were attributed as causes of negative pointer years. Totally, six pointer years of pines radial growth have been provoked by droughts during the 20th century. It was established that the number of pines affected by droughts on wet sites was even bigger than on dry sites.

ZeXin et al. (2008) carried out annual temperature reconstruction as deduced from five tree ring-width chronologies from one fir (*Abies georgei*) and four spruce (*Picea brachytyla*) stands near the upper treeline in the central Hengduan Mountain, northwestern Yunnan, China. Climate-growth response analysis revealed that radial growth is mainly controlled by temperature variations, especially in the winter season. The first principal component of the spruce chronology network accounts for 43% of the annual mean temperature (from previous October until September). By using a linear regression approach, they reconstructed annual mean temperature for the past 250 years.

Tree-ring chronology of *Pinus lagunae* was developed by Diaz et al. (2001) from the southern part of the Baja California Peninsula, Mexico and the chronology is used to reconstruct the history of precipitation variations. A September-July precipitation reconstruction is developed for the period AD 1862-1996. It also shows that 1983, one of the strongest El Nino events of the 20th century, is the wettest year. Tree-ring growth of *Pinus lagunae* was most strongly correlated with winter precipitation.

Gedalof and Smith (2001) investigated dendroclimatic response of mountain hemlock (*Tsuga mertensiana*) in Pacific North America. Response function analyses indicate that summer temperature is the most influential factor limiting growth throughout the study region. Warm summer temperatures are associated with enhanced growth in the current year but with reduced growth in the following year.

Wimmer and Grabner (2000) analysed of 16 anatomical variables measured on 20 spruce trees (*Picea abies*) from sites in the managed forest district Seyde, Germany. Ring width and latewood proportion did not show significant relationships with monthly climatic data, whereas maximum density, latewood cell-wall proportion and latewood density were highly correlated with temperature and precipitation. The climatic signals expressed in resin duct density, ray height, tracheid length and microfibril angles were less pronounced.

A 403 year old tree-ring chronology (A.D. 1595-1997) was developed by Gervais and MacDonald (2000) from living and dead Scots pine (*Pinus sylvestris*) trees growing near the treeline on the Kola Peninsula in northwestern Russia. Ring-width was significantly correlated with mean July temperatures. Analysis of instrumental climate records and pine recruitment suggested a link between warm autumn and early spring conditions in the mid-20th century and increased pine regeneration.

Rubino and McCarthy conducted (2000) dendroclimatological analysis of white oak (*Quercus alba*) from an old-growth forest of southeastern Ohio, USA to determine the relationship between climate and radial-growth rates. Increment cores and slabs were used to create both master ring-width and basal area increment chronologies spanning 374 years (1625-1998). Both ring widths and basal area increments were significantly correlated with growing season (April-July) precipitation and drought severity. Additionally, numerous current growth year and previous growth year monthly climatic conditions (precipitation, temperature, and drought severity) were significantly correlated with radial-growth rates.

Leal et al. (2008) analysed variations in tree ring growth of Cork oak (*Quercus suber*) using dendrochronological techniques on cork oak discs from trees harvested in the cork producing region of Alentejo, Portugal. The tree ring indices correlated positively with September temperature and very strongly with precipitation totals from previous October until current February showing that the water stored in the soil during the autumn and winter months prior to the growing season has a primordial effect on the growth of the given season.

Campelo et al. (2007) established relationships between climate and double rings in *Quercus ilex* from northeast Spain. Double rings were frequent and occurred consistently along the stem. Two types of double rings could be recognized according to their width: type I, with the extra growth band accounting for approximately 50% of the tree ring; and type II, with a narrow extra growth band.

The formation of double rings was triggered by rainfall in summer and the extra growth-band width was related to summer and autumn environmental conditions. Double rings in *Quercus ilex* can potentially be used in dendroclimatological studies, as they are formed in response to climatic conditions within the growing season.

2.2.2 Studies in tropical regions

The width of the increment zones in the xylem of *Swietenia macrophylla* and *Cedrela odorata* was investigated by dendroecological methods in a primary forest near Aripuana, Mato Grosso, Brazil by Dunisch et al. (2003). Correlation analyses revealed a significant relationship between the precipitation at the beginning and at the end of the growth season and the width of the increment zones in the adult xylem of *Swietenia*. In contrast, the width of the growth increment in the xylem of *Cedrela odorata* was significantly correlated with the precipitation in March and May of the previous growth period. Similarly Trouet et al. studied (2001) tree rings of *Brachystegia spiciformis* and *Isoberlinia tomentosa* and evaluated the ENSO-signal in the miombo woodland of Eastern Africa. Monthly precipitation, monthly maximum air temperature and monthly Southern Oscillation Index value correlated significantly with tree ring widths of the mean series. These correlations are strong indicators of the annual character of the growth rings.

Biondi (2001) developed a 400-year tree-ring chronology from the tropical treeline of North America using Mexican mountain pine (*Pinus hartwegii*). Most trees also exhibit extremely low growth in 1913 and 1914, following the January 1913 Plinian eruption of the Volcan de Colima. Because *Pinus hartwegii* is found on top of high mountains from Mexico to Guatemala, there is potential for developing a network of tropical treeline chronologies.

Heinrich and Banks (2005) analyzed dendroclimatological potential of *Toona ciliata*. Stem increments revealed a common period of dormancy during winter and the measurements were found to have correlation with both precipitation and temperature, depending on the site. The samples from different individuals were cross-dated and the resulting site index had the potential to reconstruct early season temperatures and late-season rainfall.

Dendroecological potential of *Tabebuia heptaphylla* was studied by Mattos et al. (2004). Pearson coefficient was used to show the correlation between growth rings and precipitation rates. The correlation of radial increment and precipitation was significant at the level of 5% on discs 1 to 5 meters. Above 6 meters the results were not significant, probably due to the small number of compared pairs. Dendrochronological analysis of annual growth rings in *Pterocarpus angolensis* from Zimbabwe by Stahle et al. (1999) indicated that the species would be useful for the reconstruction of past climate and stream flow. The mean ring-width chronologies derived from these trees were significantly correlated with regional rainfall totals during the wet season for 1901-90.

A dendrochronological study of *Tectona grandis* (Teak) was carried out in Puerto Rico by Margaret and Bernard (2003) in order to investigate patterns of growth and to determine the effect of climate on the growth of teak. They concluded that the best predictors of growth of teak are July and November temperatures. The tree ring chronology shows decreased growth during several hurricane years, followed by increased growth the following year.

Climatic signals in tree rings of *Burkea africana* and *Pterocarpus angolensis* from semiarid forests in Namibia were analyzed by Fichtler et al. (2004). *Burkea africana* was more sensitive to rainfall variation than *Pterocarpus angolensis* at both sites. Growth response to rainfall was positive, but a time-lag in the reaction occurred between the sites, corresponding to the time-lag of the beginning of the rainy season. Air temperature showed a negative correlation with stem increment at both sites. The response at the westernmost site to two ENSO indices indicates a tree growth decrease during El Nino years, which are generally dry in southern Africa.

Schongart et al. (2000) studied the wood growth patterns of *Macrolobium acaciifolium* in Amazonian black-water and white-water floodplain forests. They determined tree age, wood density and mean radial increment and synchronized ring-width patterns of single trees to construct tree-ring chronologies for every study site. In both chronologies increased wood growth during El Nino events causing negative precipitation anomalies and a lower water discharge in Amazonian rivers, which leads to an extension of the terrestrial phase. The climate signal of La Nina was not evident in the dendroclimatic proxies.

Rodriguez et al. (2005) analyzed El Nino events recorded in dry-forest species of the lowlands of northwest Peru. Short ring-width chronologies of Palo Santo (*Bursera graveolens*) show a well-developed response to the ENSO signal and good inter-site correlations. Preliminary isotopic studies in Algarrobo (*Prosopis* spp.) also showed evidence of the 1997-98 El Nino events.

Verheydenb et al. (2005) constructed high-resolution time series of vessel density in Kenyan mangrove trees that revealed a link with climate. The potential use of time series of vessel features (density, diameter, surface area and hydraulic conductivity) combined with spectral analysis as a proxy for environmental conditions in the mangrove *Rhizophora mucronata* was investigated. Intra-annual differences in the vessel features revealed a trade-off between hydraulic efficiency (large vessels) during the rainy season and hydraulic safety (small, more numerous vessels) during the dry season.

Giantomasi et al. (2009) developed chronologies based on the width of tree rings, total area of vessels, and the number of vessels per tree ring of *Prosopis flexuosa* wood samples from the xerophytic woodlands of central Argentina. The width of the rings, the number of vessels, and the total area of vessels were positively influenced by regional precipitation corresponding to the seasonalized November to December period. The width of the rings and the total area of vessels were negatively influenced by temperature during the same period, while the number of vessels was not significantly correlated with temperature.

Brienen and Zuidema (2005) related tree growth to rainfall in Bolivian rain forests. The results of the climate-growth analysis show a positive relationship between tree growth and rainfall in certain periods of the year, indicating that rainfall plays a major role in tree growth. Three species showed a strong relationship with rainfall at the beginning of the rainy season, while one species was most sensitive to the rainfall at the end of the previous growing season.

Heinrich et al. (2008) investigated on the hydroclimatic variation in North Queensland, Australia inferred from tree rings. Tree cores of *Toona ciliata* were developed into a 140 year tree-ring widths index chronology. The analyses showed that the ring-widths indices correlate with March-June precipitation. March-June precipitation was reconstructed using the tree-ring data with 35% of the variance explained. This suggests that growth of *Toona ciliata* is influenced by climate phenomena of different wave lengths which can be associated with El Nino Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO).

Baker et al. (2008) demonstrated the significant dendrochronological potential of *Callitris intratropica*, a native conifer distributed across much of the seasonal tropics of northern Australia. The strongest correlations between the climate data and tree-ring width indices were for early monsoon rainfall (October-December) and late monsoon PDSI (May). The study demonstrated the significant potential of high-quality dendrochronological research on mainland Australia in general, and of *Callitris intratropica*, specifically, to reconstruct historical variation of the Australian monsoon system.

Tree ring analyses on growth ring periodicity in *Pinus caribaea* from a Merida State plantation, Venezuela was carried out by Melandri et al. (2007). Cambial activity was related to the plantation age and precipitation conditions. The climatic data revealed a bimodal precipitation regime that explains ring width variation and narrow false ring presence, characterized by a weak transition in wall thickness of the tracheids. The correlation between tree ring chronologies and this average, as well as the total precipitation during the rainy period showed significant coefficients indicating an important common signal, and a related climate influence.

Gebrekirstos et al. (2008) conducted study on climate-growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia. High positive correlations were found between the tree-ring width chronologies and precipitation data, and all species showed similar response to external climate forcing, which supports the formation of one tree-ring per year. Strong declines in tree-ring width correlated remarkably well with past El Nino Southern Oscillation (ENSO) events and drought/famine periods in Ethiopia.

2.3 Dendroclimatological studies in India

Yadav et al. (2006) reported a 1584-year (AD 420-2003) long ring width chronology of Himalayan pencil cedar (*Juniperus macropoda*) from cold arid region in Lahaul, Himachal Pradesh, India. Ring width variations in trees at this site are found to be associated with variations in precipitation from previous growth years' September to concurrent May.

A study on climatic response of Himalayan cedar (*Cedrus deodara*) tree-ring parameters from two sites in the western Himalaya was carried out by Pant et al. (2000). Response function analyses indicate significant relationships between pre-monsoon (March-April-May) summer climate and early wood density parameters, as well as total ring width.

Singh and Yadav (2000) constructed 410 year old ring-width chronology of Himalayan pine (*Pinus wallichiana*) near Chirbasa, Gangotri, Uttar Pradesh. This makes the longest chronology of this species developed so far from the Indian region. A strong correlation noted between tree growth and winter temperature shows that winter warmth is one of the main factors responsible for the 20th century growth surge. This growth surge is closely associated with the area vacated by the Gangotri glacier. Low growth prior to the 1950s, reflecting cooler conditions, indicates that the glacier should have been stationary for a long time with some episodic advances.

Yadav and Park (2000) reconstructed precipitation pattern using ring-width chronology of Himalayan cedar from western Himalaya. A well replicated ring-width chronology for the species, derived from combined tree-ring samples from two adjacent homogeneous sites, has been used to reconstruct precipitation for the non-monsoon months back to AD 1171.

Singh and Yadav (2007) developed a 1087-year (AD 919-2005) chronology of *Pinus gerardiana* (Chilgoza pine) from Kinnaur, Himachal Pradesh. The tree growth-climate relationship using response-function analyses indicated that precipitation, except for the months of January, February and October, has a direct relationship with growth. Mean monthly temperature showed largely negative relationship with growth, except for June and August-October. The longevity and climate sensitivity of this species shows its potential in developing millennium-long climatic reconstructions needed for understanding the long-term climate variability in the Himalayan region.

Chaudhary and Bhattacharyya (2000) conducted tree ring analysis of *Larix griffithiana* a subalpine deciduous conifer growing in Sange, Arunachal Pradesh, Eastern Himalaya has been taken up to understand past climatic changes of this region. Analysis of tree growth and records of climatic parameters suggest that May temperature is the most important factor in controlling growth of this tree. Reconstruction of May temperature using ring width data of this tree has been done.

Fujiwara et al. (2002) investigated the dendroclimatic response of teak growing in India using a ring-width chronology from one site in central India. The result of this study suggested that the radial growth of the teak trees was influenced by moisture condition during the post-monsoon season, which is the beginning of the dry season. In order to confirm that the relation between ring-width chronologies and climate factors would be applicable over a wide area in central India, ring-width chronologies from 8 sites were established and their responses to the climate changes were analyzed.

Reconstruction of June-September precipitation based on tree-ring data of teak from Madhya Pradesh in India was done by Shah et al. (2007). Growth of teak from this area has been found to be limited by the low monsoon precipitation. Based on ring-width data obtained from teak, mean monsoon precipitation of June-September has been reconstructed back to AD 1835.

Ram et al. (2008) conducted a tree-ring analysis of teak in central India and its relationship with rainfall and moisture index. Significant positive relationship of moisture index and rainfall during the monsoon months as well as on the annual scale with tree-ring width variations over the region indicates the important role of moisture availability at the root zone. The results suggest that teak tree-ring chronologies can be used as high resolution proxy for past precipitation and moisture level in the environment.

Deepak et al. (2010) conducted tree-ring analysis of teak from Shimoga and Dandeli, Karnataka, India as a tool to determine drought years. The tree-ring chronology of teak and climatic data revealed that there are several alternating periods of low and high to very high rainfall years. The common low rainfall years at two sites matched with the most of drought years of India. It has been found to have good potential to know rainfall pattern, mostly the drought years. Sinha et al. (2011) studied climate related tree growth variability in *Tectona grandis* L. based on response function analysis from dry deciduous forests of Karnataka and Maharashtra. Rainfall during the monsoon months of the current year was found to be positively associated with radial growth of teak at both sites, whereas premonsoon April rainfall was found to be negatively associated. Rainfall and temperature of the current year during March have positive influence on the growth of teak at Chandrapur and Mundagod respectively.

Ram et al. (2011) developed a ring-width chronology of teak (*Tectona grandis* L.) from a moisture stressed area in Maharashtra, India. Tree-ring variations were most correlated positively with Palmer Drought Severity Index (PDSI) during different seasons compared with moisture index (MI). Significant strong positive correlation with MI, and negative association with temperature and potential evapotranspiration (PET) were found during previous and current year post-monsoon (ON). This study showed that the moisture availability during the post-monsoon of the previous year has a significant role in the development of annual growth rings.

2.4 Dendroclimatological studies using vessel features

Sass and Eckstein (1992, 1995) showed that the vessel area of *Fagus sylvatica* has a stronger relationship with climate. Woodcock (1989) studied ring-porous species such as *Quercus macrocarpa*, *Quercus rubra* and *Fraxinus pennsylvanica* for various variables such as diameter of the largest vessels, total conductive area, and vessel density. She concluded that vessel density in the latewood is appropriate for precipitation reconstruction.

Bhattacharya et al. (2007) analysed climatic changes around Parambikulam, Kerala, based on early wood mean vessel area of teak. This study shows that rainfall during October and November (north-east monsoon) of the previous year and April of the current year is the most important climatic variable in developing the early wood vessel of an annual ring. Based on this tree ring parameter, the northeast monsoon of this region has been reconstructed, which extends from AD 1743 to 1986.

Garcia and Fonti (2006) investigated on the relationships between mean monthly temperature and mean vessel lumen area (MVA) in various categories of earlywood vessels of chestnut (*Castanea sativa*) in the southern part of the Swiss Alps. The MVA of a proportion of the largest earlywood vessels in each annual ring was most closely related to March temperature, whereas MVA of the smallest earlywood vessels was better correlated with June temperature. Analyses combining large and small vessels yielded lower correlations between MVA and monthly temperature.

Influence of climate on tree rings and vessel features in red oak and white oak growing near southwestern Quebec, Canada was investigated by Tardif and Conciatori (2006). The best climate variable to reconstruct was the July Canadian Drought Code and the best reconstruction model was derived from earlywood, latewood, and ring-width chronologies. They concluded that vessel chronologies for *Quercus alba* and *Quercus rubra* have limited use in dendroclimatology. Vessel features are best used to identify event years recorded during the life of a tree. Vessel series could prove useful, however, in calibrating physiologically based models of tree growth.

Vessel chronologies from teak in Northern Thailand and their climatic signal were investigated by Pumijumnong and Park (1999). The tree rings were divided into earlywood and latewood, and four parameters (average vessel area, average vessel diameter, average conductive area and vessel density) were measured by automatic image analysis technique to obtain 50-year (1947-1996) time series. All vessel parameters of the total ring and of the earlywood were negatively correlated with precipitation during the transitional period between the dry and the wet season. The latewood vessel parameters however are negatively correlated with June temperature. The climatic signals of the vessel parameters and of the tree-ring width are different from each other.

In a changing environment, the analysis of how trees and forest ecosystems may react under scenarios involving changing climatic conditions is of major importance (Bazzaz, 1996). A prerequisite for such analyses is the knowledge of how trees have reacted to past climatic and anthropogenic events and trends. Well-replicated mean site series for a particular species, compiled from individual tree samples have been developed for thousands of locations in the temperate and boreal zones to understand these reactions. The identification of such patterns beyond a single region or nation has been possible because of the extent of regional chronologies developed and nature of collaboration between dendroclimatologists.

By going through these reviews we can observe that as compared to temperate species only limited amount of research works were conducted on tropical species. The penninsular region of India especially southern India requires more site chronologies to add into the existing data and make them more meaningful since the climate varies considerably over this region. So the present study explores the potential of teak tree-ring data, which could contribute more to the existing regional tree-ring chronologies.

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1 MATERIAL

The present investigation was conducted to develop tree-ring chronologies from plantation-grown *Tectona grandis* (teak) at three sites viz., Elanad, Vazhani and Ponganamkadu in Thrissur forest division, Kerala, to understand the relationship between climate and tree growth. The project was carried out at the Department of Wood Science, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur.

3.1.1 Experimental site

The study material was collected from Thrissur forest division and Chalakudy forest division (Fig. 1). The Thrissur division has a total forest area of 29, 805 ha out of which 1816 ha are under teak plantations. The division has 47 teak plantations of varying ages and sizes. The Chalakudy forest division has a total forest area of 27, 870 ha out of which 4535 ha are under teak plantation. Also the division has 90 teak plantations located at different sites of varying ages and sizes (KFRI, 2005).

The study areas selected in the Thrissur forest division were located in Elanad, Vazhani and Ponganamkadu. Karikadam is the study site located in Chalakudy forest division. Details of the locations selected for the study from Thrissur forest division and Chalakudy forest division are given in Table 1.

1- Elanad
2- Vazhani
3- Ponganamkadu
4- Karikadam
5- KERI, Peechi

Fig. 1 Map showing the study sites

3.1.1 Climate of the experimental site

Thrissur forest division features a tropical monsoon climate. The summer season from March to May is followed by the south west monsoon rainy season from June to September and then from October to November north east monsoon rainy season. The winter season is from December to February. The average annual rainfall is 2500 mm. On an average, there are 120 rainy days in a year. The average maximum temperature is 35^0 C while the average minimum temperature is 20^0 C. Climate data (monthly rainfall and mean monthly temperature) obtained from the Kerala Engineering Research Institute (KERI), Peechi, for the period 1980-2005 is given in fig. 2 and 3.

Table 1. Details of sampling locations

Sl. No.	Site	Forest Division & Range	Name of plantation	Area (ha)	Year of planting	Age
1	Elanad	Thrissur Machad	Valiacadu	31.92	1946	62
2	Vazhani	Thrissur Machad	Ambalapadu	50.00	1946	62
3	Ponganamkadu	Thrissur Pattikkad	Scout Hill	32.00	1946	62
4	Karikadam	Chalakudy Pariyaram	Ramavarma	33.39	1944	65

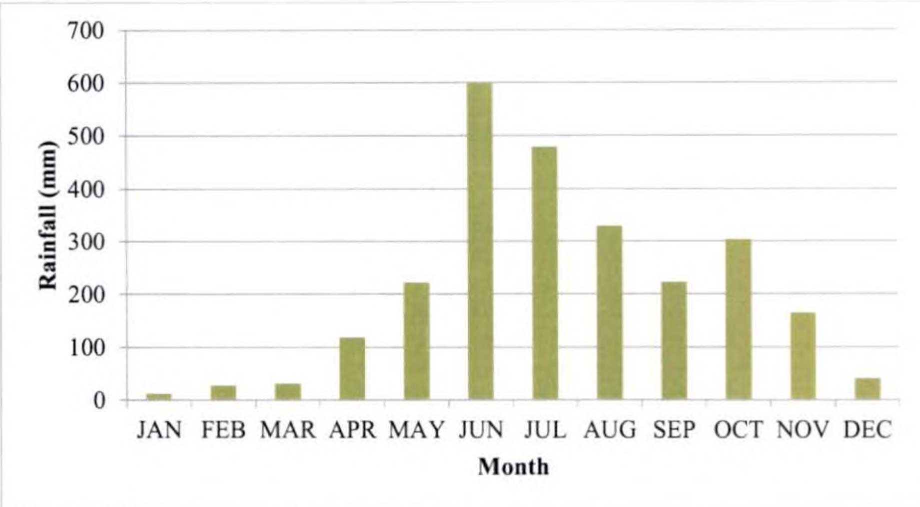


Fig. 2 Monthly variations in rainfall at Peechi, Thrissur (1980-2005)

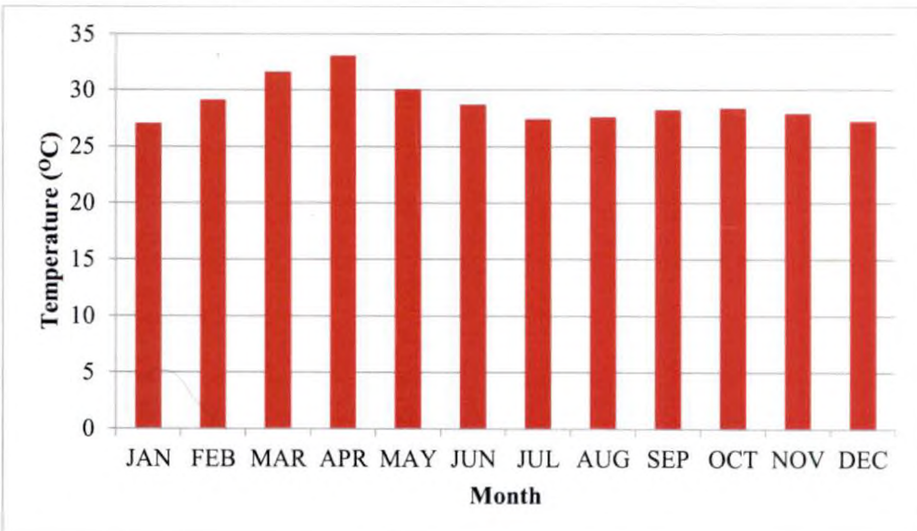


Fig. 3 Monthly variations in temperature at Peechi, Thrissur (1980-2005)

3.2 METHODOLOGY

3.2.1 Sample collection

The samples were collected from stumps left over after final felling the of plantations. Ten basal discs, one from each stump, were collected from each plantation. A portable chain saw was used to cut the basal discs from the left over stumps (Plate 1).

3.2.2 Preparation of samples

The upper surface of the basal discs collected from the field was first planed with a portable hand planer. Then the disc surfaces were smoothened with sand paper of grit sizes 26, 30, 60, 80 and 120 successively to expose the growth rings for measuring the ring width (Plate 2). For measuring the mean vessel area selected radii were first planed and sanded with sand paper of grit sizes 26, 30, 60, 80, 120 220, 320 and 400 successively (Plate 3). The samples were then washed with a water jet to make vessel lumen clearly visible.

3.2.3 Measurement of ring width

The growth rings were counted and cross matched within and between on four opposite radii on each disc from specific sites after polishing. Images of the selected rings were captured across the radius using a digital camera and ring widths were measured using the image analysis software Digimizer (Version 3.8.1). The average ring width of each year obtained from the different radii was used to construct the chronology.

3.2.4 Measurement of mean vessel area

Four radii were selected from each site to measure the mean vessel area. Macro images of the selected rings were captured across the radius using a digital camera

Plate 1. Removal of basal disc from left over stumps using a portable chain saw

(Plate 4) and vessel area was measured using the image analysis software Digimizer (Version 3.8.1).

3.2.5 Statistical analysis

3.2.5.1 Standardization

Standardization is a process in which the non-climatic signal of biological and/or tree disturbances (exogenous) are removed from the tree-ring data by employing an appropriate curve fit to the tree-ring data series and calculating a new time series. In this investigation a smoothing spline (Briffa and Jones, 1990) was used for standardization using the statistical package PAST (Paleontological Statistics Version 2.07).

3.2.5.2 Construction of index values and chronology

The selected radii were cross dated using the procedures suggested by Stokes and Smiley (1968). Ring width and mean vessel area (MVA) chronologies were developed using the index values obtained.

$$RI_t = R_t/Y_t$$

Where,

RI_t -Ring width / Mean vessel area Index value for the year t

R_t - Measured tree-ring datum for the year t

Y_t - Expected yearly growth obtained from the smoothing spline

3.2.5.3 Correlation analysis

The relationship between climate and tree growth was examined for the available climate data period 1980-2005. Correlation analysis of tree ring data (ring width index and mean vessel area index) versus seasonal rainfall and temperature using the statistical package PAST (Paleontological Statistics Version 2.07) was performed.

Plate 2. Sanding of the teak basal disc

Plate 3. Basal disc from Elanad (Valiyacadu plantation), after sanding

1mm

1973 1974 1975 1976

Plate 4. Enlarged view of growth rings showing year of formation and arrangement of vessels (100x, Valiacadu plantation, Elanad)

Seasons were defined as previous south west monsoon (–JJAS), previous north east monsoon (-ON), south west monsoon (June–September; JJAS), post-monsoon or northeast monsoon October–November; ON), winter (December–February; DJF), summer (March–May; MAM) and annual (Ram et al., 2008).

The following criteria which are important for dendroclimatological reliability of chronology were calculated using the following equations using Pearson's correlation coefficient (r) and number of trees/radii (N).

Signal to Noise Ratio (SNR) = Nr/ (1-r)

Expressed Population Signal (EPS) = Nr/ (Nr+1-r)

RESULTS

RESULTS

The present study involved a detailed investigation of tree-ring chronologies from plantation grown teak at Elanad, Vazhani and Ponganamkadu in Thrissur forest division and from Karikadam in Chalakudy forest division, to understand the relationship between climate and tree growth. The results obtained from the study are presented in this chapter.

4.1 Ring width

Ring width at all four sites showed an age related growth trend. At initial years of growth the ring width was large and with increase in age the ring width decreased. Average ring widths for each year from different sites are shown in tables 3a and 3b. Average raw ring widths and its trend in samples fitted with a smoothing spline curve from four sites are shown in fig. 4-7. Average raw ring width obtained were 4.66 mm in Elanad, 5.56 mm in Vazhani, 4.98 mm in Ponganamkadu and 3.36 mm in Karikadam (Table 2, Fig. 8).

4.2 Mean vessel area

Mean vessel area also showed a similar trend like ring width in all the four sites. With the increase in age initial years of mean vessel area was decreasing radially from pith to periphery. Mean vessel area for different sites in each year from different sites is shown in tables 4a and 4b. The mean vessel area and its declining trend in samples fitted with a smoothing spline curve from four sites are shown in fig. 9-12. The mean vessel area obtained were 41020 μm^2 in Elanad, 47250 μm^2 in Vazhani, 37319 μm^2 in Ponganamkadu and 23096 μm^2 in Karikadam (Table 2, Fig. 13).

4.3 Ring width indices

Raw ring width values were converted into dimensionless indices using standardization. A total of four chronologies from four different sites have been standardized using smoothing spline technique (Table 5a and 5b). A ring width index chronology was developed from all the four sites as shown in fig. 14-17.

Table 2. Tree ring chronology statistics of *Tectona grandis* from the study sites

Tree ring chronology statistics	Study sites			
	Elanad	Vazhani	Ponganamkadu	Karikadam
Chronology time span	1946-2008	1946-2008	1946-2008	1945-2009
Number of trees	10	10	10	10
Number of radii	40	40	40	40
Mean correlation among all radii	0.422+ 0.645*	0.219+ 0.631*	0.363+ 0.533*	0.452+ 0.525*
Mean correlation between trees	0.767+ 0.638*	0.693+ 0.755*	0.699+ 0.747*	0.581+ 0.588*
Signal to noise ratio	6.90+ 5.61*	6.24+ 6.79*	6.29+ 6.72*	5.23+ 5.29*
Expressed population signal	1.233+ 1.362*	1.307+ 1.245*	1.301+ 1.253*	1.419+ 1.412*

+ Value derived from ring width index
* Value derived from mean vessel area index

4.4 Mean vessel area indices

The measured mean vessel area in each year was converted into dimensionless indices using standardization. A total of four mean vessel area chronologies from four different sites have been standardized using smoothing spline technique (Tab 6a and 6b). Mean vessel area chronology was developed from all the four sites as shown in fig. 18-21.

Table 3a. Average ring width (mm) of teak at the study sites during 1945-1977.

Year	Average ring width (mm)			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1945	-	-	-	8.153
1946	-	-	-	8.371
1947	14.758	10.617	13.048	8.442
1948	16.105	12.542	14.012	7.209
1949	15.795	11.798	11.981	7.128
1950	12.619	11.563	11.140	6.233
1951	11.869	9.550	10.989	6.008
1952	12.364	9.609	9.891	6.412
1953	10.544	10.665	10.118	6.085
1954	10.097	9.768	7.831	7.766
1955	9.510	7.214	6.960	6.057
1956	9.307	7.420	6.598	5.819
1957	8.316	9.533	6.472	4.801
1958	7.672	9.197	6.347	3.902
1959	7.677	7.608	6.709	3.975
1960	6.745	6.542	6.619	3.729
1961	6.619	6.340	5.569	3.650
1962	6.116	6.548	5.814	3.021
1963	4.875	8.012	5.841	3.002
1964	4.360	7.429	6.436	3.359
1965	4.309	6.897	5.583	3.508
1966	4.254	6.303	5.985	2.870
1967	4.221	6.824	5.045	2.843
1968	4.553	6.659	4.836	3.232
1969	4.737	6.442	4.995	3.172
1970	4.148	6.277	4.562	2.372
1971	4.310	6.470	4.999	2.179
1972	4.018	6.025	5.253	2.316
1973	4.518	4.904	5.120	1.718
1974	3.781	4.670	4.167	1.999
1975	3.178	5.609	3.878	1.949
1976	4.422	5.501	3.947	1.903
1977	3.695	5.594	3.568	2.137

Table 3b. Average ring width (mm) of teak at the study sites during 1978-2009.

Year	Average ring width (mm)			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1978	3.217	5.731	3.706	2.327
1979	3.017	5.223	3.471	2.555
1980	2.310	4.509	2.645	2.636
1981	3.063	5.095	2.824	2.928
1982	2.529	5.296	3.075	2.672
1983	3.537	4.162	3.000	2.068
1984	3.058	3.852	3.215	2.384
1985	3.526	2.935	2.904	3.093
1986	3.942	3.472	2.753	2.847
1987	4.163	3.615	2.621	3.114
1988	3.391	3.412	2.809	2.641
1989	3.405	3.404	2.569	2.611
1990	3.085	2.956	2.106	2.668
1991	2.191	3.458	2.221	2.441
1992	2.470	3.602	1.961	2.495
1993	2.366	3.389	2.184	2.200
1994	2.745	3.301	2.098	2.237
1995	2.324	2.710	1.839	1.975
1996	2.050	2.541	1.928	1.904
1997	2.292	2.002	1.994	1.681
1998	2.108	2.672	2.459	1.737
1999	2.152	2.415	2.266	1.844
2000	1.975	2.569	2.033	1.646
2001	1.797	2.464	1.820	1.721
2002	1.825	2.962	2.124	1.736
2003	2.167	3.598	2.163	1.461
2004	1.907	2.514	2.200	1.331
2005	1.849	3.451	2.223	1.064
2006	1.609	2.473	1.878	1.043
2007	1.437	2.508	2.015	1.153
2008	1.494	2.479	1.855	1.371
2009	-	-	-	1.043
Mean	4.66 (0.73)	5.56 (0.87)	4.98 (0.78)	3.36 (0.53)

Values in parentheses indicate standard error

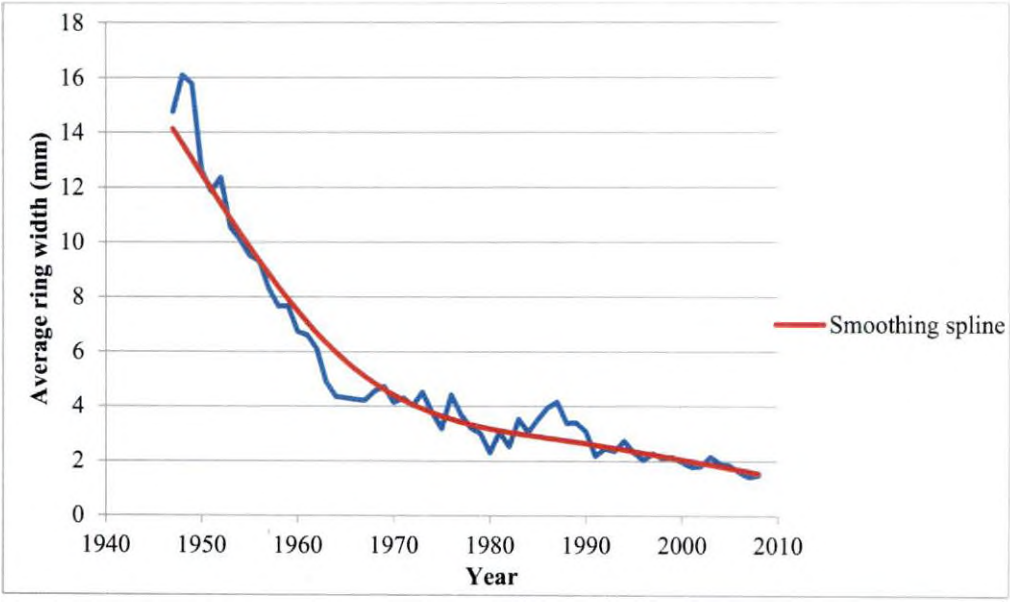


Fig. 4 Average ring width series of *Tectona grandis* at Elanad

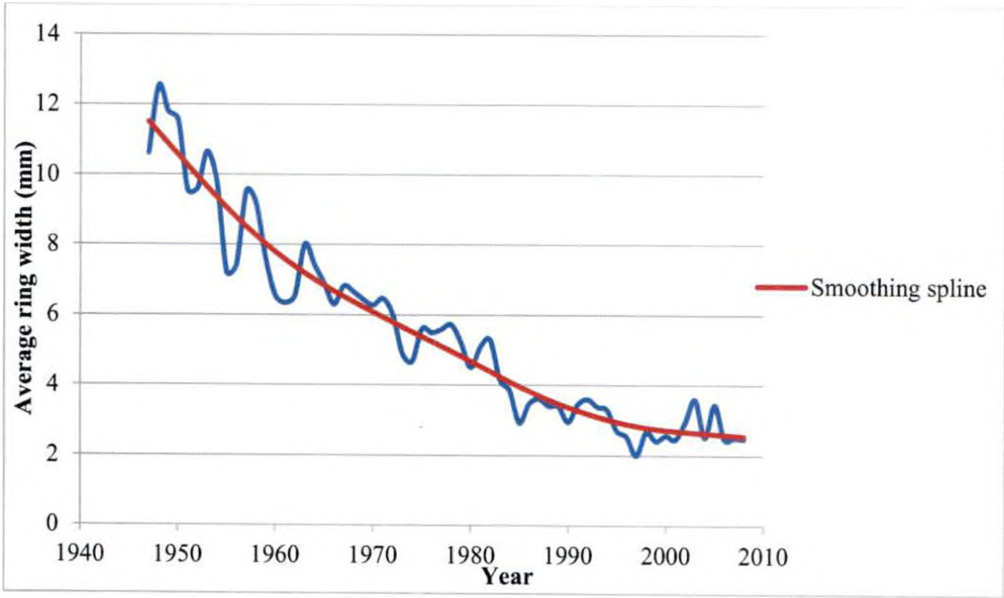


Fig. 5 Average ring width series of *Tectona grandis* at Vazhani

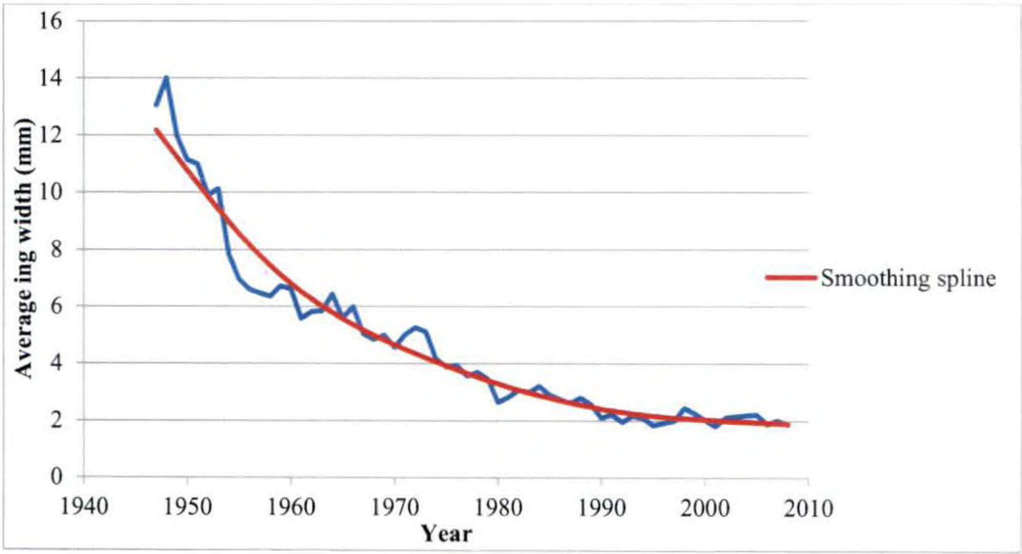


Fig. 6 Average ring width series of *Tectona grandis* at Ponganamkadu

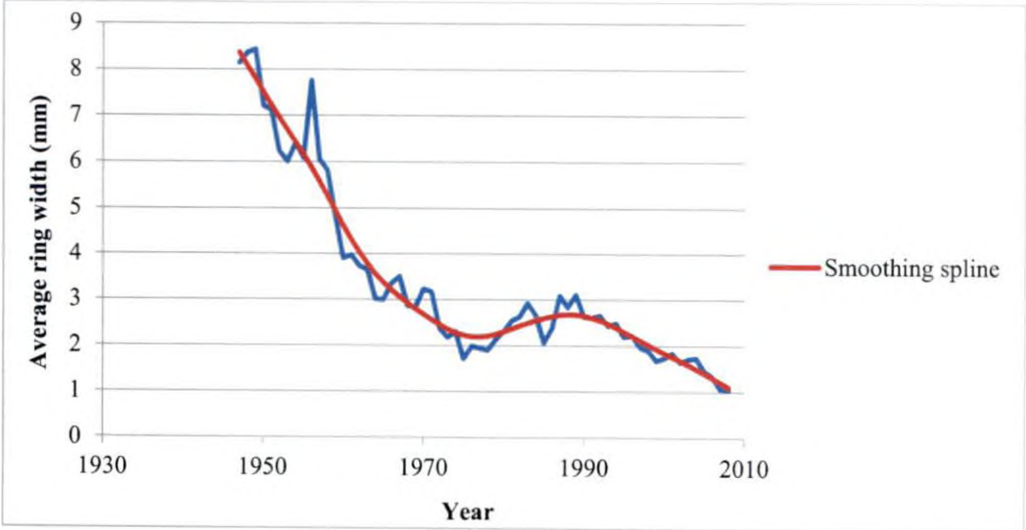


Fig. 7 Average ring width series of *Tectona grandis* at Karikadam

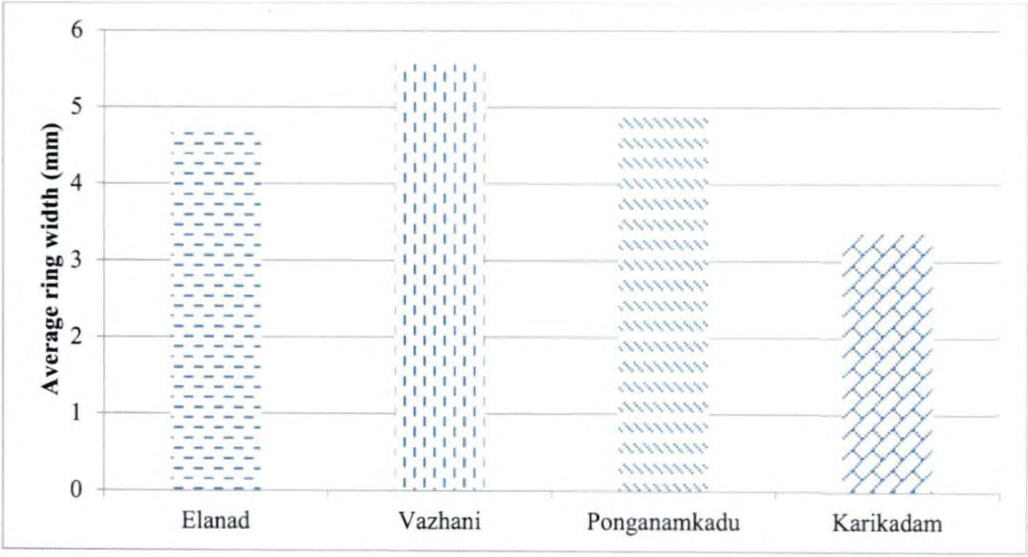


Fig. 8 Average ring width of *Tectona grandis* at study sites

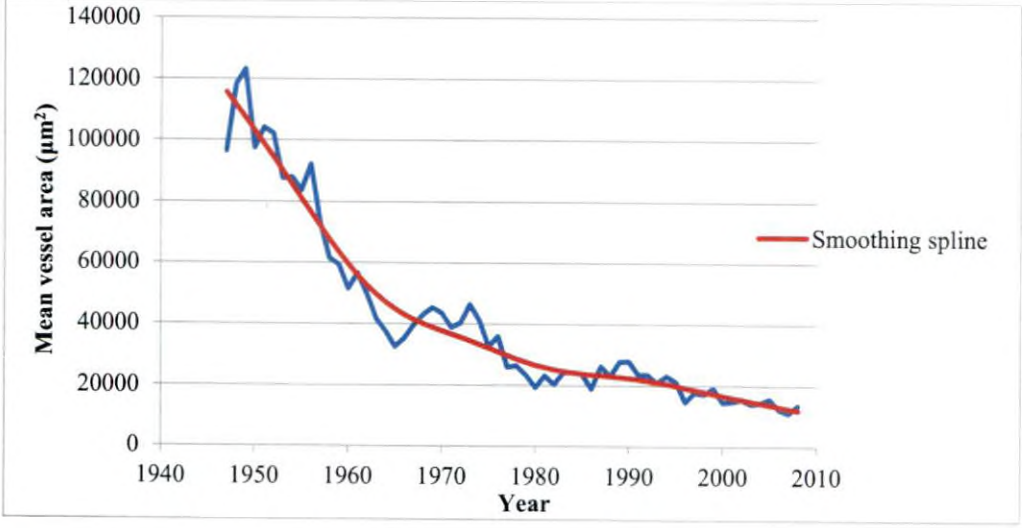


Fig. 9 Mean vessel area (MVA) series of *Tectona grandis* at Elanad

Table 4a. Mean vessel area (μm^2) of teak at the study sites during 1945-1977.

Year	Mean vessel area (μm^2)			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1945	-	-	-	85520
1946	-	-	-	98853
1947	96495	126274	109471	54224
1948	118561	133862	117622	60529
1949	123297	123439	108167	64048
1950	97555	122170	97856	46577
1951	104283	105999	96992	32617
1952	102212	86471	82449	51214
1953	87651	96769	73802	47358
1954	87981	82399	66733	28922
1955	83685	56165	59775	35438
1956	92112	51121	50652	34173
1957	73599	71645	50165	23097
1958	61594	67689	49026	19437
1959	59399	42616	50281	16644
1960	51487	31595	53533	25568
1961	56694	32493	50404	22785
1962	49810	50053	49354	17225
1963	41554	58081	55063	17897
1964	37559	59924	61160	25870
1965	32601	54431	48003	25523
1966	35256	33622	48251	16271
1967	42989	50890	45357	27129
1968	45293	47523	48268	29074
1969	43590	36878	43184	21973
1970	38834	37362	42552	14495
1971	40240	47041	39221	10530
1972	46406	43127	35288	11851
1973	41230	42950	31819	9217
1974	32649	65936	25447	13329
1975	35952	64720	23922	9400
1976	26080	55327	24125	8469
1977	26463	59610	25893	12817

Table 4b. Mean vessel area (μm^2) of teak at the study sites during 1978-2009.

Year	Mean vessel area (μm^2)			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1978	23368	46558	26447	18261
1979	19407	39829	20971	18171
1980	23223	38203	22089	21806
1981	20347	45284	18343	21556
1982	24329	44262	19838	15167
1983	24386	36563	21123	12493
1984	23630	31009	17632	14911
1985	18960	35599	14872	27180
1986	26391	38166	17306	36049
1987	23023	26232	22140	32999
1988	27930	28226	15047	22034
1989	23517	31970	15959	24896
1990	23555	24568	14114	17278
1991	20852	31624	20070	15128
1992	23158	28427	18356	11635
1993	21261	25814	13481	11895
1994	14638	26174	13231	15634
1995	17847	13379	13435	18227
1996	17278	16687	13820	12488
1997	19174	20352	14093	13320
1998	14611	21601	15415	15152
1999	14848	16381	12838	12264
2000	15656	21412	15366	14257
2001	14028	24052	14647	9976
2002	14472	20408	16541	11372
2003	15791	19702	19205	9911
2004	12318	27635	12634	7008
2005	11047	20837	15477	7346
2006	13677	23595	12887	9667
2007	96495	126274	109471	9450
2008	118561	133862	117622	8576
2009	-	-	-	5412
Mean	37319 (5904)	41020 (6490)	47250 (7476)	23096 (3654)

Values in parentheses indicate standard error

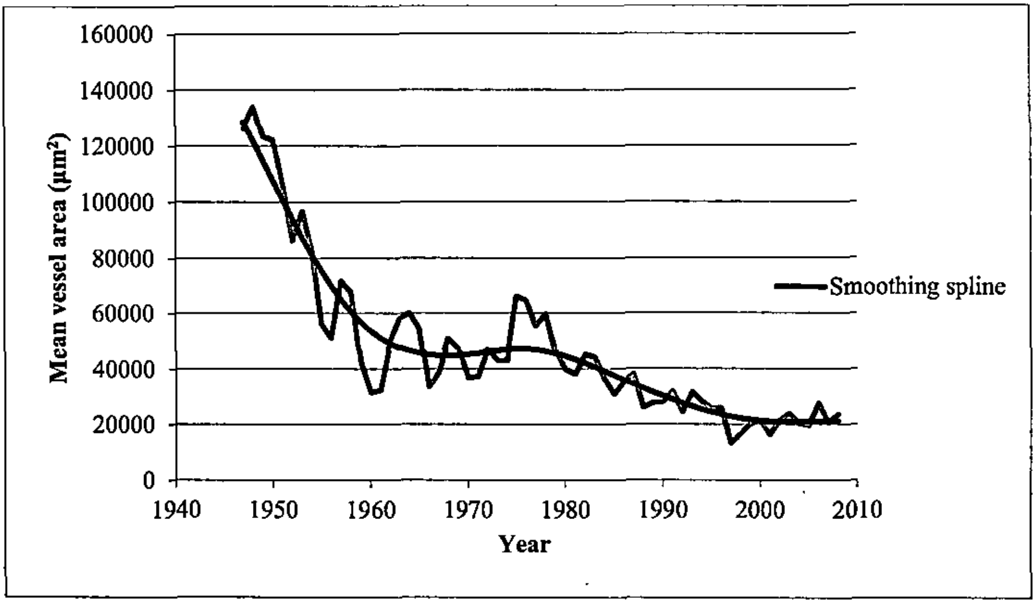


Fig. 10 Mean vessel area (MVA) series of *Tectona grandis* at Vazhani

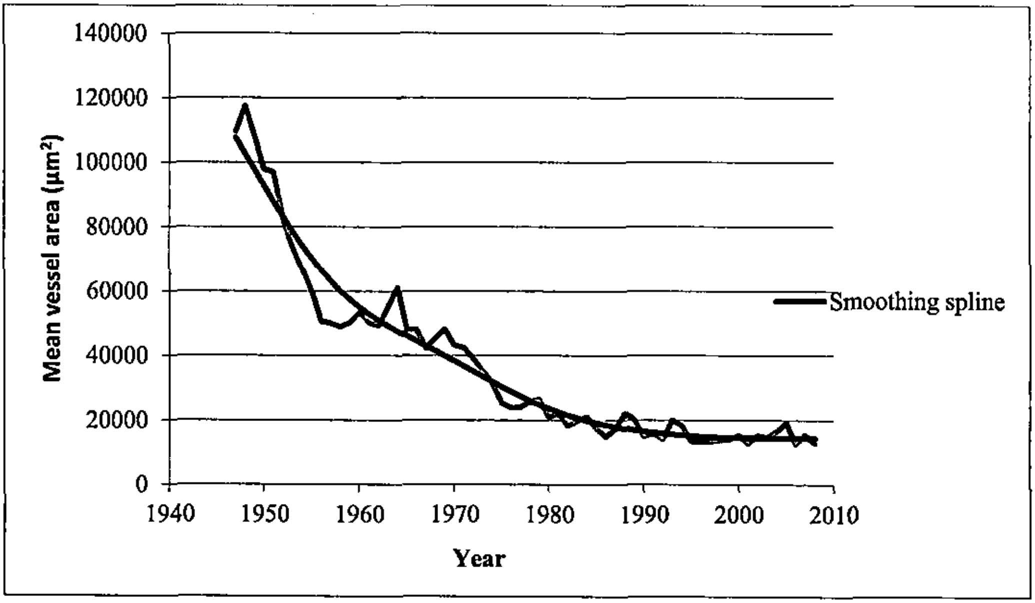


Fig. 11 Mean vessel area (MVA) series of *Tectona grandis* at Ponganamkadu

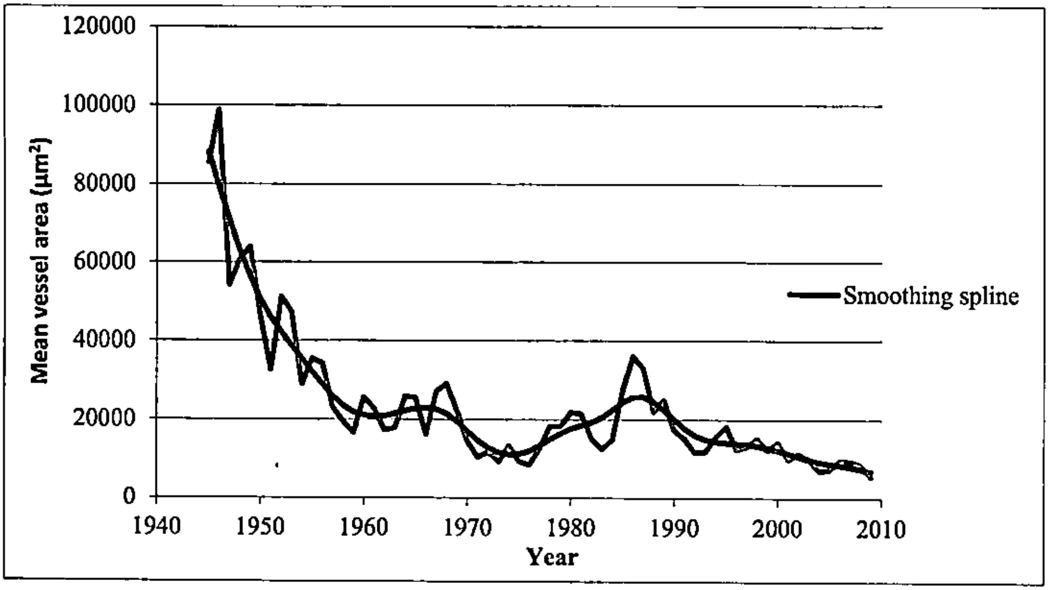


Fig. 12 Mean vessel area (MVA) series of *Tectona grandis* at Karikadam

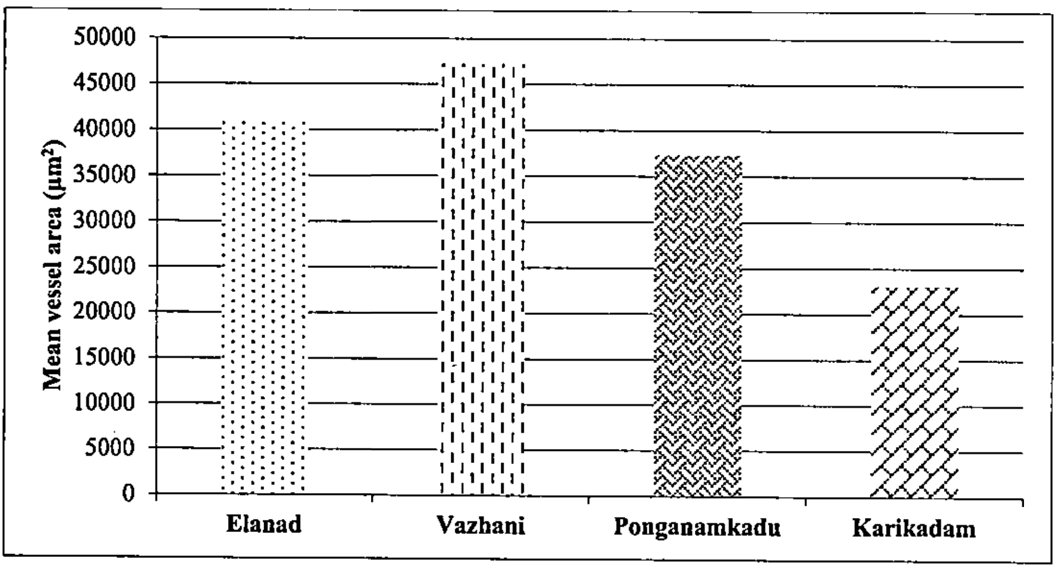


Fig. 13 Mean vessel area (MVA) of *Tectona grandis* from study sites

Table 5a. Ring width index of teak from the study sites during 1945-1977.

Year	Ring width index			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1945	-	-	-	0.859929
1946	-	-	-	0.816309
1947	1.043130	0.911251	1.071536	0.973144
1948	1.184355	1.083843	1.197008	1.034360
1949	1.210536	1.038330	1.066307	1.081526
1950	1.009495	1.051565	1.034419	0.958799
1951	0.992893	0.906380	1.066163	0.985145
1952	1.083367	0.952986	1.003951	0.895687
1953	0.969086	1.106006	1.075487	0.897830
1954	0.975116	1.064678	0.872272	0.997398
1955	0.966383	0.825063	0.812751	0.987274
1956	0.996636	0.877034	0.807627	1.319775
1957	0.939388	1.152567	0.830187	1.084628
1958	0.915370	1.147709	0.852382	1.104811
1959	0.968098	0.994462	0.942582	0.971607
1960	0.899766	0.896314	0.971729	0.844360
1961	0.934182	0.895424	0.853412	0.920449
1962	0.913436	0.932645	0.928740	0.923182
1963	0.770228	1.137701	0.971313	0.963162
1964	0.728371	1.058096	1.112941	0.846458
1965	0.760264	0.994554	1.002963	0.888489
1966	0.791715	0.924124	1.115771	1.045413
1967	0.938126	1.010263	0.968716	0.978859
1968	1.023919	1.000071	1.035969	1.012728
1969	0.938486	1.003699	0.979442	1.201963
1970	1.018432	1.074100	1.110763	1.232241
1971	0.989344	1.046275	1.207889	0.961842
1972	1.156331	0.888685	1.218519	0.919815
1973	1.003519	0.866911	1.026675	1.011773
1974	0.872487	1.044080	0.989482	0.769793
1975	1.253092	1.018061	1.043074	0.908726
1976	1.078203	1.032634	0.976445	0.888290
1977	0.964444	1.067348	1.050468	0.859929

Table 5b. Ring width index of teak from the study sites during 1978-2009.

Year	Ring width index			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1978	0.927037	0.995572	1.018835	0.948150
1979	0.726191	0.888858	0.803506	1.007690
1980	0.983247	1.046450	0.887565	1.076449
1981	0.828050	1.150993	0.999506	1.080268
1982	1.179153	0.976391	1.007771	1.169900
1983	1.037487	0.982785	1.115348	1.044355
1984	1.216520	0.805419	1.039421	0.793321
1985	1.383563	0.997873	1.016517	0.900401
1986	1.486973	1.063464	0.997221	1.155461
1987	1.233440	1.015567	1.099974	1.058557
1988	1.166482	0.884279	0.870841	0.993478
1989	0.845772	1.032391	0.941485	0.998342
1990	0.974536	1.085070	0.851087	1.043937
1991	0.954822	1.053474	0.968090	0.983029
1992	1.134208	1.084623	0.948691	1.039264
1993	0.984268	0.958167	0.846296	0.952366
1994	0.890566	0.965840	0.901452	1.009318
1995	1.022294	0.800518	0.945594	0.931470
1996	0.966167	1.083808	1.180860	0.939473
1997	1.014987	0.965331	1.100525	0.868529
1998	0.958854	0.989466	0.997919	0.940129
1999	0.899688	0.903218	0.902242	1.046207
2000	0.942558	1.032916	1.062825	0.980963
2001	1.156242	1.216654	1.091606	1.081665
2002	1.052611	0.848908	1.119898	1.156810
2003	1.057334	1.190397	1.141553	1.039660
2004	0.954335	0.891776	0.972808	1.018719
2005	0.885646	0.955781	1.053038	0.882014
2006	0.957545	1.002645	0.977926	0.944192
2007	1.043130	0.911251	1.071536	0.973144
2008	1.184355	1.083843	1.197008	1.034360
2009	-	-	-	0.974183
Mean	1.003196 (0.148644)	0.998489 (0.093215)	1.001081 (0.101779)	0.997703 (0.106051)

Values in parentheses indicate standard error

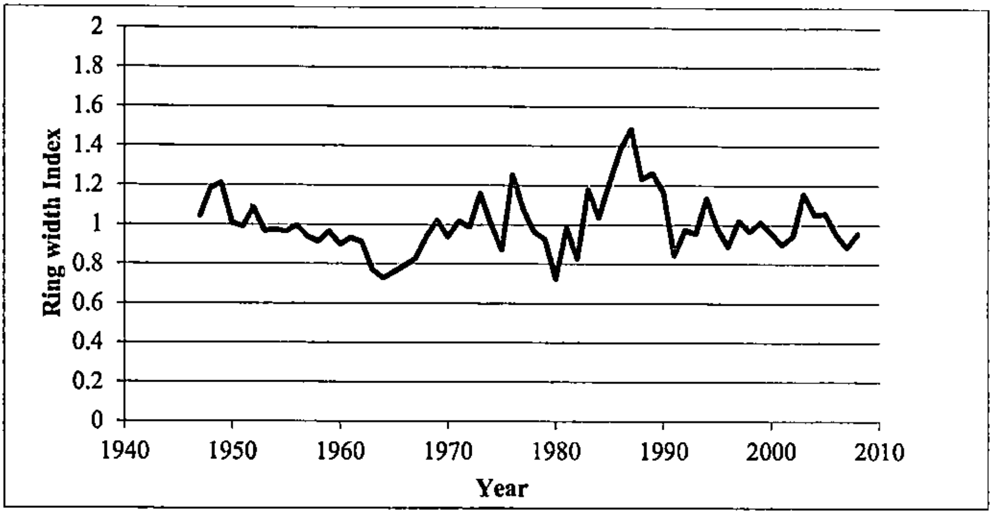


Fig. 14 Average ring width index chronology of *Tectona grandis* at Elanad

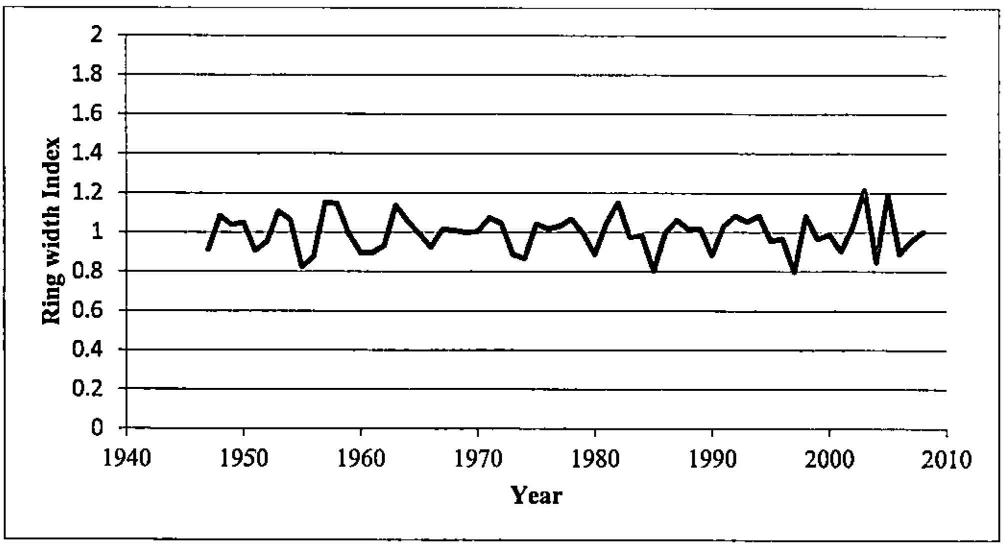


Fig. 15 Average ring width index chronology of *Tectona grandis* at Vazhani

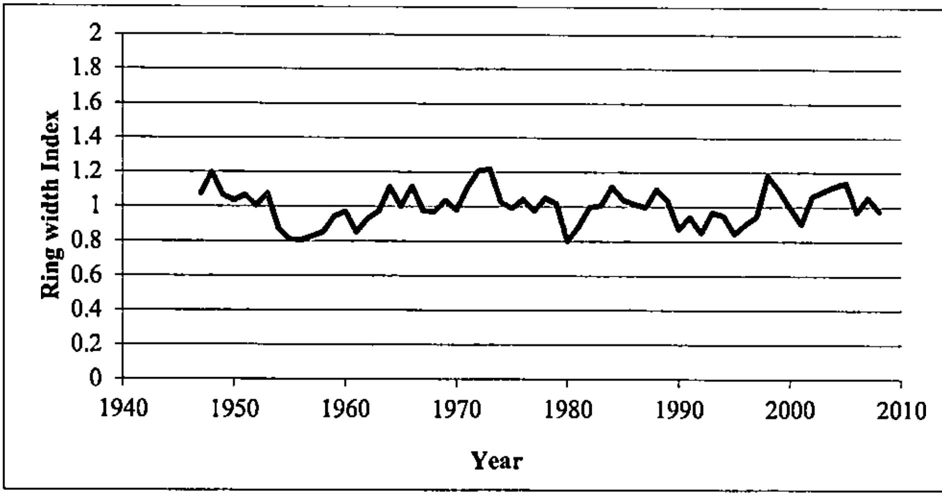


Fig.16 Average ring width index chronology of *Tectona grandis* at Ponganamkadu

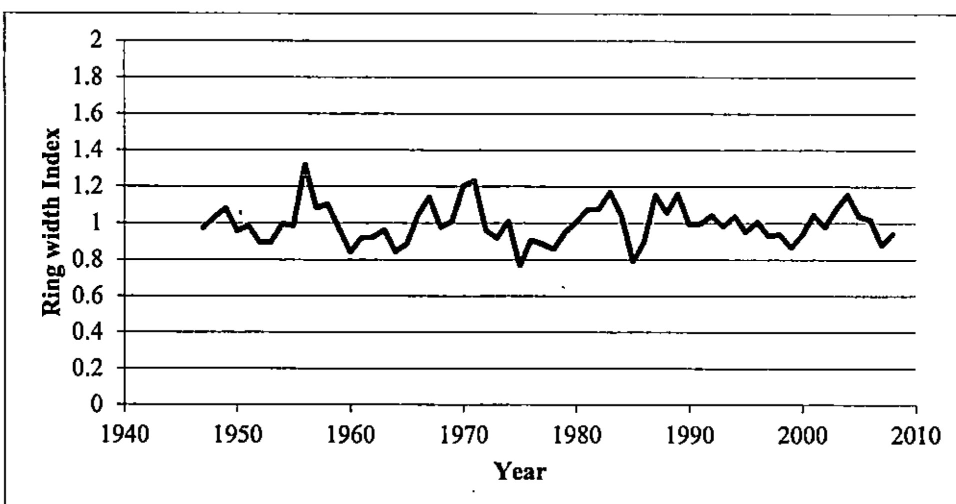


Fig.17 Average ring width index chronology of *Tectona grandis* at Karikadam

Table 6a. Mean vessel area index of teak from the study sites during 1945-1977.

Year	Mean vessel area index			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1945	-	-	-	0.969695
1946	-	-	-	1.242066
1947	0.833295	0.982226	1.015976	0.763465
1948	1.061618	1.101024	1.144413	0.956275
1949	1.146738	1.077037	1.105883	1.132212
1950	0.944576	1.134885	1.053675	0.917906
1951	1.053689	1.052003	1.102164	0.708884
1952	1.080625	0.919848	0.990386	1.211063
1953	0.97245	1.10629	0.938074	1.218476
1954	1.027355	1.014345	0.897769	0.816309
1955	1.031599	0.745089	0.850541	1.103242
1956	1.202366	0.730334	0.761091	1.182511
1957	1.020247	1.099942	0.794029	0.892546
1958	0.908781	1.113075	0.814929	0.829231
1959	0.93402	0.747005	0.87479	0.761871
1960	0.863055	0.586433	0.971579	1.214185
1961	1.012295	0.633399	0.951324	1.096663
1962	0.945583	1.015882	0.966266	0.824387
1963	0.836149	1.217344	1.116086	0.835762
1964	0.797603	1.287595	1.282135	1.168688
1965	0.726778	1.191223	1.040475	1.125346
1966	0.820394	0.744825	1.081677	0.712034
1967	1.073535	1.135535	1.090777	1.354143
1968	1.165736	1.057027	1.205176	1.126416
1969	1.15458	0.81492	1.121975	0.850251
1970	1.058382	0.81826	1.153243	0.717953
1971	1.1294	1.019777	1.111624	0.926785
1972	1.343711	0.925612	1.048379	0.796126
1973	1.234728	0.914193	0.992838	1.202661
1974	1.013759	1.396363	0.835051	0.836234
1975	1.159599	1.370289	0.826125	0.702568
1976	0.874643	1.177874	0.876877	0.955599
1977	0.922495	1.283695	0.990123	1.217562

Table 6b. Mean vessel area index of teak from the study sites during 1978-2009.

Year	Mean vessel area index			
	Elanad	Vazhani	Ponganamkadu	Karikadam
1978	0.845347	1.020083	1.063101	1.104220
1979	0.726441	0.892469	0.885095	1.238321
1980	0.896032	0.879365	0.977207	1.167320
1981	0.805794	1.075072	0.848791	0.785888
1982	0.984765	1.087742	0.957757	0.608273
1983	1.00288	0.933041	1.061127	0.667172
1984	0.988648	0.823679	0.918961	1.116629
1985	0.803428	0.986283	0.801747	1.403298
1986	1.131018	1.104298	0.962108	1.281830
1987	0.997894	0.79335	1.265958	0.899145
1988	1.243774	0.932856	0.904102	0.863819
1989	1.065899	1.103851	0.979785	0.854004
1990	1.090032	0.885667	0.883559	0.729126
1991	0.988331	1.189211	1.27863	0.798763
1992	1.127574	1.113889	1.188095	1.086050
1993	1.066483	1.052259	0.884912	1.288007
1994	0.758109	1.107124	0.878993	0.896921
1995	0.955878	0.585043	0.901381	0.974183
1996	0.95834	0.750601	0.934636	1.135674
1997	1.102528	0.936414	0.95806	0.954239
1998	0.871965	1.010778	1.051938	1.167459
1999	0.920316	0.77544	0.87829	0.872018
2000	1.008615	1.020307	1.05273	1.068652
2001	0.940049	1.149184	1.004322	1.003582
2002	1.009795	0.974866	1.135019	0.759787
2003	1.148707	0.938816	1.319046	0.839708
2004	0.935662	1.311778	0.868921	1.152889
2005	0.877568	0.984809	1.066221	1.183128
2006	1.138314	1.110003	0.88943	1.147741
2007	0.833295	0.982226	1.015976	0.763465
2008	1.061618	1.101024	1.144413	0.956275
2009	-	-	-	0.788801
Mean	0.998712 (0.135708)	0.994999 (0.181160)	0.999582 (0.132228)	0.992215 (0.196955)

Values in parentheses indicate standard error

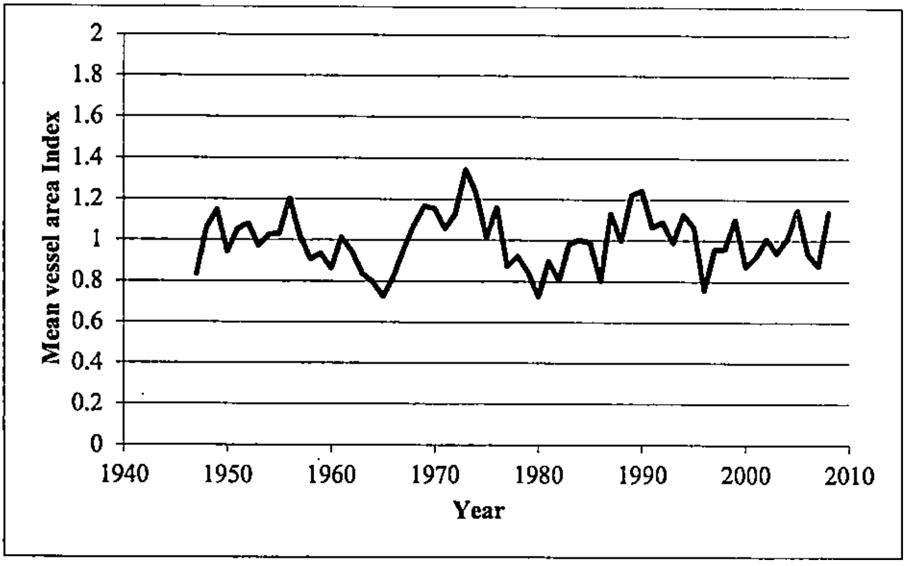


Fig.18 Mean vessel area index chronology of *Tectona grandis* at Elanad

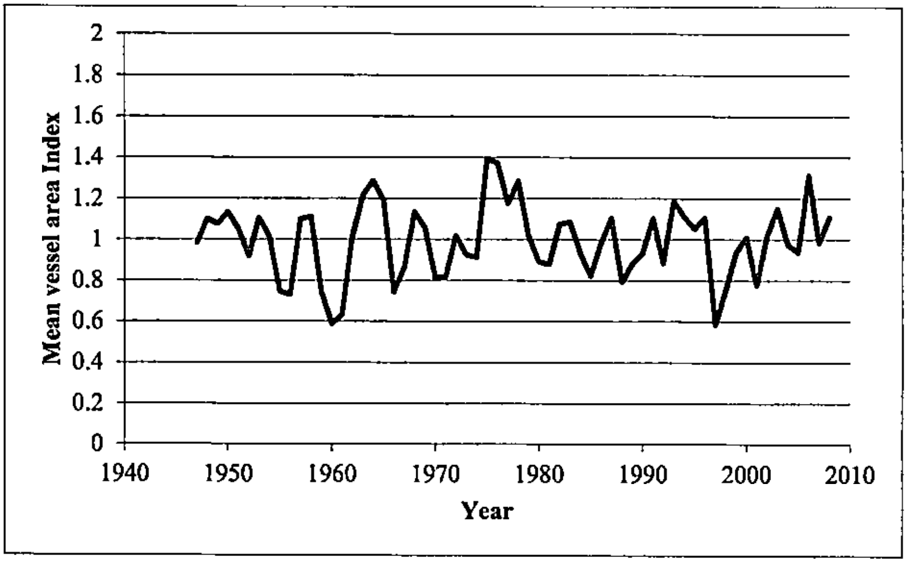


Fig.19 Mean vessel area index chronology of *Tectona grandis* at Vazhani

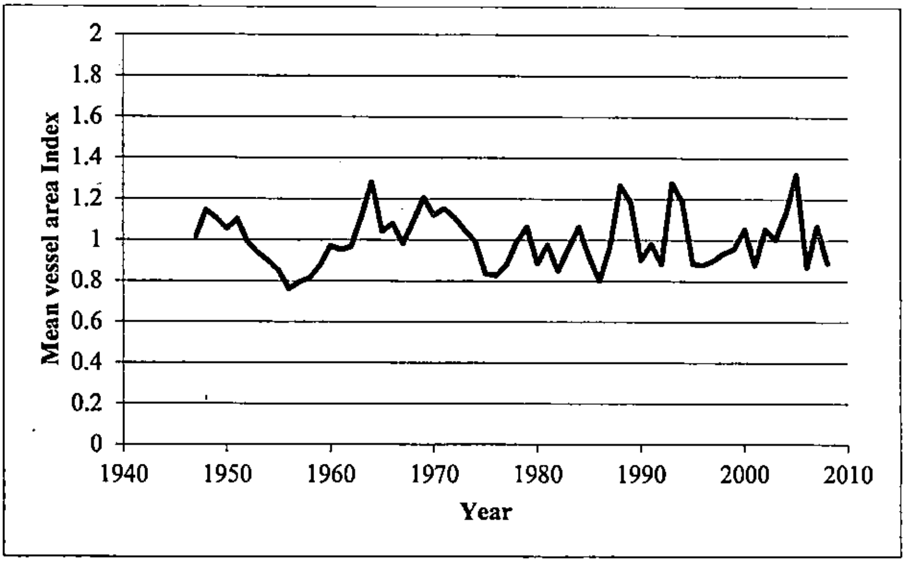


Fig.20 Mean vessel area index chronology of *Tectona grandis* at Ponganamkadu

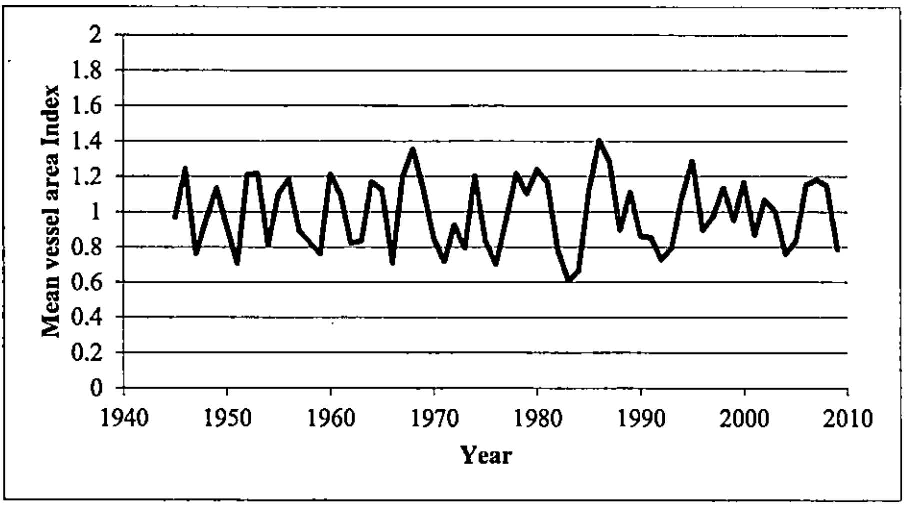


Fig.21 Mean vessel area index chronology of *Tectona grandis* at Karikadam

4.5 Tree growth- Climate relationship

4.5.1 Elanad (10^0 37' N, 76^0 22' E, 93.87m MSL)

4.5.1.1 Ring width Index and climate

The correlation analysis between ring width index chronology and rainfall from Elanad indicates that south west monsoon of the previous year (r =0.218) and annual rainfall (r =0.345) showed a significant positive association with ring width index (Table 7). The correlation analysis between ring width index chronology and temperature from Elanad showed no significant association among the variables.

4.5.1.2 Mean vessel area index and climate

Mean vessel area (MVA) index shows significant positive correlation with rainfall of north east monsoon (r= 0.311) and annual rainfall (r= 0.284; Table 7). The MVA index also has significant positive correlation with October-November temperature (r= 0.292).

4.5.2 Vazhani (10^0 36' N, 76^0 10' E, 53.30m MSL)

4.5.2.1 Ring width Index and climate

The south west monsoon, north east monsoon and annual rainfall did not show any significant correlation with the ring width index at Vazhani (Table 8). The summer rainfall how ever showed a negative correlation with the ring width index (r= -0.321). The October-November temperature also had a negative association with the ring width index chronology of Vazhani (r= -0.156).

Table 7. Correlation coefficients between tree-ring index chronology, rainfall and temperature during different seasons for Elanad

Index	Climatic variable	Seasons						
		-JJAS	-ON	JJAS	ON	DJF	MAM	ANN
Ring width	Rainfall	0.218*	-0.134	0.141	-0.142	0.264	-0.003	0.345*
	Temperature	-0.064	-0.093	-0.083	0.153	-0.061	-0.190	-0.080
Mean vessel area	Rainfall	-0.003	0.196	-0.054	0.311*	-0.169	0.079	0.284*
	Temperature	-0.098	0.292*	-0.018	0.154	0.004	0.023	0.030

*Significant at 5% level

-JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Table 8. Correlation coefficients between tree-ring index chronology and rainfall and temperature during different seasons for Vazhani

Index	Climatic variable	Seasons						
		-JJAS	-ON	JJAS	ON	DJF	MAM	ANN
Ring width	Rainfall	0.063	0.110	0.039	0.105	0.145	-0.321*	0.094
	Temperature	0.093	-0.156*	0.026	0.046	0.018	-0.079	0.010
Mean vessel area	Rainfall	-0.103	0.030	0.273	0.028	0.096	-0.148	0.309*
	Temperature	-0.023	0.260*	-0.008	-0.006	0.013	-0.108	-0.032

*Significant at 5% level

-JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

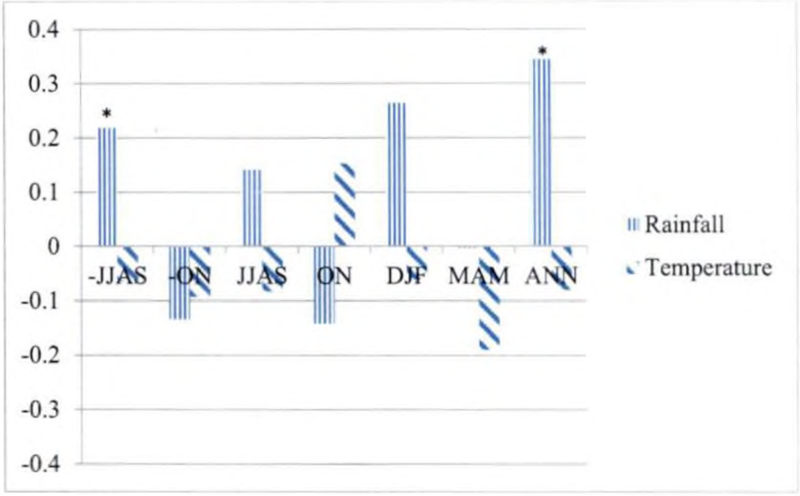
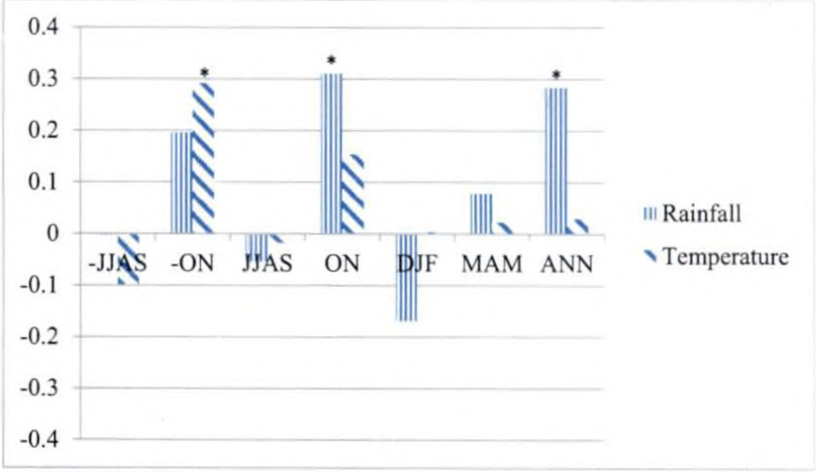


Fig. 22 Correlation between ring width index and climate during different seasons at Elanad



*significant at 5% level; -JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Fig. 23 Correlation between mean vessel area index and climate during different seasons at Elanad

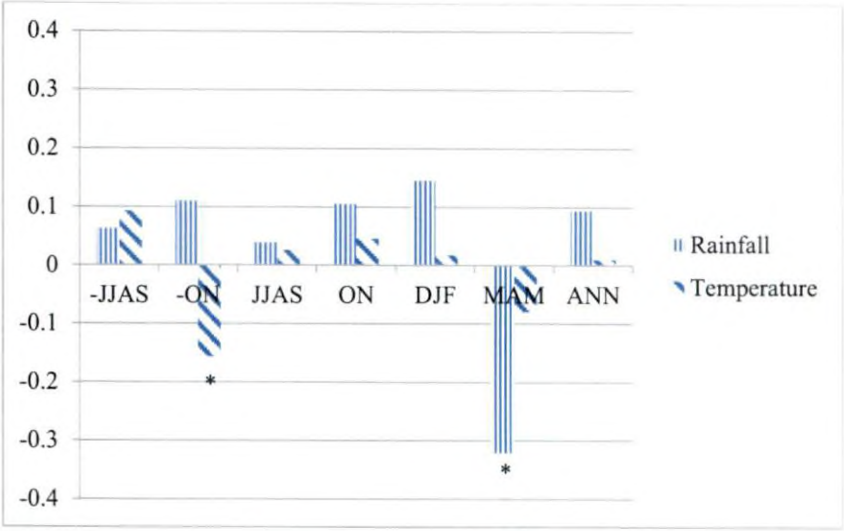
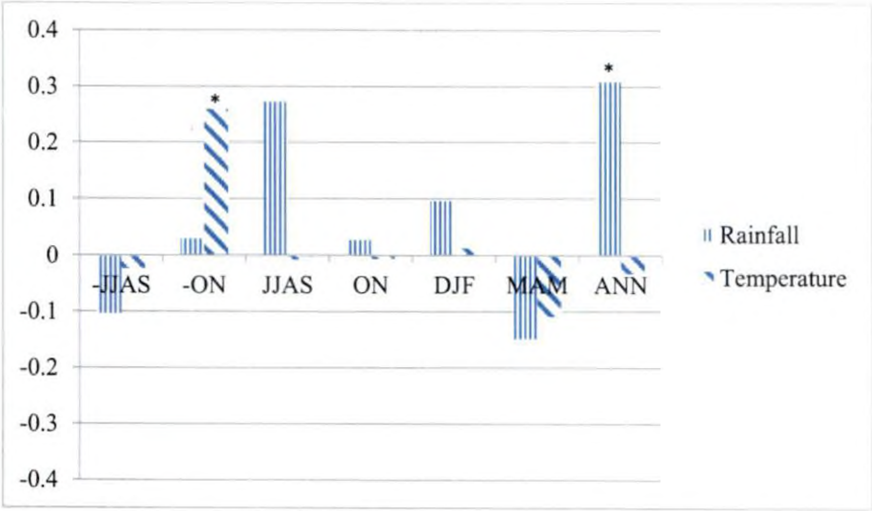


Fig. 24 Correlation between ring width index and climate during different seasons at Vazhani



*significant at 5% level; -JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Fig. 25 Correlation between mean vessel area index and climate during different seasons at Vazhani

4.5.2.2 Mean vessel area index and climate

The Vazhani mean vessel area index showed a positive association with annual rainfall (r= 0.273). The chronology also revealed that there exists a significant positive correlation between mean vessel area index of Vazhani (Table 8) and previous year October- November temperature (r= 0.260).

4.5.3 Ponganamkadu (10^0 14' N, 76^0 15' E, 42.97m MSL)

4.5.31. Ring width Index and climate

The ring width index at Ponganamkadu was positively correlated with previous monsoon rainfall (r= 0.354) and previous north east monsoon rainfall (r= 0.324). The winter and annual temperatures showed a positive correlation of 0.270 and 0.179 respectively (Table 9).

4.5.3.2 Mean vessel area index and climate

The rainfall of previous monsoon had a significant positive correlation with mean vessel area index of Ponganamkadu (r= 0.240). The summer temperature was negatively correlated (r= -0.228) with the MVA index chronology (Table 9).

4.5.4 Karikadam (10^0 29' N, 76^0 20' E, 47.54m MSL)

4.5.4.1. Ring width Index and climate

The previous north east monsoon had a significant positive correlation with r= 0.139. The previous year north east monsoon and north east monsoon were negatively correlated with the ring width index with correlation coefficients -0.446 and - 0.477 respectively (Table 10).

Table 9. Correlation coefficients between tree-ring index chronology and rainfall and temperature during different seasons for Ponganamkadu

Index	Climatic variable	Seasons						
		-JJAS	-ON	JJAS	ON	DJF	MAM	ANN
Ring width	Rainfall	0.354*	0.324*	-0.054	-0.030	-0.030	0.203	0.201
	Temperature	0.161	-0.070	0.129	0.115	0.270*	0.096	0.179*
Mean vessel area	Rainfall	0.240*	0.061	-0.022	0.058	0.112	0.100	0.014
	Temperature	-0.052	0.099	-0.039	0.056	0.043	-0.228*	-0.032

* Significant at 5% level

-JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Table 10. Correlation coefficients between tree-ring index chronology and rainfall and temperature during different seasons for Karikadam

Index	Climatic variable	Seasons						
		-JJAS	-ON	JJAS	ON	DJF	MAM	ANN
Ring width	Rainfall	-0.075	0.139*	0.009	-0.029	-0.080	-0.150	-0.039
	Temperature	-0.446*	-0.175	-0.477*	-0.254	-0.320	-0.416	-0.457
Mean vessel area	Rainfall	0.300*	0.0729	-0.137	0.310*	-0.131	-0.005	0.333*
	Temperature	0.087	0.038	0.169	0.320*	-0.002	0.008	0.266*

* Significant at 5% level

-JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

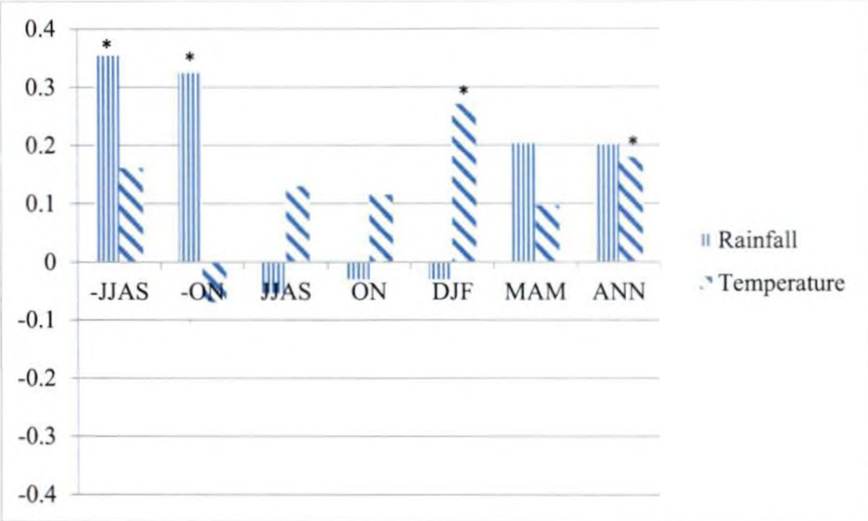


Fig. 26 Correlation between ring width index and climate during different seasons at Ponganamkadu

*significant at 5% level; -JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Fig. 27 Correlation between mean vessel area index and climate during different seasons at Ponganamkadu

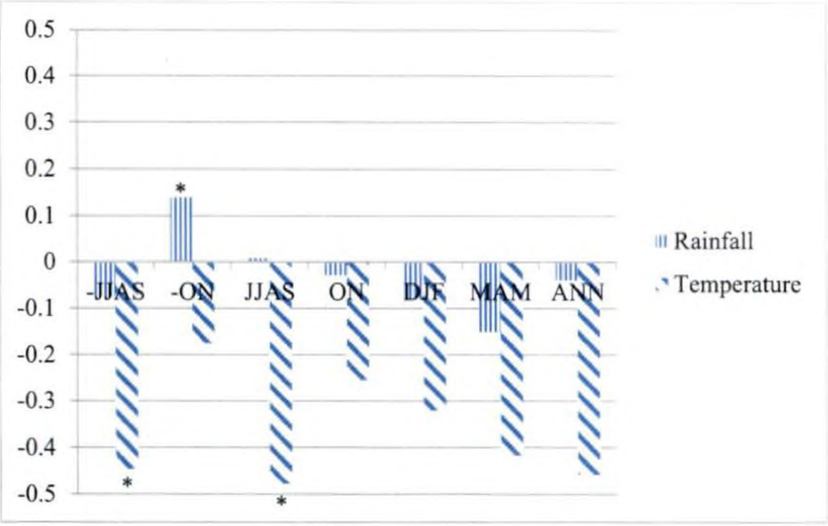
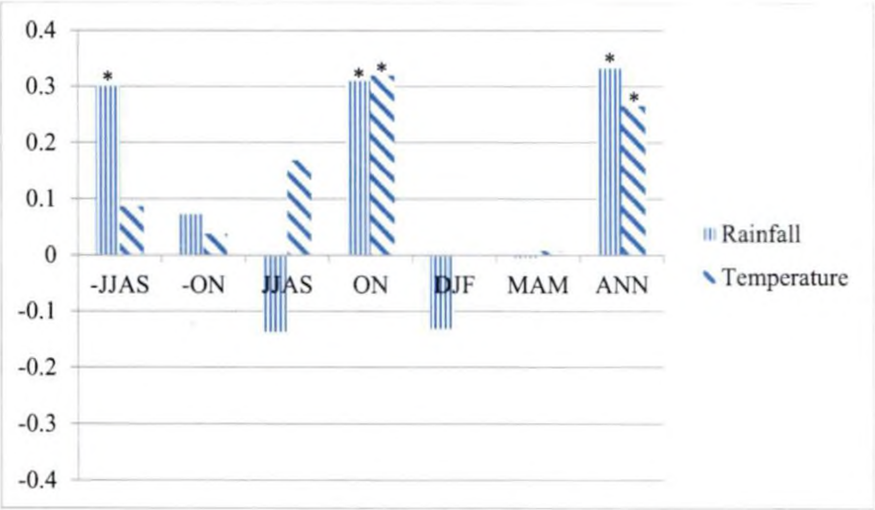


Fig. 28 Correlation between ring width index and climate during different seasons at Karikadam



*significant at 5% level; -JJAS: Previous south west monsoon; -ON: Previous north east monsoon; JJAS: Southwest monsoon; ON: North east monsoon; DJF: Winter; MAM: Summer; ANN: Annual

Fig. 29 Correlation between mean vessel area index and climate during different seasons at Karikadam

4.5.4.2 Mean vessel area index and climate

Mean vessel area index chronology of Karikadam indicated a positive significant correlation of 0.300 with previous south west monsoon, with north east monsoon (r = 0.310) and also with annual rainfall with a correlation coefficient of 0.333 (Table 11). The chronology showed a significant positive correlation with north east monsoon temperature (r= 0.320) and annual temperature (r= 0.266).

DISCUSSION

DISCUSSION

A detailed dendroclimatological investigation on teak (*Tectona grandis*) in selected locations in Thrissur forest division and also from Chalakudy forest division of Kerala was taken up in the present study. The results obtained showed that there is significant correlation between tree growth and climate in all the four study sites. The salient findings of the study are discussed hereunder.

5.1 Ring width

The ring width at all four study sites showed an age related growth trend in which initial rate of growth was high. Also, with increase in age, the average ring width decreased at all the four study sites. The average raw ring widths and its trend in samples fitted with a smoothing spline curve from the four sites are shown in fig. 2-5. The highest average raw ring width was observed in Vazhani (5.56 mm) and the lowest was at Karikadam (3.36 mm) while those of Elanad (4.66 mm) and Ponganamkadu (4.98mm) were intermediate. The ring width data of Elanad showed highest standard deviation of (3.70) and the Karikadam ring width data showed the least standard deviation (1.96).

Deepak et al. (2010) reported average raw ring width from other sites in Peninsular India such as 57 year old teak from Dandeli (2.15mm) and 59 year old teak from Shimoga (3.10mm). Similarly Sinha et al. (2011) who studied 57 year teak from Mundagod (Karnataka) and 130 years old teak from Chandrapur (Maharashtra) found that average raw ring widths were 2.14 mm and 2.97 mm respectively. These teak samples were slow grown compared to the study sites in the present investigation, whereas Margaret and Bernard (2003) reported average ring width of 30 year old teak from two different sites of Puerto Rico as 5.33 mm at Rio Abajo and 5.59 mm at

Sabana. Site-level and age differences produce significant variation in tree-ring width series (Brookhouse and Brack, 2008). It is reported that the location factor contributes 31.4 % for variability in teak growth (Purkayastha and Satyamurthi, 1975). The sites located in Karnataka and Maharashtra experiences low rainfall compared to that of Kerala, while the Puerto Rican sites are high rainfall areas. The site factors such as differences in moisture and nutrient availability and also the age have contributed to the differences in average ring widths.

5.2 Mean vessel area

The mean vessel area (MVA) obtained from the tree rings from the four study sites were in the order Ponganamkadu (47250 μm^2) > Vazhani (41020 μm^2) > Elanad (37319 μm^2) > Karikadam (23096 μm^2). The mean vessel area from Ponganamkadu showed highest amount of variation while that of Karikadam showed the least variation as is evident from their SD values. Both ring width and mean vessel area showed similar pattern in Karikadam only. Mean vessel area did not show a similar pattern as compared to ring width in the other three sites. The vessel parameters in teak are different from those of tree- ring width (Pumijumnong and Park, 1999).

5.3 Tree ring chronologies

5.3.1 Ring width index chronology

The statistical properties of ring-width-index chronologies from the four sites were assessed for their dendroclimatic potential. The Karikadam ring width index chronology showed highest mean correlation among all radii (0.452) followed by Elanad (0.422), Ponganamkadu (0.363) and Vazhani (0.219) chronologies. The mean correlation between trees was high in Elanad ring width index chronology (0.767), followed by Ponganamkadu (0.699), Vazhani (0.693) and Karikadam (0.581) chronologies.

To estimate the tree-ring index confidence, several statistics are being used such as the Signal-to-Noise Ratio (SNR), Expressed Population Signal (EPS) etc. Index signal-to-noise ratio has been used to evaluate the relationship strength of the common variance signal in tree-ring indices (Cook and Kairiukstis, 1990). SNR values are often quoted as a measure of index quality and it has no upper bounds. Signal to noise ratio (SNR) > 1 indicates the signal in tree rings are more useful than the noise. The value of SNR is moderately high for all the four ring width index chronologies with the highest SNR of Elanad chronology (6.90) followed by Ponganamkadu (6.29), Vazhani (6.24) and Karikadam chronologies (5.23).

The expressed population signal (EPS) is used to measure how well the finite-sample index compares with the theoretical population index based on an infinite number of trees (Cook and Kairiukstis, 1990). EPS ranges from 0 to 1.0, which means from no agreement to perfect agreement with the population index. In the lower running-EPS plot, a value of 0.85 is plotted as a rough cut off point for accepting EPS. EPS values below 0.85 may be considered unacceptable. Wigley et al. (1984) suggested that chronologies with expressed population signal (EPS) $\geq$ 0.85 can be accepted as reliable chronology for dendroclimatic analysis. The value of EPS is also moderately higher for all the ring width index chronologies. All chronologies have the acceptable range of EPS values such as 1.233 for Elanad, 1.307 for Vazhani, 1.301 for Ponganamkadu and 1.419 for Karikadam ring width index chronology.

5.3.2 Mean vessel area index chronology

In the case of mean vessel area index chronology, Elanad (0.645) ring width index chronology showed highest mean correlation among all radii, followed by Vazhani (0.631), Ponganamkadu (0.533) and Karikadam (0.525) chronologies. The mean correlation between trees was highest at Vazhani (0.755) followed by Ponganamkadu (0.747), Elanad (0.638) and Karikadam mean vessel area index chronologies (0.588).

The value of SNR for ring width index chronologies of the four study sites is moderately high. SNRs were in the order Vazhani (6.79) > Ponganamkadu (6.72)> Karikadam (5.29) > Elanad (5.61). Also, the value of EPS is moderately higher for all the mean vessel area index chronologies. All chronologies have the acceptable range of EPS values as 1.362 for Elanad, 1.245 for Vazhani, 1.253 for Ponganamkadu and 1.412 for Karikadam. The chronology suitable for dendroclimatic study is generally believed to have good correlation between trees, high standard deviation, high SNR, and high EPS. Moderately high values of standard deviation, EPS and mean correlation among all the tree samples indicate the high dendroclimatic potential of these local ring width and mean vessel area index chronologies from Thrissur and Chalakudy forest divisions in Kerala.

5.4 Tree growth – climate relationship

5.4.1 Ring width Index and rainfall

The ring width index chronology of all the four sites showed significant correlation with the previous year south west monsoon, previous year north east monsoon, summer and annual rainfall at different sites. The monsoon as well as the total annual rainfall indicates significant positive relationship with tree-ring width variations (Bhattacharyya et al., 1992). The previous south west monsoon has the highest significant correlation (0.354) with the Ponganamkadu ring width index chronology followed by Elanad chronology (0.218). The chronologies from Ponganamkadu and Karikadam were correlated with previous north east monsoon with correlation values of 0.324 and 0.139 respectively.

The current year south west monsoon did not show any association with ring width index chronologies from any site. The north east monsoon and winter rainfall also did not show any significant correlation with the ring width index chronologies derived from the four sites. Positive tree growth and climate relationship during previous June-September suggests that the southwest monsoon rainfall plays an important role in the growth of teak. Besides, rainfall during October-November, the north east monsoon, of the previous year also plays an important role.

Earlier tree ring studies of teak from peninsular India showed that rainfall of the previous year's rainy season and the usual onset month of the current year's rainy season has significant relation to teak growth (Deepak et al., 2010; Sinha et al., 2011). Similar observations were also made by Shah et al. (2007) and Ram et al. (2008) who found significant relationship between monsoon rainfall and radial growth of teak from central India. This indicates that the moisture balance of the soil before the beginning of the next year growing season is important for teak growth.

The ring width chronology from Ponganamkadu has highest correlation with previous north east monsoon (0.324). This might be due to mobilization of stored nutrients that aid in the initiation of growth for the coming growing season. The summer (March-May) rainfall was negatively correlated (-0.321) only with the Vazhani ring width index chronology, while other sites had no significant relationships. The inverse relationship with summer rainfall might be due to lower net photosynthetic rate, presumably due to higher evapotranspiration (Sinha et al., 2011). During these months, rainfall is less, but temperature is at its maximum in the region. Thus, increased rainfall during the hot summer accelerates the rate of evapotranspiration, which might have caused water stress-like conditions for teak trees (Shah et al., 2007). The annual rainfall was correlated with only Elanad ring width index chronology and no other chronologies. Ram et al. (2008) has also reported significant relationship between annual rainfall and ring width index.

5.4.2 Ring width index and temperature

The temperature at the study sites did not show much association with the ring width index chronologies as compared to rainfall. The chronology was negatively correlated with previous October-November temperature at Vazhani (-0.156) and with previous

June-September temperature (-0.446) and current June- September temperature (-0.477) at Karikadam.

Teak grown in Bori, central India showed negative correlation with current year's October-November temperature and annual temperature (Ram et al., 2008) but Margaret and Bernard (2003) reported that the best predictors of growth of teak in Puerto Rico are July and November temperatures. Higher temperature cause increased evaporation and evapotranspiration, which reduces soil moisture availability during subsequent growing season. In addition, higher temperature can be limiting to both photosynthesis and respiration (Fritts, 1976). The optimum temperature for net photosynthesis may also vary throughout the season, and from site to site, depending on prior light intensities, moisture availability which precondition the tree (Fritts, 1976) and therefore, the negative response of temperature observed in the analysis.

The Ponganamkadu ring width index chronology had significant positive correlation with December-February (0.270) and annual temperature (0.179). Earlier studies have suggested that temperature of the current year during March have positive influence on the growth of teak and annual temperature had negative influence respectively (Sinha et al., 2011). The results of the present study are different from early reports. This may be due to the presence of more moisture prevailing in the site.

5.4.3 Mean vessel area index and rainfall

The mean vessel area index (MVA) chronology of all the four sites had significant correlation with the previous year south west monsoon, north east monsoon and annual rainfall. The MVA chronology had significant positive correlation with previous year south west monsoon at Ponganamkadu (0.240) and Karikadam (0.300). The north east monsoon showed correlation with Elanad (0.311) and Karikadam (0.310) MVA chronologies. Also, the annual rainfall was significant positively correlated with Elanad, Vazhani and Karikadam chronologies. The findings agree with the views of Bhattacharya et al. (2007) who suggested that rainfall during October and November (north east monsoon) of the previous year and April of the current year is the most important climatic variable in developing the early wood vessel of an annual ring and deviates from the findings of Pumijumnong and Park (1999). They found that vessel area of the total ring was negatively correlated with current April rainfall and positively correlated with current May rainfall. The mean lumen area of earlywood vessels in oak was smaller in drought years (Eilmann et al., 2006).

The vessel lumen area is an indicator of the water availability at the time of cell differentiation (Sass and Eckstein, 1995). From these records, it appears that early wood vessel development in teak starts around March and ceases during June, and by the first week of October there is no wood formation. The increased soil moisture at the beginning of the dry season also favours the physiological processes of the tree during subsequent growing season (Priya and Bhat, 1997). Moisture availability at the root zone before the growing season is favourable in the tree's growth process. Stored energy of the previous year's growth and water availability at the beginning of the growing period are also important for the development of teak tree vessels.

5.4.4 Mean vessel area index and temperature

The mean vessel area indices of the study sites showed significant positive correlation with previous October-November temperature, March-May temperature, October-November temperature and annual temperature. The MVA index chronology has significant positive association with previous October- November temperature at Elanad (0.292) and Vazhani (0.260). The index has significant positive correlation with October-November temperature (Karikadam; 0.320) and with annual temperature (Karikadam; 0.266). Significant negative correlation was shown between summer temperature (-0.228) and Ponganamkadu mean vessel area index chronology In *Castanea sativa*, mean monthly temperature and mean vessel lumen area was most closely related to March and June temperature (Garcia and Fonti, 2006). Increased temperature during pre-monsoon month was found to have an important role in the initiation of cambial activity (Bhattacharya et al., 2007). The relationship between previous year north east monsoon and north east monsoon with mean vessel area as observed in this study show deviation from the earlier studies. The above association with temperature signal and vessel enlargement can be explained by the fact that wood formation is the result of a complex system of internal plant signals which are regulated by the environment (Fonti et al., 2006).

5.5 Conclusion

The present study shows significant relationship between climate, ring width and mean vessel area (MVA) of teak and these parameters have prospect for climatic reconstruction of the study area. Both temperature and rainfall influence ring width in teak whereas temperature, rainfall during summer influence ring width and MVA. The significant relationship between MVA of teak and rainfall of the study sites suggests that it can be used as a proxy for reconstruction of precipitation data of south west and north east monsoons in Kerala. Tree-ring analysis of teak from Kerala has great importance since it adds novel information to understanding the chronological variability in the growth of teak with changes in climate. This study validates the earlier findings that the pattern of radial growth in teak varies with the local edaphic and climatic conditions, mainly rainfall, relative humidity and different locations and plays a significant role in influencing the growth of teak.

The long-term chronology from different sites of Kerala can be developed and will help in understanding long-term monsoon variability over longer time-spans. A wide network of tree-ring data from this region might be useful to study past environmental history including past fire and earthquakes.

SUMMARY

SUMMARY

Dendroclimatological investigations on teak (*Tectona grandis*) in Thrissur forest of Kerala was conducted in the Department of Wood Science, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur. Results of the investigations are summarised below.

- There exists a significant tree growth-climate relationship from all the four sites and the tree ring chronologies of teak have good dendroclimatic potential of these study sites.

- The highest average raw ring width was recorded in Vazhani (5.56 mm) of Thrissur forest division and the lowest was at Karikadam (3.36 mm) of Chalakudy forest division.

- The highest mean vessel area (MVA) was obtained from Ponganamkadu (47250 μm^2) of Thrissur forest division and the lowest from Karikadam (23096 μm^2) of Chalakudy forest division.

- Ring width index chronologies showed highest mean correlation among all radii at Karikadam (0.452) and the lowest at Vazhani (0.219). Mean correlation between trees was the highest in Elanad (0.767) and the lowest in Karikadam (0.581).

- The value of signal to noise ratio (SNR) in ring width index chronologies was highest in Elanad (6.90) and lowest in Karikadam (5.23). The expressed population signal (EPS) value for ring width index chronologies was highest in Ponganamkadu (1.419) and lowest in Karikadam (1.301).

- In the case of mean vessel area index chronology, Elanad (0.645) gave highest mean correlation among all radii while Karikadam (0.525) gave the lowest.

The mean correlation between trees was the highest at Vazhani (0.755) and lowest at Karikadam (0.588).

- SNR value in mean vessel area index chronologies was highest in Vazhani (6.79) and lowest in Elanad (5.61). The EPS value for mean vessel area index chronologies was highest in Elanad (1.362) and the lowest was in Karikadam (1.412).

- The ring width index chronologies showed significant positive correlation with the previous year south west monsoon, previous year north east monsoon, annual rainfall and significant negative correlation with summer rainfall.

- The ring width index chronologies were negatively correlated with previous October-November temperature, previous June-September and current June-September temperature.

- The mean vessel area index (MVA) chronologies of the study sites had shown significant positive correlation with the previous year south west monsoon, north east monsoon and annual rainfall.

- Significant positive correlation was obsereved between mean vessel area indices of the study sites with previous October-November temperature, October-November temperature and annual temperature.

- Significant negative correlation was observed between mean vessel area index chronology and March-May temperature.

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DENDROCLIMATOLOGICAL INVESTIGATIONS ON TEAK (*Tectona grandis* L. F.) IN THRISSUR FOREST DIVISION OF KERALA

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ABSTRACT

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ABSTRACT

In a study entitled "Dendroclimatological investigations on teak (*Tectona grandis* L. f.) in Thrissur forest division of Kerala, conducted in the College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur, the dendroclimatic potential of ring width and mean vessel area of teak was assessed at four study sites. The ring width index chronologies were positively correlated with the previous year south west monsoon, previous year north east monsoon, annual rainfall, whereas negatively correlated with summer rainfall, October-November temperature, previous June-September and current June- September temperature. The mean vessel area index (MVA) chronologies showed significant positive correlation with the previous year south west monsoon, north east monsoon, annual rainfall, previous October-November temperature, October-November temperature and annual temperature whereas a significant negative correlation was observed between mean vessel area index chronology and March-May temperature. In conclusion the tree ring chronologies of teak have good dendroclimatic potential in Thrissur and Chalakudy experiencing typical tropical climate.