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

By

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(2012-27-102)

THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Dendroclimatological investigations on teak (*Tectona grandis* L. F.) in Nilambur (North) 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 Nilambur (North) Forest Division of Kerala"** is a record of research work done independently by **Mr. Sreejith Babu (2012-27-102)** 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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We, the undersigned members of the advisory committee of **Mr. Sreejith Babu (2012-27-102)** a candidate for the degree of **Doctor of Philosophy in Forestry** agree that this thesis entitled **"Dendroclimatological investigations on teak (*Tectona grandis* L. F.) in Nilambur (North) Forest Division of Kerala"** may be submitted by **Mr. Sreejith Babu (2012-27-102)** in partial fulfillment of the requirement for the degree.

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Sreejith

To my Family
To my God
To Time

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1. INTRODUCTION

INTRODUCTION

Tree rings are universally acknowledged as one of the most valuable proxies for paleoclimate research and ecological investigation due to their annual resolution and accurate dating method (Ma *et al.*, 2015). Around the world tree ring data has been successfully used in climatic reconstruction for the past millennia and ecological studies. Growth rings in trees serve as a useful tool for the determination of age and growth rate of the trees of managed stands (Ram *et al.*, 2011). The variability of annual radial increments is predominantly determined by the climate of the vegetation period (Kirchhefer, 1999). 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. The absence of a clear dormancy of the cambial activity fails to produce distinct growth rings resulting majority of them as 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 the 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 an 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 been reported by several workers (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 focused on analysis of the tree-ring chronologies in teak grown as plantations at Nilambur (North) 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 Nilambur.

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.

2. REVIEW OF LITERATURE

REVIEW OF LITERATURE

2.1 Tree-ring research across the world

Tree-ring chronologies are important indicators of pre-instrumental, natural climate variability. Some of the longest chronologies are from high latitudes, where ring width measurement series from living trees are combined with series from sub-fossil trees, preserved in shallow lakes, to form millennial-length records. (Duthorn *et al.*, 2013). The climate phenomena seen through tree rings have a wide range of spatial and temporal scales (Hughes, 2002). Basic methods and the underlying rationale for tree-ring analysis are well established and continue to be refined (Schweingruber, 2012). The beginning of scientific study of tree rings is generally credited to the early 1900s and to an astronomer named Andrew Ellicott Douglass (Sheppard, 2010). 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 (Sheppard, 2010). 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 (Web, 1986).

2.2 Dendroclimatological studies using ring width in temperate regions

A sizeable amount of dendroclimatological works take place in high latitude, temperate and subtropical regions of the world due to occurrence of clearly differentiable seasons and which in turn creates distinct annual rings in species present most of them being gymnosperms. The influence of precipitation, saturation deficit, relative humidity, and temperature on the growth of *Pinus sylvestris* growing on 21 different sites 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. 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) were reconstructed for Animas Mountains, and annual precipitation (July-July) and current July PDSI were reconstructed for Sierra los Ajos. However significant relationship was found between climatic variables and fire occurrence in Sierra los Ajos, apparently as a consequence of different land uses.

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. 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. 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. 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. 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. Brauning (2001) developed a network of 15 *Juniperus* species 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. 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. 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. Low precipitation was an important limiting factor for growth. 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.

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.

Cia and Liu (2013) presented the results of a dendroclimatological investigation of three coniferous tree species, *Larix principis-rupprechtii, Picea meyeri* and *Pinus tabulaeformis* growing along an altitudinal gradient at the Lüliang Mountains in Northern China. Correlation analysis indicated that the chronologies from lower to middle-high sites were highly correlated, and different species from the same site showed the highest correlation. Growth–climate analysis indicated that the chronology of *Larix principis-rupprechti* at the uppermost site near the tree line did not exhibit a significant response to the seasonal climatic factors, whereas the other four lower chronologies were consistently and significantly influenced by both the mean temperature from May to July and the total precipitation from March to June, regardless of tree species and elevation.

Mazza *et al.* (2014) observed where fir grows in optimal conditions, the most significant growth responses to climate were the positive influence of late-spring and summer precipitations of the previous year and the negative effect of summer temperatures of both previous and current year, although decreasing during the last decades. On the other hand, the site lower altitude showed a low and not very consistent climate sensitivity as compared to the preferred altitudes. At the highest site (1375 m asl) the positive effect of previous year spring–summer precipitation and summer temperature of both previous and current year disappeared

Wang *et al.* (2013) developed the ring-width chronologies of Korean pine (*Pinus koraiensis*), one of the main constructive species of Changbai Mountain in northeastern China, to examine the radial growth–climate relationships. The stability of these relationships before and after abrupt climate change was evaluated. We built regression equations to project the future growth of the species under future climate change scenarios projected by the Providing Regional Climates for Impacts Studies (PRECISs) climate model. The width chronology of Korean pine at one site was positively correlated with the precipitation in September of the previous year and June of the current year. The chronology at another site was positively correlated with the temperature in March and April of the current year. Whereas the current July temperature and the previous September precipitation were the main limiting factors for the growth of Korean pine.

Wu *et al.* (2013) did a study in the Tianshan Mountain, China about age-dependent tree-ring growth responses of Schrenk spruce (*Picea schrenkiana*) to climate. The results show that climate can account for a high amount of variance in tree-ring width and higher climate sensitivity was detected in younger trees. Younger trees (<210a) exhibit significantly negative growth responses to mean monthly air temperature of previous June and positive relationship with total monthly precipitation of current April and May, while mean monthly air temperature of current March may inhibit growth of older trees (>210a). Tree-ring chronology statistics and response function reveal that the age-growth patterns are non-monotonic. Our results together with previous studies demonstrate that the age effects on tree-ring growth–climate response is attributed to a combination of genetic characteristics and site microclimate/.

Galvin *et al.* (2014) successfully constructed a 31-tree, 204-year *Taxus baccata* chronology was from Killarney National Park, southwest Ireland. The chronology exhibited promising dendroclimatological potential, with climatic responsiveness equivalent to that of the other major Irish tree taxa, including Quercus. The chronology showed the strongest relationship with May–June precipitation from Muckross House synoptic station (1970–2007; $r = 0.521$, $p < 0.01$) and Valentia Observatory (1941–2007; $r = 0.545$, $p < 0.01$). November–April temperatures also exhibited a strong relationship with the chronology post-1970 ($r = 0.605$, $p < 0.01$ for Muckross House, $r = 0.567$, $p < 0.01$ for Valentia Observatory).

Leal *et al.* (2015) made first attempt to assemble long tree-ring chronologies from Portugal potentially useful for climate reconstructions. Three oak species (*Quercus pyrenaica*, *Quercus faginea*, and *Quercus ilex*) were sampled at three sites in southern Portugal to obtain tree-ring chronologies. The longest tree ring series covers 173 years extending back to 1840. The tree-ring records showed, depending on the site, moderate-to-high correlations with precipitation in different seasons (from $r = 0.40$, $p < 0.01$, to 0.81, $p < 0.001$) and temporal stability in the growth/climate relationship for two sites. Calibration-verification trials confirmed the reliability of climate/growth models for climatic reconstructions back to periods represented by tree-ring records from these two sites. The results are a promising kick-off for Portuguese dendroclimatology, since they represent a significant breakthrough in the Mediterranean region, especially for Iberian Peninsula, where there is a considerable lack of dendroclimatic reconstructions.

Parker *et al.* (2014) examined tree-ring growth in a naturally seeded old-growth slash pine (*Pinus elliottii* Engelm. var. *elliottii*) stand in coastal Georgia, USA to develop growth-climate models and reconstruct past climatic conditions during the mid and late 1800s. They used correlation and response function analysis to relate tree-ring growth to climatic variables and El Nino/Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) indices. Water availability (represented by PDSI and secondarily, precipitation) was the most important factor determining growth for all three series, with latewood and September PDSI showing the strongest relationship. Like other species in the southeastern United States, moisture in the late winter and spring was crucial for earlywood development, while latewood and annual growth was enhanced in cooler, wetter summers, particularly with hurricanes bringing rainfall late in the growing season.

2.3 Studies in tropical regions

Tree–ring analysis in the tropics exists since more than hundred years. In more than 20 tropical countries and numerous tree species the existence of annual rings is proven doubtless (Worbes, 2002). Stress factors which occur seasonally are low winter temperatures in the temperate zones and higher elevations as well as dry seasons and floodings in the tropics (Worbes, 1995). 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.* (2001) studied 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. 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.* (2005) 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.

Magre *et al.* (2014) studied on dendroclimatology of *Pinus pseudostrobus* and in the state of Michoacán (Mexico). Correlation functions indicate that the width of the rings of both species is regulated significantly by rainfall and the average maximum temperature. Both species react similarly to the climate, but with some differences. There was a positive relationship between radial growth of *Pinus pseudostrobus* and the increasing rainfall in April of the current year; and there was a negative relationship between radial growth and the increasing average maximum temperature in August the previous year. For *Pinus devoniana* there was a negative relationship between radial growth and the increasing rainfall in November of the previous year, and a positive relationship in February of the current year; and there was a negative relationship between radial growth and the increasing average of maximum temperature in July and August last year.

Paredes-Villanueva *et al.* (2015) used *Amburana cearensis*, an important timber species in tropical lowland dry forests in Bolivia, to evaluate its climatic sensitivity and to identify its potential for the reconstruction of climate. They collected eleven wood discs from randomly selected mature trees. Despite the eccentricity of the discs and existence of false and wedging rings, all samples were successfully cross-dated. The average radial growth was 0.58 cm yr−1. Significant correlation was found between the A. cearensis samples (0.34). Tree-ring width was positively correlated with monthly rainfall and negatively correlated with maximum temperatures during the 6-month rainy season (November–April). It exhibits a potential for reconstructing climate in the Bolivian Chiquitania region.

2.4 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. Target species for successful tree-ring research in India is *Tectona grandis* (Suresh, 2012). 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* 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.* (2011a) 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.

Borgaonkar *et al.* (2010) investigated on El Niño and related monsoon drought signals in 523-year-long ring width records of teak trees from south India. They presented a 523-year (A.D. 1481–2003) tree-ring width index chronology of Teak from Kerala, Southern India, prepared from three forest sites. Dendroclimatological investigations indicate a significant positive relationship between the tree-ring index series and Indian summer monsoon rainfall (ISMR) and related global parameters like the Southern Oscillation Index (SOI). A higher frequency of occurrence of low tree growth is observed in years of deficient Indian monsoon rainfall (droughts) associated with El Niño since the late 18th century. Prior to that time, many low tree growth years are detected during known El Niño events, probably related to deficient Indian monsoon rainfall. Ram *et al.* (2011b) investigated growth and climate relationship in teak trees from Conolly's plot, South India and found out significant positive association with PDSI and rainfall during the previous year monsoon (-JJAS). PDSI and rainfall reveal significantly positive relationship with both raw-ring width data and tree- ring index during pre-monsoon (MAM). In the case of temperature, the seasons showed highly significant negative correlation with raw ring-width data.

Investigations on relationship between short period chronological characters (ring width, mean vessel area) and climate (rainfall, temperature) of teak plantations in Thrissur district, Kerala were carried out by Babu *et al.* (2015). Ring width index chronologies were positively correlated with the previous year monsoons (south west and north east) and annual rainfall. They concluded that short period tree ring chronologies of teak have good potential for dendroclimatic reconstruction for Kerala.

2.5 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. 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.

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. Fonti and García-González (2006) showed that the earlywood vessel area in *Castanea sativa* is a suitable ecological indicator. The vessel size is mainly related to the temperature during two physiologically crucial periods for vessel growth: the end of the previous vegetation period (during reserve storage) and the onset of cambial activity. Fonti and García-González (2004) 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. Babu *et al.* (2015) observed mean vessel area index (MVA) chronologies of teak showed significant positive correlation with the previous year south west monsoon, north east monsoon, annual rainfall, previous year October-November temperature, October-November temperature and annual temperature in Thrissur district, Kerala. Results from various research reveal vessel parameters in total rings in early wood of teak correlated negatively with rainfall during the transition period between the dry and wet seasons (Pumijumnong, 2013). It is felt necessary to explore more trees growing in diverse geographical regions to understand the regional climate of India (Bhattacharyya and Shah, 2009).

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 and in understanding the detailed regional climatic dynamics.

3. MATERIALS AND METHODS

MATERIALS AND METHODS

3.1 STUDY SITE

The present investigation was conducted to develop tree-ring chronologies from plantation-grown *Tectona grandis* (teak) at different sites of Nilambur (North) forest division, Kerala, to understand the relationship between climate and tree growth.

Nilambur 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 followed by north east monsoon rainy season from October to November. The winter season is from December to February. Nilambur has significant rainfall during most months, with a short dry season. The temperature here averages 27.7°C. About 2666 mm of precipitation falls annually.

The study material was collected from Nilmbur (North) forest division. The 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 (KFRI, 2005). The study areas selected were located in Edakkode, Kanakuthu, Karinmpuzha and Conolly's plot (Fig. 1). The laboratory work was carried out at the Department of Wood Science, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur.

3.2 METHODOLOGY

3.2.1 Sample collection

The samples were collected from tree stumps/logs after final felling of the plantations. One basal disc (10-15 cm thick) was collected from each log. A portable chain saw was used to cut the basal discs from the left over stumps/logs, (Plate 1). Ten discs were collected from Edakkode and Kanakuthu, two from Conolly's plot and one from

Karimpuzha thus making the total samples as 23 basal discs (Table 1). For the sake of analysis from here on Karimpuzha and Conolly's plot will be considered as one site as Conollys's plot since the age of the trees were almost comparable.

Table 1. Details of the teak plantations in Nilambur (North) Division from which samples were collected.

Sl. No.	Name of Plantation	Range	Year of Planting	Age of trees at felling/ windfall (years)	Number of samples collected	Remarks
1.	Conolly's Plot near Aruvakkode	Nilambur	1841	140	2	Wind Fallen Trees
2.	Teak plantation near Karimpuzha bridge	Nilambur	1886	125	1	Leftover stump after harvesting the tree that has fallen into Karimpuzha River.
3.	Edakkode	Edavanna	1949	64	10	Final felling
4.	Kanakuthu	Edavanna	1949	64	10	Final felling

Plate 1. A. Collection of discs from Edakkode B. a disc from Conolly's plot

3.2.2 Preparation of samples

The upper surface of the basal discs, in the normal axis of the tree, collected from the field was first planed with a portable hand planer to make the surface even. Then the disc surfaces were smoothened with sand papers of grit sizes 60, 80, 150, 220, 320, 400 in selected 3 to 4 radii successively to expose the growth rings for measuring the ring width (Plate 2). For measuring the mean vessel area selected radii were further sanded with sand paper of grit sizes 600, 800, 1000 and 1500 successively. The samples were then washed with a water jet to make vessel lumen clearly visible.

3.2.3 Measurement of physical properties

3.2.3.1 Wood density

Wood density is defined as mass of wood per unit volume (Chave et al. 2009). The density was measured using the pilodyn penetration depth method which is a non-destructive method. Readings were taken from the pith, middle and periphery of the collected discs.

3.2.3.2 Heartwood-Sapwood ratio

In all cases, the heartwood was clearly distinguished from the pale coloured sapwood by a dark brown colour (Knapic et al., 2006). Heartwood-Sapwood ratio was determined by image analysis of basal discs using the software Digimizer 4.0. First, the image of the discs were captured using a good resolution digital camera and then the image was analyzed to work out the heartwood to sapwood ratio.

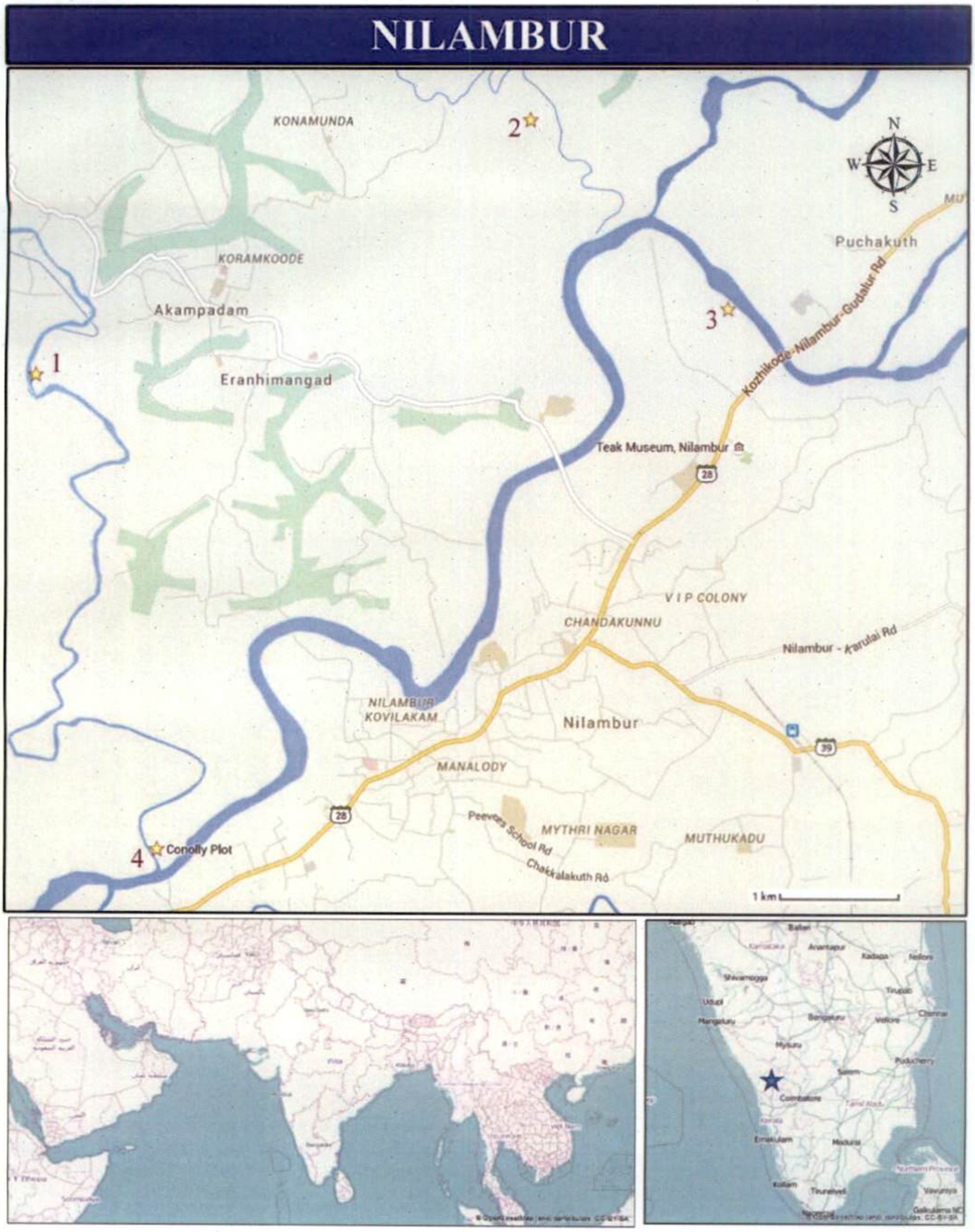

Fig 1. Nilambur map showing the study sites 1.Edakode 2. Kanakuthu 3.Karimpuzha 4.Conolly's plot

3.2.4 Measurement of ring width

The growth rings were counted and cross matched on three to four radii on each disc from specific sites after polishing. Live images of the selected rings across the radius were viewed on a computer screen using digital camera attached to a stereomicroscope (Motic) and ring widths were measured using tree ring measurement platform LINTAB-6. The ring widths (earlywood, latewood, totalwood) of each year obtained from the different radii were digitally recorded in 0.001 mm precision using TSAP Win software (Plate 3).

3.2.5 Calculation of growth rate

The growth rate was calculated from the measured output from the TSAP Win software. The rate was calculated as number of annual rings per centimeter.

3.2.6 Measurement of mean vessel area and vessel parameters

Four radii were selected from each site to measure vessel parameters (mean vessel area, vessel frequency and vessel diameter) of earlywood, latewood and total wood in each annual ring. Macro images of the selected rings with 20x zoom were captured across the radius using a digital camera fitted to a seterozoom microscope (Motic, Plate 2) and vessel area, vessel frequency and vessel diameter were measured and digitally recorded using the image analysis software Moticam Image Plus 2.0.

Plate 2. A. Polishing of wooden basal disc B. Measurement of ringwidth using tree ring station and stereo microscope

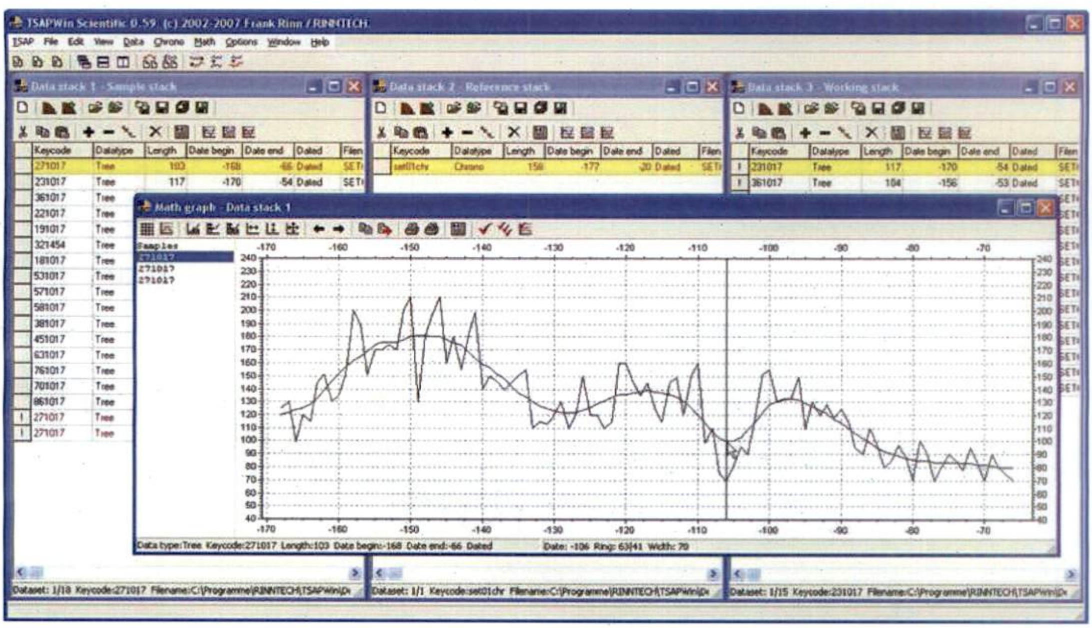

Plate 3. Screenshot of the software TSAP Win with different working stacks

3.2.7 Crossdating

The selected radii were crossdated using the procedures suggested by Stokes and Smiley (1968). Crossdating of tree ring data is used for verification of series and the elimination of possible errors and to find the correct dated position in time. After measurement, crossdating is an important step before analysis of time series. Elimination of measurement errors like removal of false rings and insertion of missing rings were done.

3.2.7.1 Skeleton plotting

The skeleton plot is the basic, traditional, simple yet unavoidable method of crossdating tree rings. It is the process of marking a tree's ring width variation on graph paper strips. Similar patterns of variation in individual plots (representing individual radius) are matched among trees and further among sites. (Stokes and Smiley, 1968)

3.2.7.2 Software-assisted crossdating

It is done using the software TSAP-Win which uses a combination of both visual (graphical) and statistical cross dating. Statistical models are excellent tools to find possible matches or to verify the dates of pre-dated time series.

3.2.7.2.1 Cross-dating parameters

In dendrochronology two main concepts are used to express the quality of accordance between time series: Gleichlaeufigkeit and/or t-values. While the t-statistic is a widely known test for correlation significance, Gleichlaeufigkeit was developed as a special tool for cross-dating of tree-ring series (Eckstein and Bauch, 1969). These concepts are characterised by a different sensitivity to tree-ring patterns. While Gleichlaeufigkeit represents the overall accordance of two series, t-values are sensitive to extreme values, such as event years. A combination of both is realized in the Cross-Date Index (CDI). Since the CDI is a very powerful parameter in cross-dating, the possible matches are ordered by descending CDI in the output in TSAP Win. Table 2 shows the crossdating parameters used with their explanations.

Table 2. Crossdating parameters used in TSAP Win software

<table>
<tr><th>Parameter</th><th>Equation</th><th>Explanation</th></tr>
<tr><td>Gleichlaeufigkeit</td><td>$Glk = \sum (y_{ij} = x_{ij})$ in %</td><td>Sum of the equal slope intervals in %</td></tr>
<tr><td>Signature Gleichlaeufigkeit (SGlk.)</td><td>$SGlk = \sum (y_{ij} = x_{ij})$ in %</td><td>Sum of the equal slope intervals in %, calculated referring to chronology signature years only</td></tr>
<tr><td>Standard Signature Gleichlaeufigkeit (_SGlk)</td><td rowspan="4">$$CC = \frac{\sum(s_i - s)*(r_i - r)}{\sqrt{\sum(s_i - s)^2 * \sum(r_i - r)^2}}$$</td><td>Sample= Sample series
Reference= Chronology</td></tr>
<tr><td>Signature Standard-Gleichlaeufigkeit (S_Glk)</td><td>Sample= Chronology
Reference= Sample series</td></tr>
<tr><td>Signature-Signature Gleichlaeufigkeit (SSGlk)</td><td>Sample= Chronology
Reference= Chronology</td></tr>
<tr><td>Cross correlation (CC)</td><td>Standard cross-correlation,
Range: -1 to +1</td></tr>
<tr><td>T-Value</td><td rowspan="3">$$t = \frac{CC * \sqrt{n-2}}{\sqrt{(1-CC)^2}}$$</td><td>Standard t-value</td></tr>
<tr><td>t-value Baillie-Pilcher (TV BP)</td><td>t-value after detrending with moving average with bandwidth =5 and logarithm to base e (Baillie and Pilcher 1973), max=100</td></tr>
<tr><td>t-value Hollstein (TV H)</td><td>t-value after detrending with the Wuchswert, max=100
$w_i = 100 * \log 10 \frac{y_i}{y_{i-1}}$</td></tr>
<tr><td>Cross Date Index (CDI)</td><td>$$CDI = \frac{G - 50 + 50 * \sqrt{\frac{overlap}{\max overlap}} * T}{10}$$
$$G = \frac{Glk + \_SGl + S\_Glk + SSGlk}{n}$$</td><td>Date index, combined from t-values and Gleichlaeufigkeit, max=1.000</td></tr>
</table>

	$T = \frac{TVBP + TVH}{2}$ (n= number of operators in the numerators)	

Table 3. Significance of Glk-value

Significance of the Glk-value	
* = 95.0%	$50 + \frac{1.654 * 50}{\sqrt{n}}$
** = 99.0%	$50 + \frac{2.326 * 50}{\sqrt{n}}$
*** = 99.9%	$50 + \frac{3.09 * 50}{\sqrt{n}}$
n=number of points *, **, ***= *levels of significance*	

3.2.7.2.2 Match condition options

Table 4. The following match condition options of the statistical parameters were selected

Minimum overlap:	Left: 30 Right: 30
Minimum density for chrono signature	4
Minimum chrono glk for signature (%)	75
Minimum Gleichlaeufigkeit for match (%)	60
Minimum Signature- Glk	70
Minimum Signature- Signature-Glk	70
Minimum T- Value for match	3
Minimum cross- correlation for match	0.6
Minimum signatures for SGlk	10
Minimum value for Date Index	10
Match conditions (logical AND/ OR)	OR

3.2.8 Chronology building

Chronologies are represented by a mean time series (average values of several different series) and additional information on density, slope behavior and is saved in Heidelberg (.fh) format. TSAP-Win chronologies contain 4 values per year. The series which are included in a chronology are called members, no matter whether they are single time series or chronologies themselves. Only dated series are included in the calculation. The values of the increasing and decreasing series refer to the slope from the preceding to the current values (Table 3).

Table 5. Chronology values in heidelberg format

Column in file	Series	Explanation
1	Value	Average of all values of implemented series in this year
2	Density	Number of all series implemented in this year
3	Increasing	Number of all increasing values in this year
4	Decreasing	Number of all decreasing values in this year

The values are calculated according to the following equation:

$$\text{Chronology value year} = \sum_{m=0}^{M} Xm + \sum_{k=0}^{K} (dk * yk)$$

d = density
M = Number of single series values included in the year (i)
K = Number of chronology series values included in the year (i)

3.2.9 Standardization

For each tree, the series of raw data were detrended and standardized using ARSTAN software (Cook *et al.*, 1990). This was done in order to remove biological and geometrical trends (age and size related growth trends). A cubic smoothing spline was used with a 50 % frequency response cutoff of 2/3 mean series length to maintain the high-to-medium frequency response to climatic variability (Cook and Peters, 1981). Autoregressive modeling was performed on each detrended ring-width series to remove most of the first-order autocorrelation, and the prewhitened series were finally averaged using a biweight robust mean to obtain residual chronology. Both standard and residual versions of the chronology were used for further analysis.

3.2.11 Dendroclimatic analysis

The relationship between climate and tree growth was examined for the period 1901 - 2012 using high resolution, 0.5^0 x 0.5^0, grid data obtained from CRU TS V. 3.21 (Harris *et al.*, 2014). Correlation analysis of tree ring data (ring width index and mean vessel area index) versus monthly, seasonal rainfall and monthly, seasonal temperature using the statistical package DENDROCLIM (Biondi and Waikul, 2002) was performed. For the analysis a dendroclimatic year of 18 months starting from June of previous year to December of current year was used. Seven 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). Bootstrapped correlation and bootstrapped response function analyses were carried out with moving intervals to find out tree growth – climate relationship.

3.2.12 Climatic reconstruction

From the response function analysis the climatic variables which has the strongest influence on tree ring parameters were selected and transfer function equations were made. Using the equations climatic data for the period which is not available from the instrumental record (1870-1900) for Nilambur were reconstructed.

4. RESULTS

RESULTS

The results of detailed investigation of tree-ring chronologies from plantation grown teak at Edakkode, Kanakuthu and Conolly's plot of Nilambur (North) forest division to understand the relationship between climate and tree growth. The results obtained from the study are presented in this chapter.

4.1 Wood density

The air dry wood density (g/cm³) estimated through non-destructive pilodyn penetration depth method of the three sites were 0.73 g/cm³, 0.75 g/cm³ and 0.84 g/cm³ for Edakkode, Kanakuthu and Conolly's plot respectively (Fig 2).

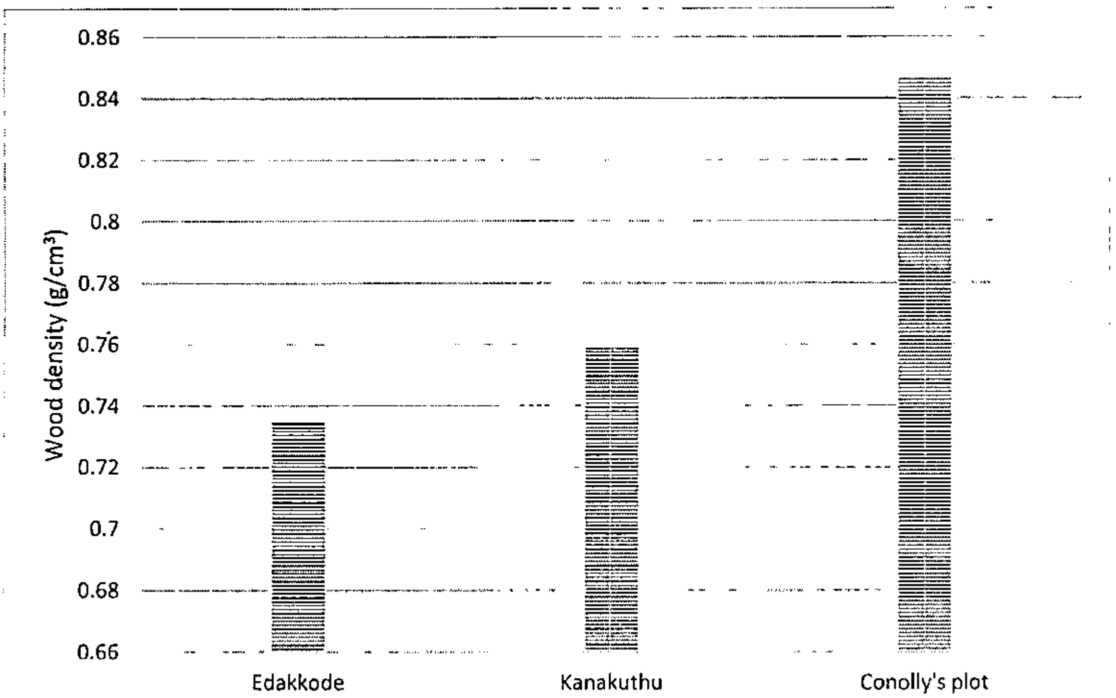

Fig 2. Air dry wood density (g/cm³) from the study sites

4.2 Heartwood-Sapwood ratio

The heartwood to sapwood ratio was highest in Conolly's plot (6.99) followed by Kanakuthu (5.71) and Edakkode (4.81) (Table 6). The heartwood percentage also followed the same pattern with Conollly's plot having the highest value of 87.49% (Fig 3) followed by Kanakuthu (85.11%) and Edakkode (82.81%)

4.3 Measurement of ring width

Edakkode had highest total and average ring widths (24.44 mm; 3.82 mm; Table 7) followed by Kanakuthu (20.51 mm; 3.20 mm) and Conolly's plot (20.52 mm; 1.46 mm). The growth rate was highest at Edakkode (0.38 rings/cm) followed by Kanakuthu (0.32 rings/cm) and Conolly's plot (0.14 rings /cm).

Table 6. Heartwood-Sapwood measurements of samples from study sites

Sl no	Study site	Heartwood area (Hw) (cm^2)	Sapwood area (Sw) (cm^2)	Total c.s area (Hw+Sw) (cm^2)	Hw/Sw ratio	Hw %
1	Conolly's	1563.29	223.49	1786.79	6.99	87.49
2	Edakkode	976.64	202.64	1179.28	4.82	82.82
3	Kanakuthu	850.41	148.73	999.15	5.72	85.11

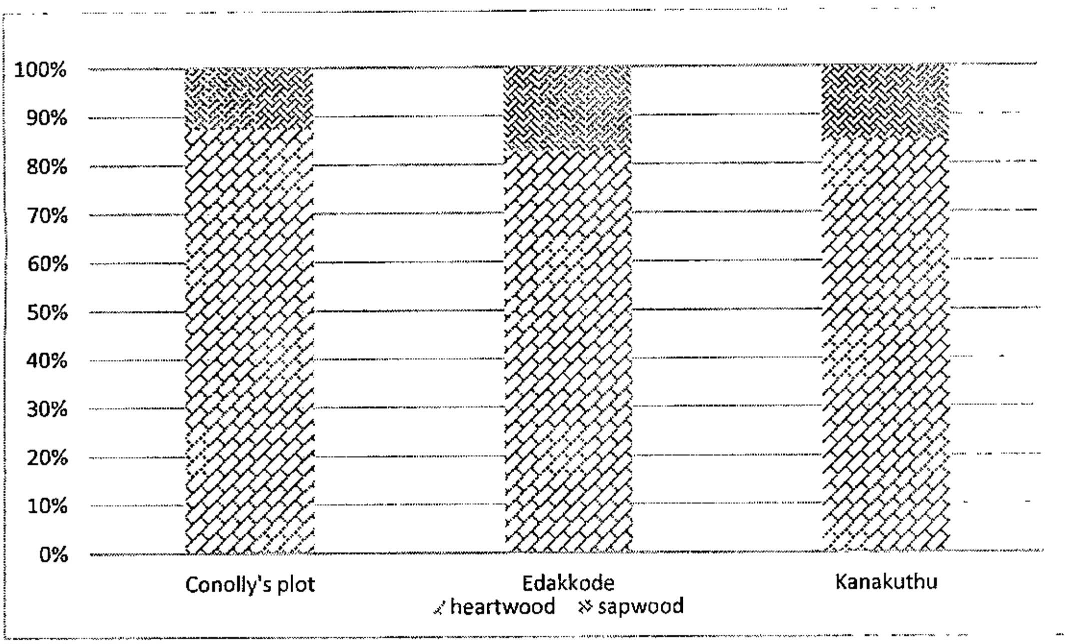

Fig 3. Heartwood-Sapwood ratio of samples from study sites

Table 7 Ring width and growth rate of samples from the study sites

	total ringwidth	average ring width	growth rate
Conolly's plot	20.527	1.466	0.1466
Edakkode	24.449	3.821	0.3821
Kanakuthu	20.514	3.205	0.3205

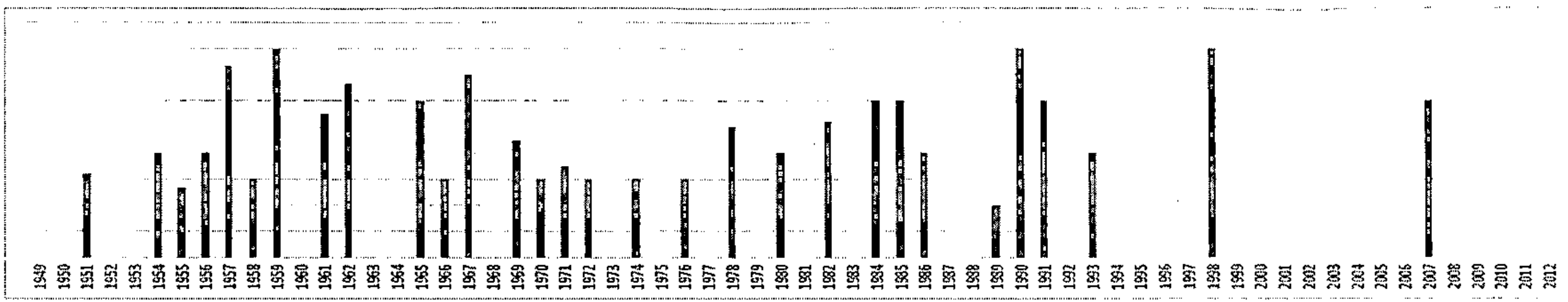

Fig 4 Skeleton plot of samples from Edakkode

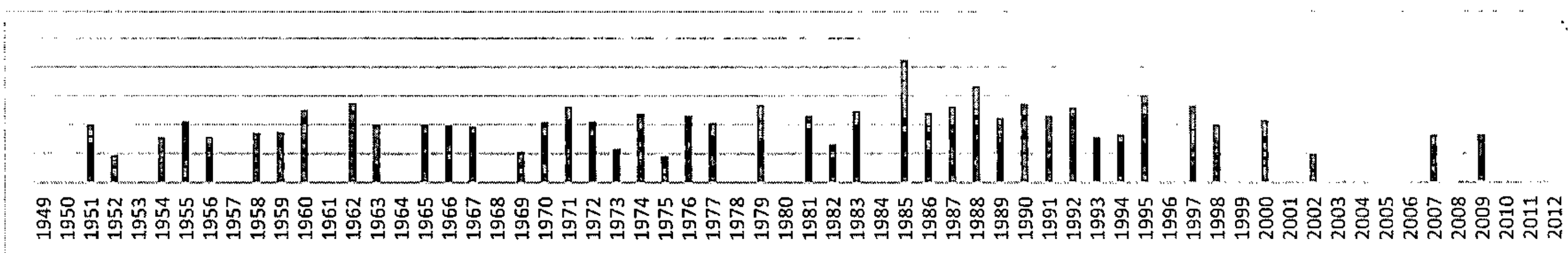

Fig 5 Skeleton plot of samples from Kanakuthu

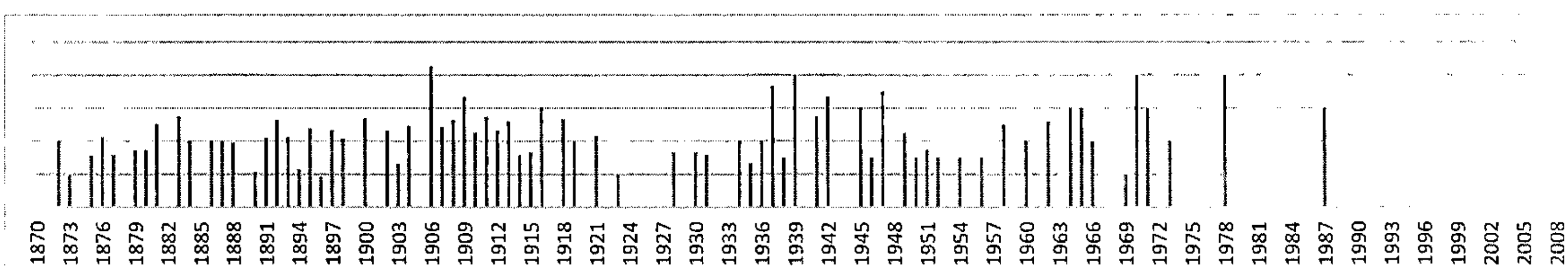

Fig 6 Skeleton plot of samples from Connolly's plot

Ring width (early wood, late wood and total) at all 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 raw ring width obtained were 3205.44μm (1823.91μm for earlywood, 1381.52μm for latewood) in Kanakuthu, 3820.27μm (2230.15μm for earlywood and 1590.11μm for late wood) in Edakkode, and 1455.87μm (834.58μm for earlywood, 621.29μm for latewood) in Conolly's plot (Table 8, Fig. 7). Average ring widths for each year from different sites are shown in figures 8 to 10. The skeleton plots of the three sites are shown in fig 4-6. Average raw ring widths and its trend in samples were fitted with a cubic smoothing spline curve using the program ARSTAN.

Table 8 Average ringwidth measured from the study sites

Sl no	Site	Early wood (μm)	Late wood (μm)	Total ring width (μm)
1	Kanakuthu	1823.91	1381.52	3205.44
2	Edakkode	2230.15	1590.11	3820.27
3	Conolly's plot	834.580	621.293	1455.87

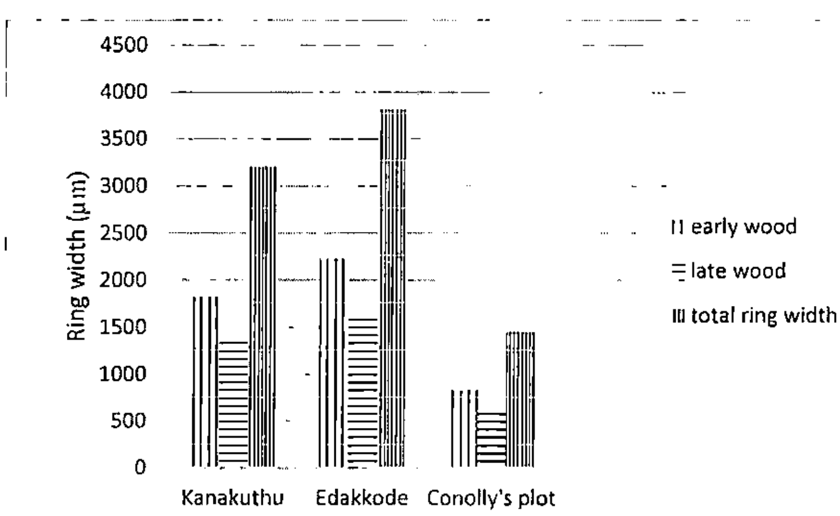

Fig 7 Average ring widths from the study sites

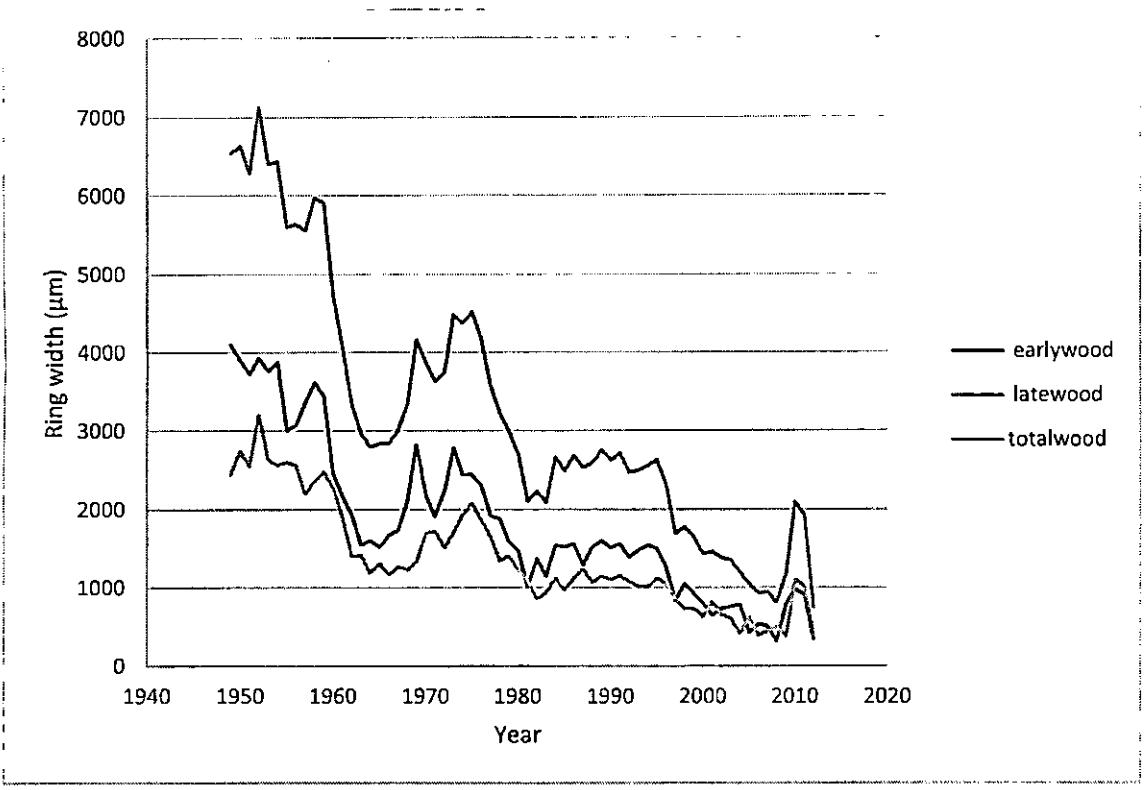

Fig 8 Average raw ringwidths at Kanakuthu

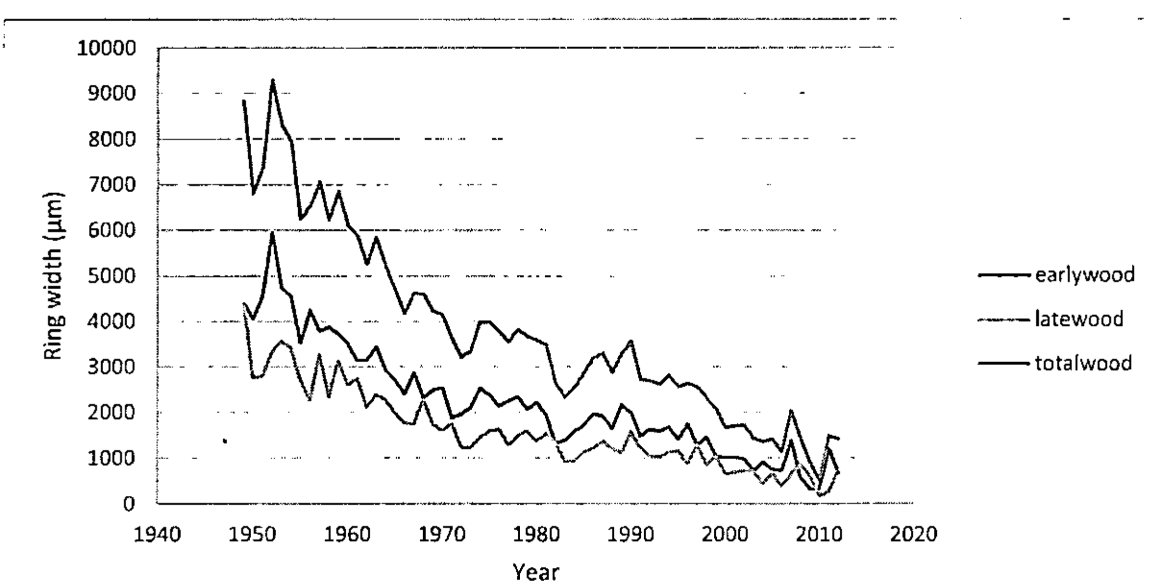

Fig 9 Average raw ring widths at Edakkode

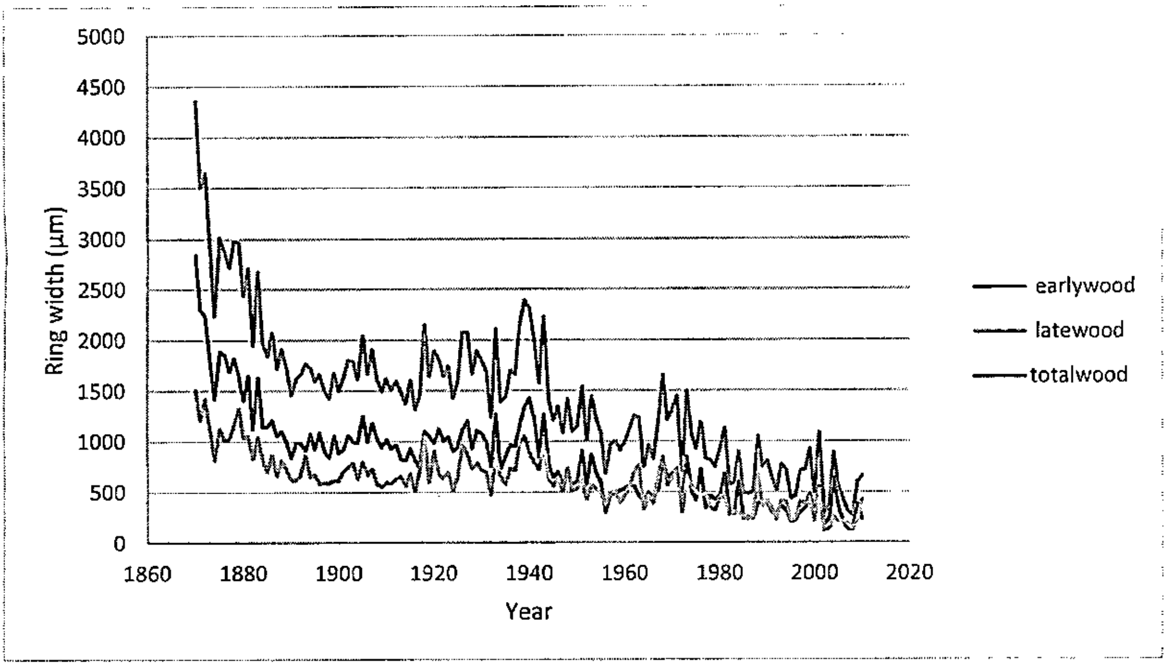

Fig 10 Average raw ringwidths at Conolly's plot

4.4 Mean vessel area

Mean vessel area also showed a different trend in ring width at all the three sites. With increase in age, mean vessel area during initial years was showing decreasing-increasing trend radially from pith to periphery. Mean vessel area for different sites are shown in table 8. The mean vessel area and its varying trend in samples later fitted with a cubic smoothing spline curve from three sites are shown in fig. 12-14. The mean vessel area obtained were 28205.27µm^2 (17640.57µm^2 for earlywood, 10564.70µm^2 for latewood) in Kanakuthu, 25241.08µm^2 (13153.23µm^2 for earlywood and 12332.82µm^2 for late wood) in Edakkode, and 34185.28µm^2 (19615.56µm for earlywood, 17346.77µm^2 for latewood) in Conolly's plot (Table 9, Fig. 11).

Table 9 Mean Vessel Area (MVA) obtained from different study sites

Sl no	Site	Earlywood MVA (μm^2)	Latewood MVA(μm^2)	Total MVA(μm^2)
1	Kanakuthu	17640.57	10564.70	28205.27
2	Edakkode	13153.23	12332.82	25486.05
3	Conolly's plot	19615.56	17346.77	36962.33

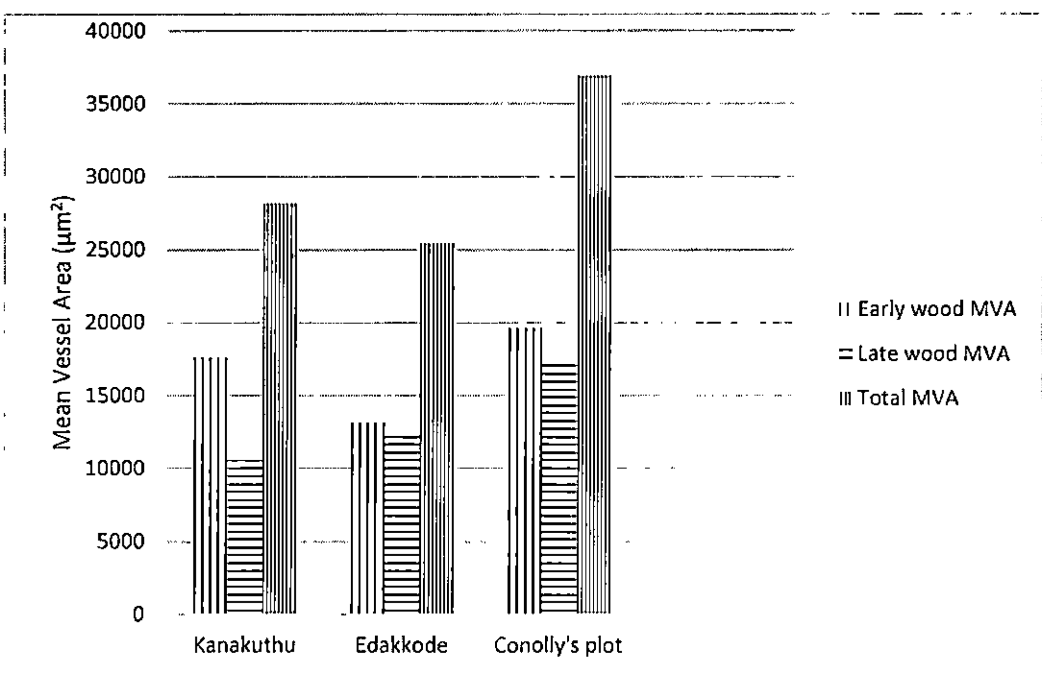

Fig 11 Mean Vessel Area (MVA) at different study sites

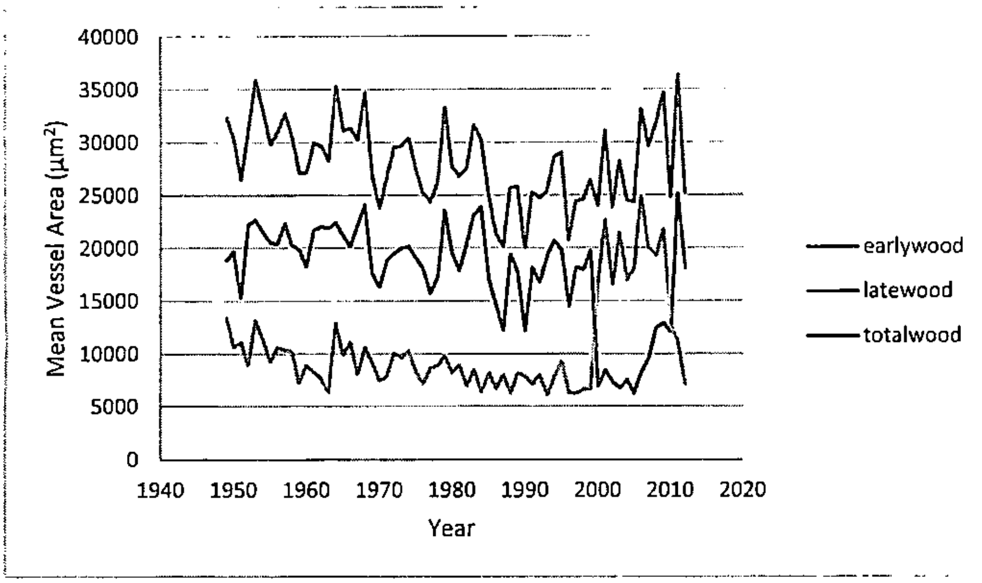

Fig 12 Mean vessel area of teak from Kanakuthu

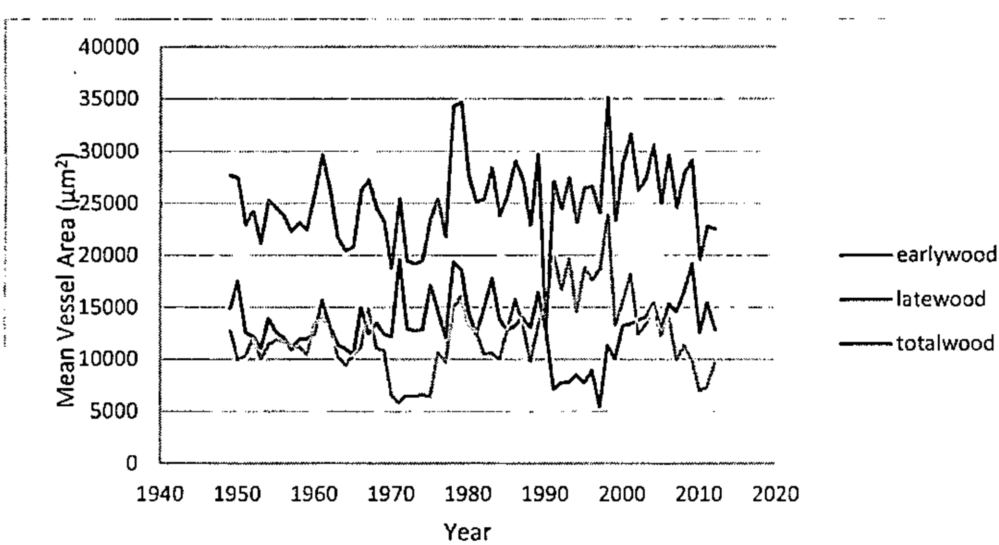

Fig 13 Mean vessel area of teak from Edakkode

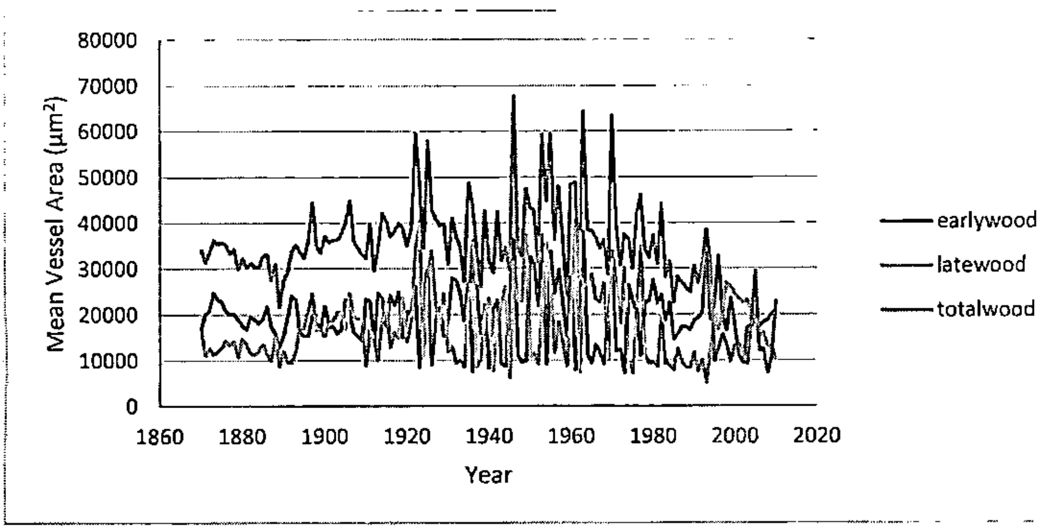

Fig 14 Mean vessel area of teak from Conolly's plot

4.5 Vessel frequency

The earlywood vessel frequency was highest at Edakkode (53) followed by Kanakuthu (31) and Conolly's plot (30). The latewood vessel frequency was highest at Edakkode (33) followed by Conolly's plot (32) and Kanakuthu (30). The totalwood frequency was also highest in Edakkode (86) followed by Conolly's plot (62) and Kanakuthu (61) (Table 10, Figures 15-17)

Table 10 Vessel frequencies (no/ μm^2) at different study sites

(Values in parentheses are standard deviations)

	Conolly's	Edakkode	Kanakuthu
earlywood	30 (19)	53 (27)	31 (19)
latewood	32 (24)	33 (18)	30 (21)
totalwood	62 (35)	86 (41)	61 (36)

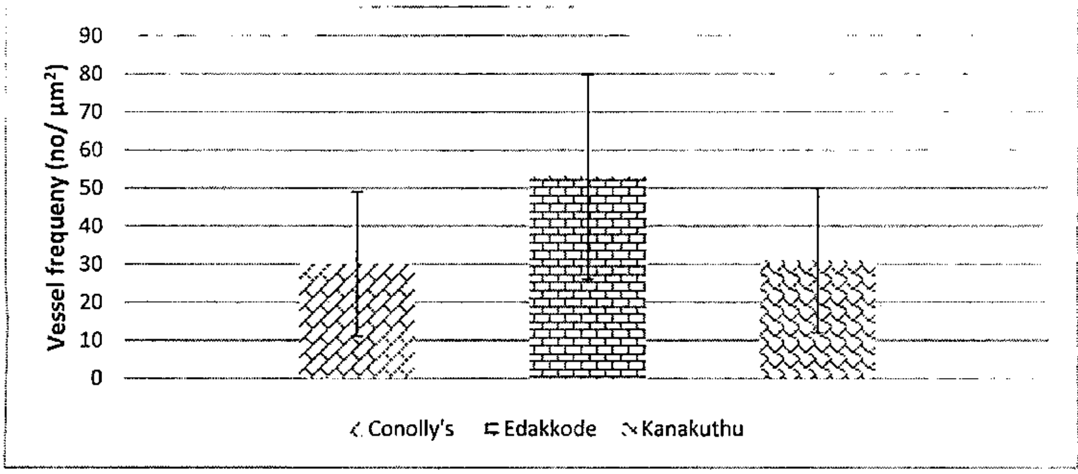

Fig 15 Earlywood vessel frequencies at the study sites

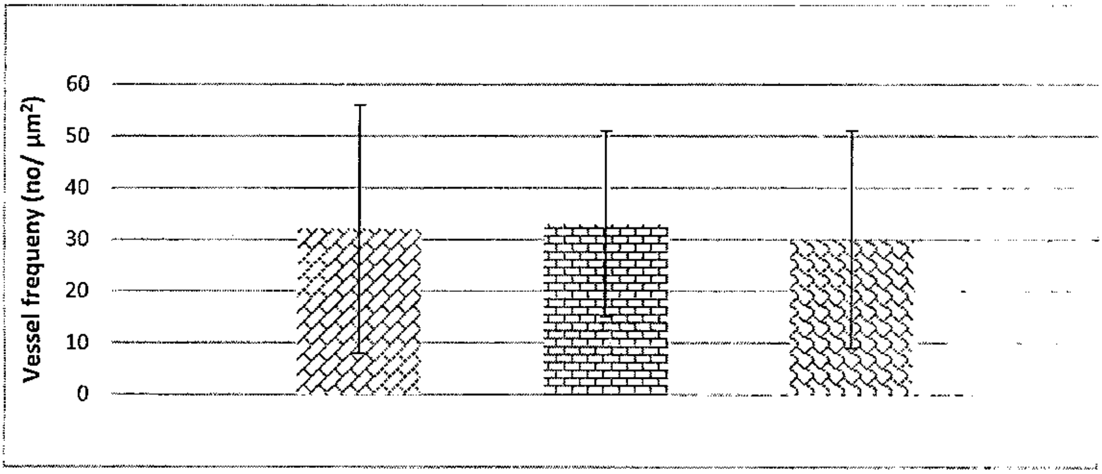

Fig 16 Latewood vessel frequencies at the study sites

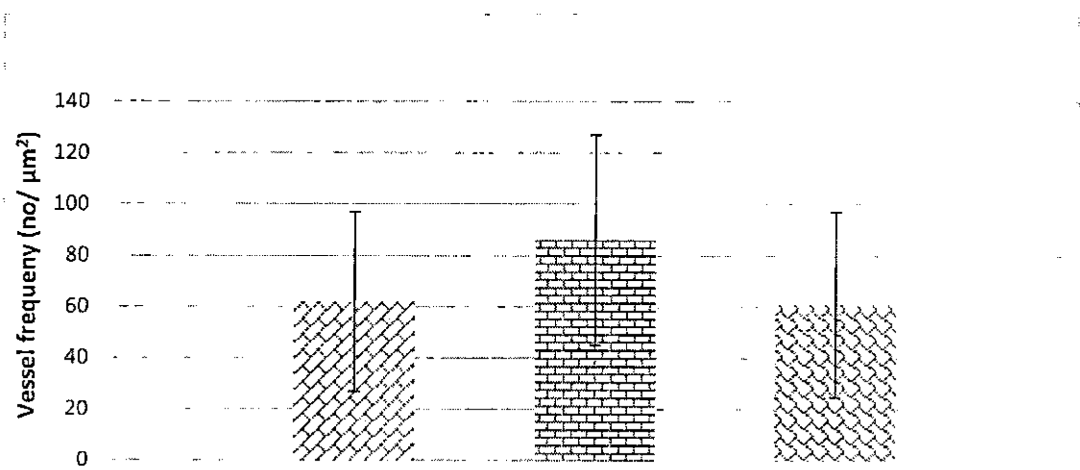

Fig 17 Totalwood frequencies at the study sites

4.6 Vessel diameter

The vessel diameter of Conolly's plot was highest among the three sites for earlywood (183.49µm), latewood (141.80µm) as well as totalwood (162.64µm). Edakkode had the second highest values for earlywood (181.30µm) and totalwood (149.37µm) and least value for latewood (117.44µm) (Table 11; Figures 18-20)

Table 11 Variations in vessel diameter at study sites

Vessel diameter (µm)	Conolly's plot	Edakkode	Kanakuthu
Earlywood (µm)	183.49 (31.84)	181.30 (19.93)	164.77 (26.23)
Latewood (µm)	141.80 (35.66)	117.44 (13.63)	121.73 (20.71)
Totalwood (µm)	162.64 (33.75)	149.37 (16.78)	143.25 (23.47)

(Values in parentheses are standard deviations)

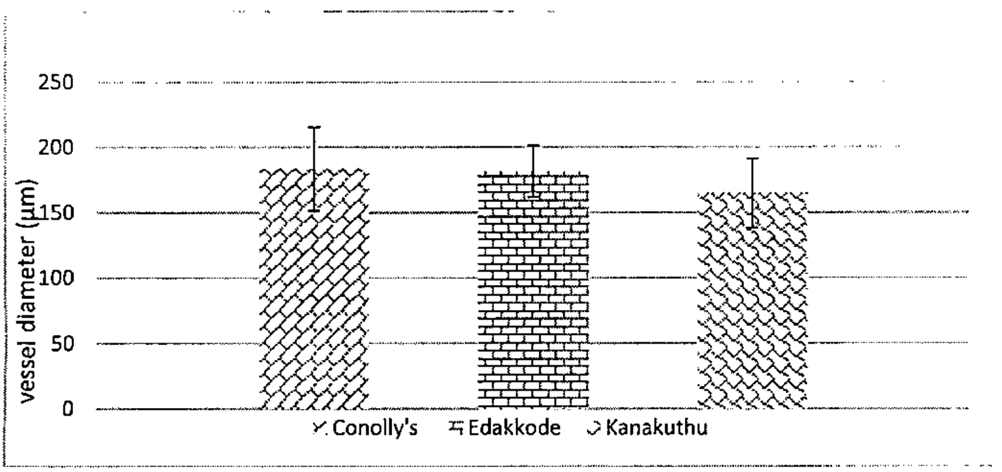

Fig 18 Earlywood vessel diameter at the study sites

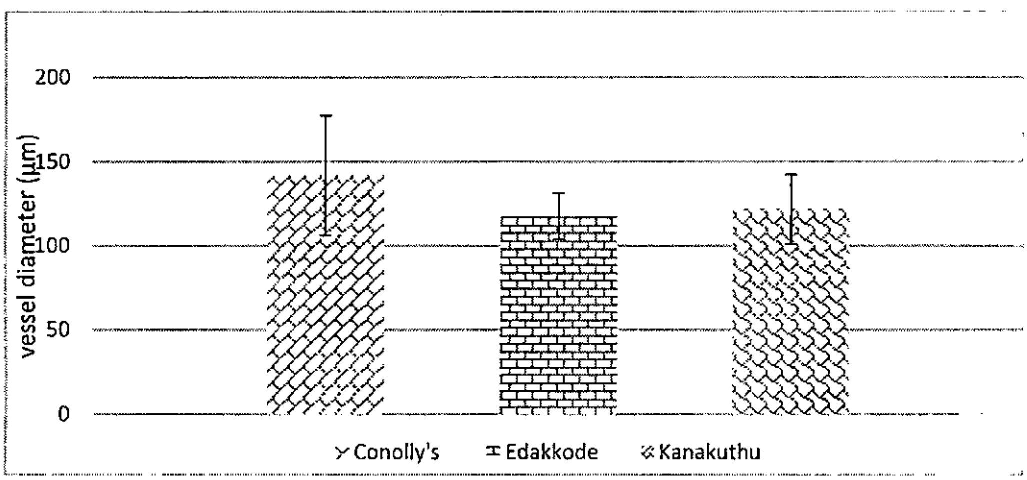

Fig 19 Latewood diameter at the study sites

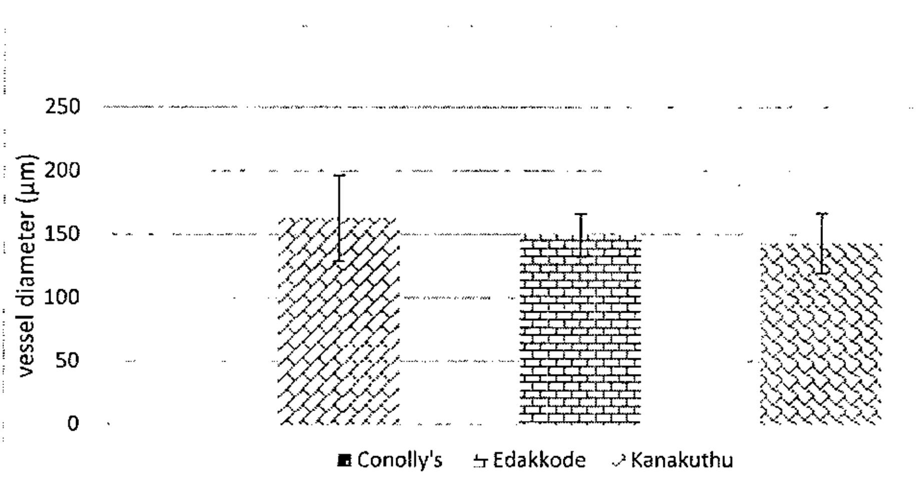

Fig 20 Totalwood diameter at the study sites

4.7 Tree ring chronologies

4.7.1 Ring width index chronology

The statistical properties of ring-width-index chronologies from the four sites were assessed for their dendroclimatic potential (Table 12). The Edakkode ring width index chronology showed highest mean correlation among all radii (0.522) followed by Kanakuthu (0.458) and Conolly's plot (0.363) chronologies. The mean correlation between trees was high in Conolly's plot ring width index chronology (0.559), followed by Edakkode (0.493) and Kanakuthu (0.447) 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 that 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 for Kanakuthu (2.95) followed by Edakkode (2.22) and Conolly's plot (1.09).

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). In the lower running-EPS plot, a value of 0.85 is plotted as a rough cutoff 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 1.029 for Kanakuthu, 1.022 for Edakkode and 1.109 for Conolly's plot ring width index chronology.

Table 12. Tree ring chronology statistics of *Tectona grandis* from the study sites

Tree ring chronology statistics	Study sites		
	Kanakuthu	Edakkode	Conolly's plot
Chronology time span	1949-2012	1949-2012	1870-2010
Number of trees	10	10	3
Number of radii	32	30	16
Mean correlation among all radii	0.458+ 0.325*	0.522+ 0.221*	0.363+ 0.175*
Mean correlation between trees	0.367+ 0.521*	0.493+ 0.577*	0.559+ 0.447*
Signal to noise ratio	2.95+ 5.19*	2.22+ 7.88*	1.09+ 2.94*
Expressed population signal	1.029+ 1.051*	1.022+ 1.088*	1.109+ 1.294*

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

4.7.2 Mean vessel area index chronology

In the case of mean vessel area index chronology, Kanakuthu (0.325) ring width index chronology showed highest mean correlation among all radii, followed by Edakkode (0.221) and Conolly's plot (0.175) chronologies. The mean correlation between trees was highest at Edakkode (0.577) followed by Kanakuthu (0.521) and Conolly's plot mean vessel area index chronologies (0.447).

The value of SNR for ring width index chronologies of the three study sites is high. SNRs were in the order Edakkode (7.88) > Kanakuthu (5.19) > Conolly's plot (3.58). Also, the value of EPS is higher for all the mean vessel area index chronologies. All chronologies have the acceptable range of EPS values as 1.051 for Kanakuthu, 1.088 for Edakkode and 1.294 for Conolly's plot. 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 Nilambur (North) forest division in Kerala.

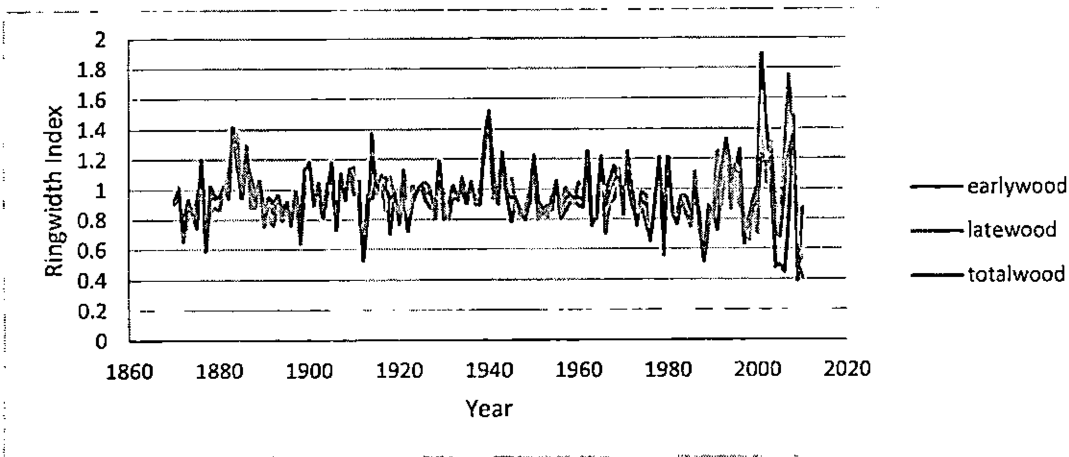

Fig 21 Standard ring width index chronologies from Conolly's plot

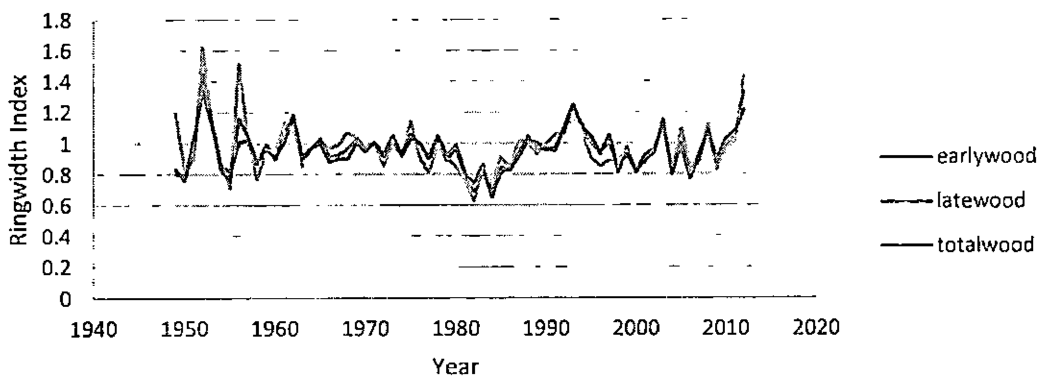

Fig 22 Standard ring width index chronologies from Edakkode

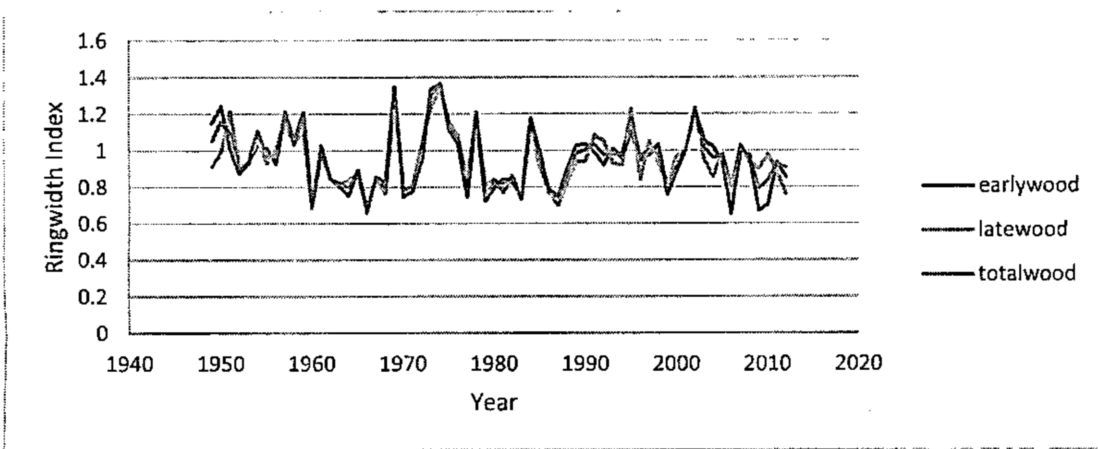

Fig 23 Standard ring width index chronologies from Kanakuthu

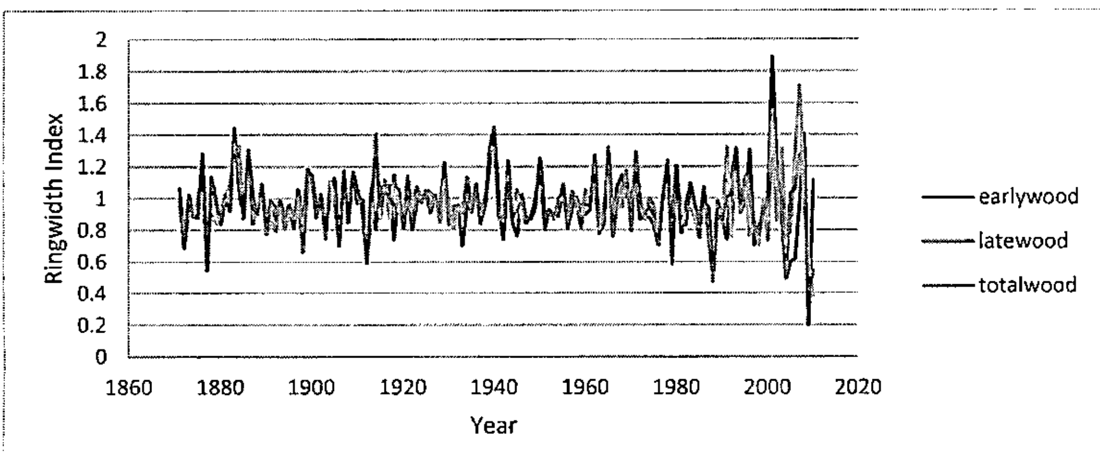

Fig 24 Residual ring width index chronologies from Conolly's plot

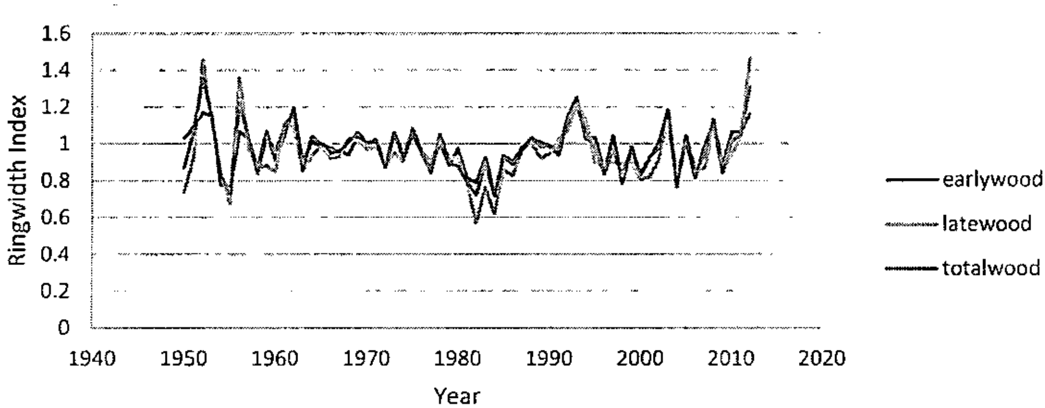

Fig 25 Residual ring width index chronologies from Edakkode

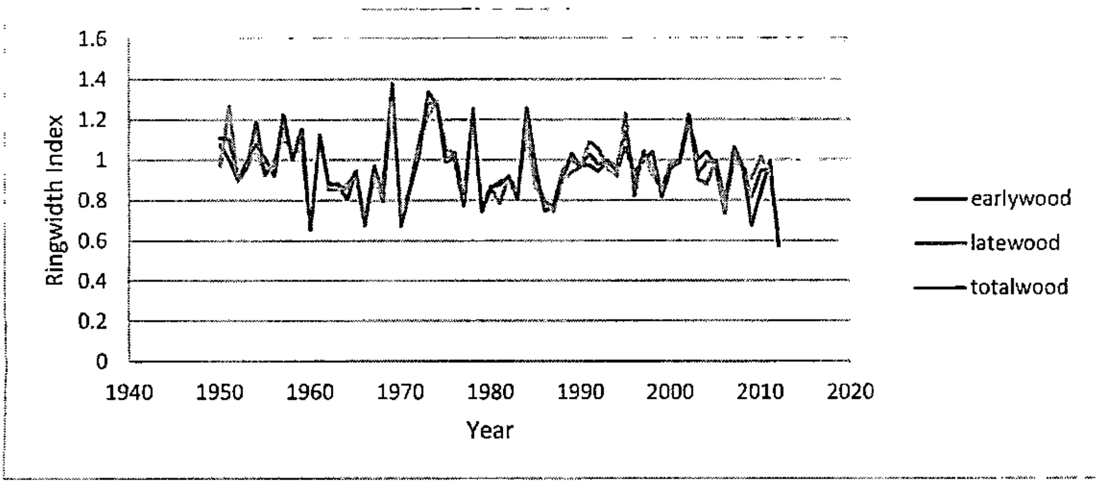

Fig 26 Residual ring width index chronologies from Kanakuthu

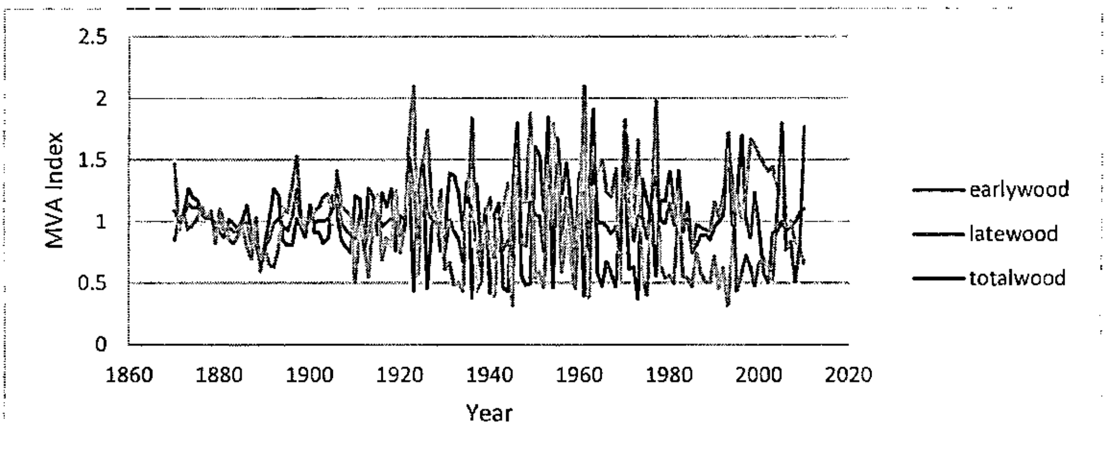

Fig 27 Standard mean vessel area index chronologies from Conolly's plot

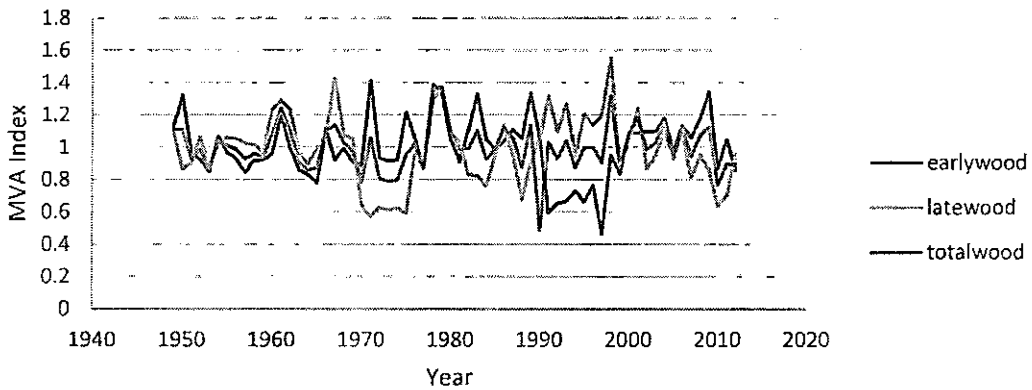

Fig 28 Standard mean vessel area index chronologies from Edakkode

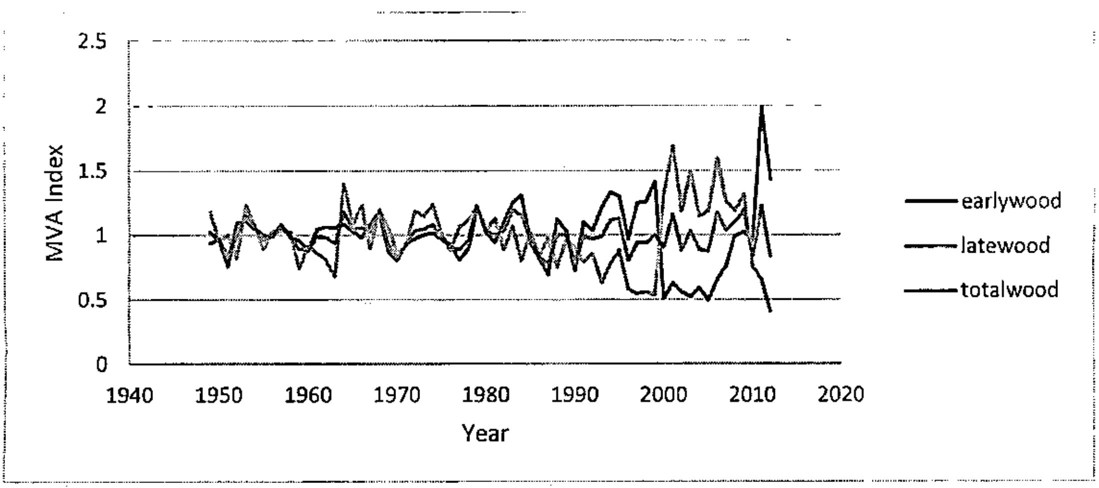

Fig 29 Standard mean vessel area index chronologies from Kanakuthu

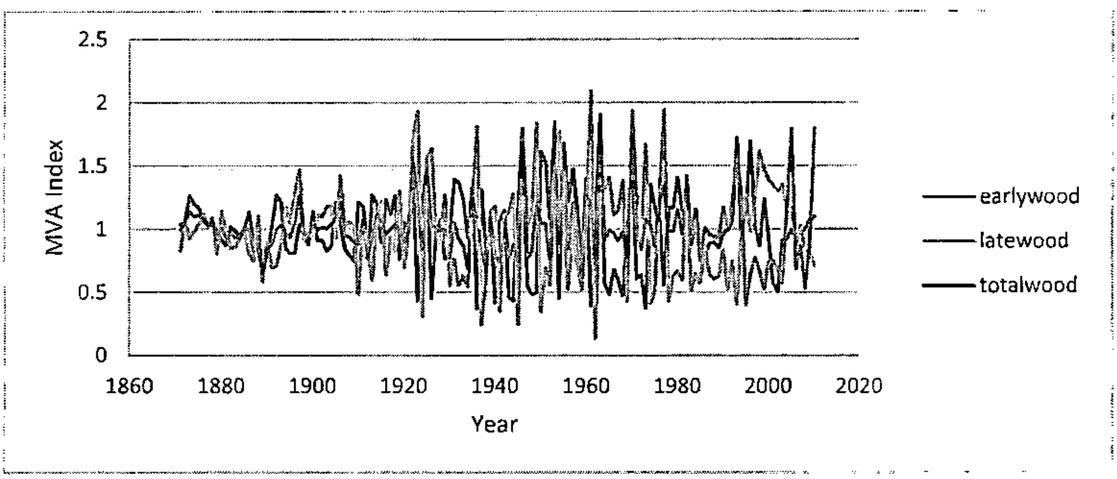

Fig 30 Residual mean vessel area index chronologies from Conolly's plot

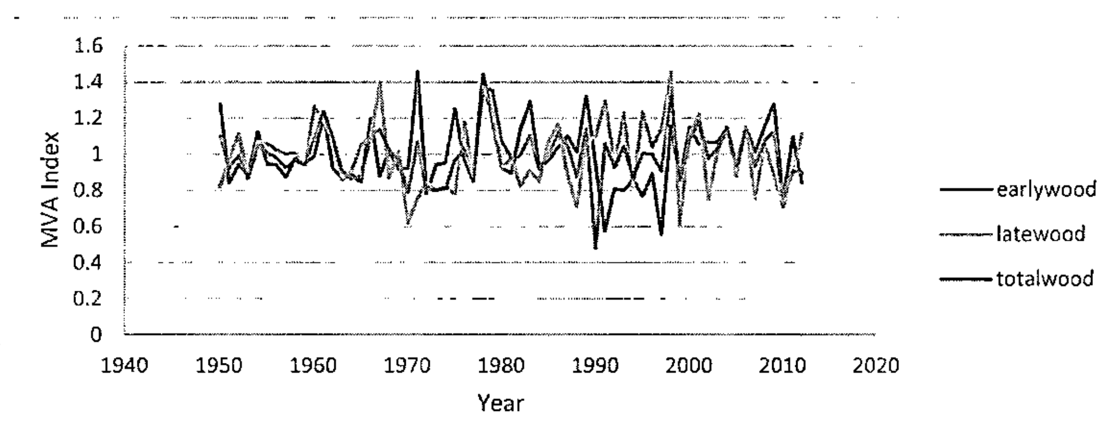

Fig 31 Residual mean vessel area index chronologies from Edakkode

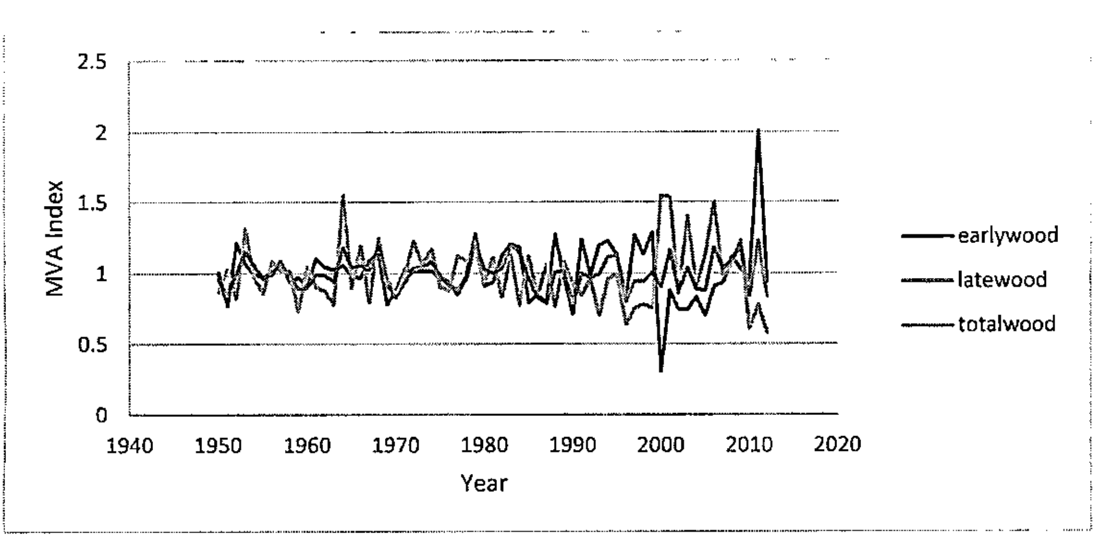

Fig 32 Residual mean vessel area index chronologies from Kanakuthu

4.8 Correlation between climate and ring widths

4.8.1 Monthly rainfall and ring width

Both earlywood standard and residual chronologies of Conolly's plot showed a positive correlation (0.371) with June precipitation of the current year. The latewood standard chronology showed a negative correlation (-0.471) of previous December rainfall at Conolly's plot. At Edakkode the previous November rainfall had a positive strong influence (0.550) on standard totalwood chronology while rainfall in current May had a negative influence on standard latewood chronology. In the case of residual chronologies the same pattern followed at Edakkode. July rainfall (0.378) had a highest correlation with standard total ring width chronology at Kanakuthu. The residual chronologies showed a higher correlation (0.384) while May precipitation showed negative correlation (0.383) with residual totalwood chronology at Kanakuthu. (Table 13-18; Figure 33-50).

4.8.2 Seasonal climate and ring width

The October-November temperature showed negative correlation with standard (-0.285) as well as residual (0.332) totalwood ringwidth chronologies from Conolly's plot. In Edakkode previous southwest monsoon temperature (pJJAS) had negative effects on standard latewood (-0.479) as well residual (-0.456) ringwidth chronologies. The current southwest monsoon (JJAS) had positive correlation with standard (0.420) latewood and residual (0.429) latewood chronologies in Edakkode. In Kanakuthu previous October-November temperature had negative correlation (-0.452) with standard latewood chronology while previous June-September temperature had negative correlation (-0.413) with residual earlywood chronology. In the case of seasonal rainfall previous June-September had positive influence on standard latewood (0.319) and residual latewood (0.329) ringwidth chronologies. (Table 19-24; Figure 51-68).

Table 13 Bootstrapped correlation between precipitation and standard ring width chronologies at Conolly's plot

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.317	0.290	-0.253			-0.275				0.255	0.27	0.371		-0.251	-0.293	0.319		0.308
Late	0.277	0.301	0.274				-0.471			-0.202	-0.283	0.329				-0.247		0.343	-0.286
Total		0.317	0.258	-0.229			-0.312				-0.282	0.320	0.310	0.213		-0.231		0.320	0.283

Table 14 Bootstrapped correlation between precipitation and residual ring width chronologies at Conolly's plot

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.317	0.287	-0.253			-0.275					0.270	0.371		-0.251	-0.293	0.319		0.308
Late		0.312					-0.380		-0.264	-0.221	-0.278	0.332				-0.270		0.300	-0.306
Total	-0.300	0.316	0.279				-0.343				-0.291	0.317	0.348			-0.247			-0.237

Table 15 Bootstrapped correlation between precipitation and standard ring width chronologies at Edakkode

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		-0.242			-0.311		-0.291		0.219			0.229		-0.331		0.321			
Late	0.315		-0.336	-0.306		0.487				-0.235		-0.371	0.299					0.359	
Total	0.209					0.550			0.317				0.321	-0.282				0.399	0.319

Table 16 Bootstrapped correlation between precipitation and residual ring width chronologies at Edakkode

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early					-0.312		-0.255				-0.242			-0.339	0.387				
Late	0.32		-0.318	-0.289		0.385				-0.313	-0.340	-0.281						0.394	
Total	0.23					0.534			0.307			-0.429		-0.263					0.255

Table 17 Bootstrapped correlation between precipitation and standard ring width chronologies at Kanakuthu

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.324	0.275				0.301		0.325	0.342		-0.376		0.377					
Late				-0.254				-0.354											
Total							0.276				0.356	-0.369		0.378	0.297				

Table 18 Bootstrapped correlation between precipitation and residual ring width chronologies at Kanakuthu

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.204	0.281		0.285		0.322	-0.257		0.248		-0.334		0.383	0.272				
Late				-0.307	-0.263														
Total							0.277	-0.188			0.357	-0.366		0.384	0.301				

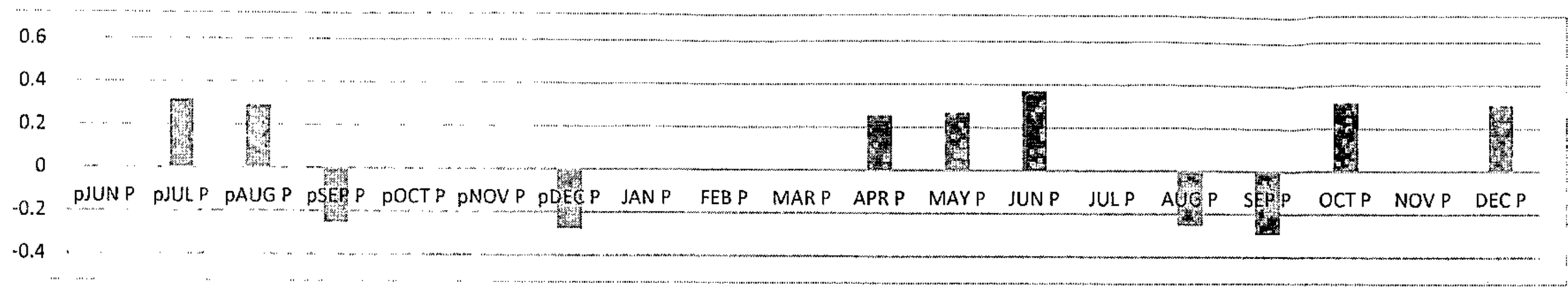

Fig 33 Bootstrapped correlation between rainfall and standard earlywood ring chronologies at Conolly's plot

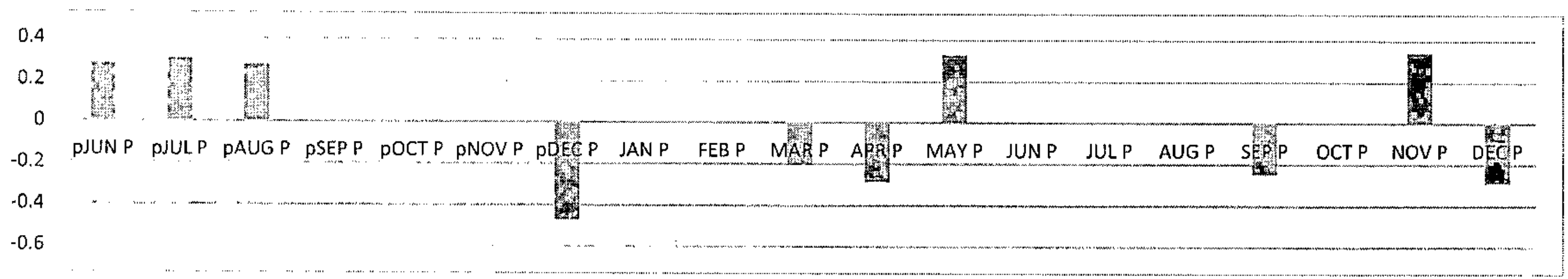

Fig 34 Bootstrapped correlation between rainfall and standard latewood ring chronologies at Conolly's plot

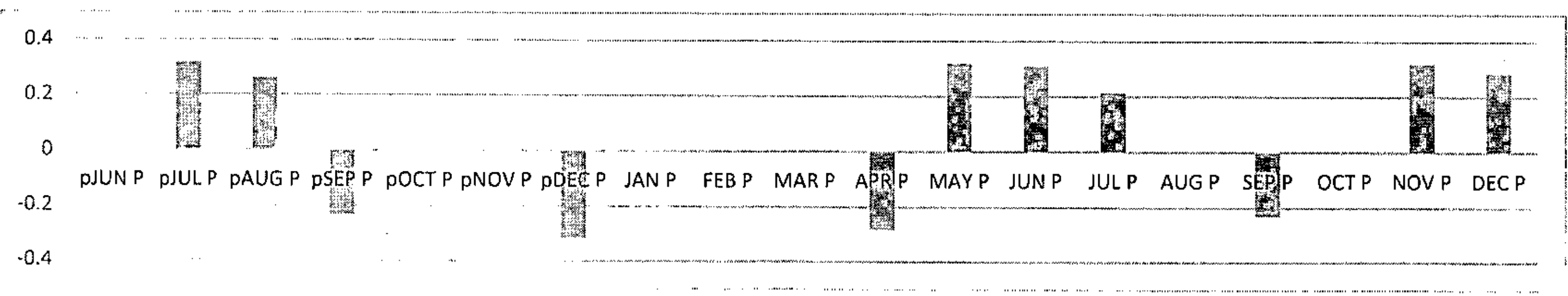

Fig 35 Bootstrapped correlation between rainfall and standard totalwood ring chronologies at Conolly's plot

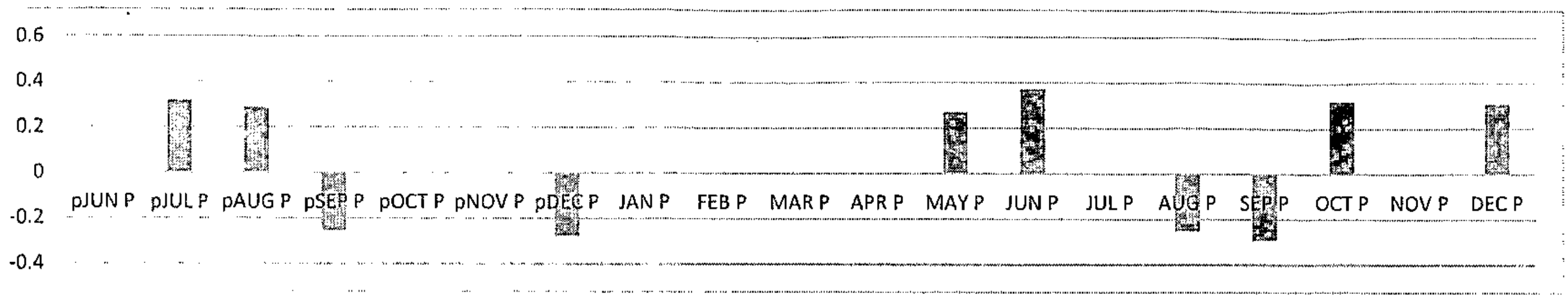

Fig 36 Bootstrapped correlation between rainfall and residual earlywood ring chronologies at Conolly's plot

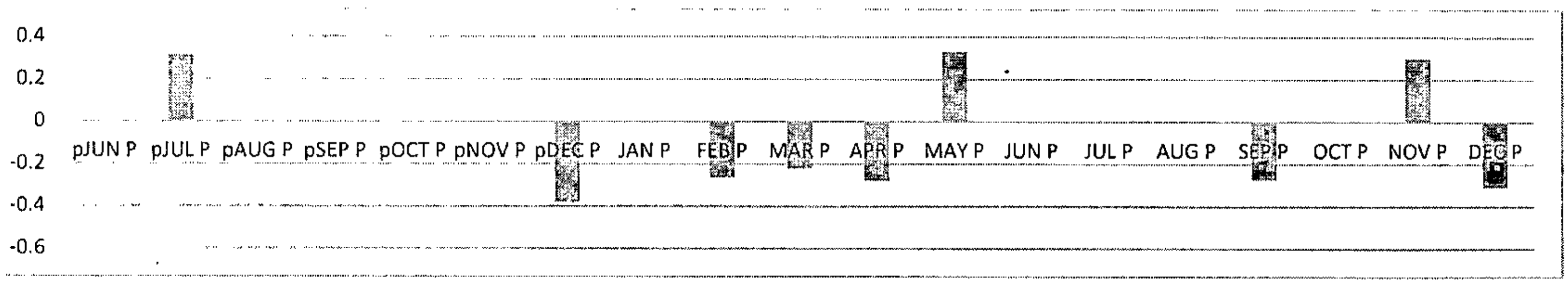

Fig 37 Bootstrapped correlation between rainfall and residual latewood ring chronologies at Conolly's plot

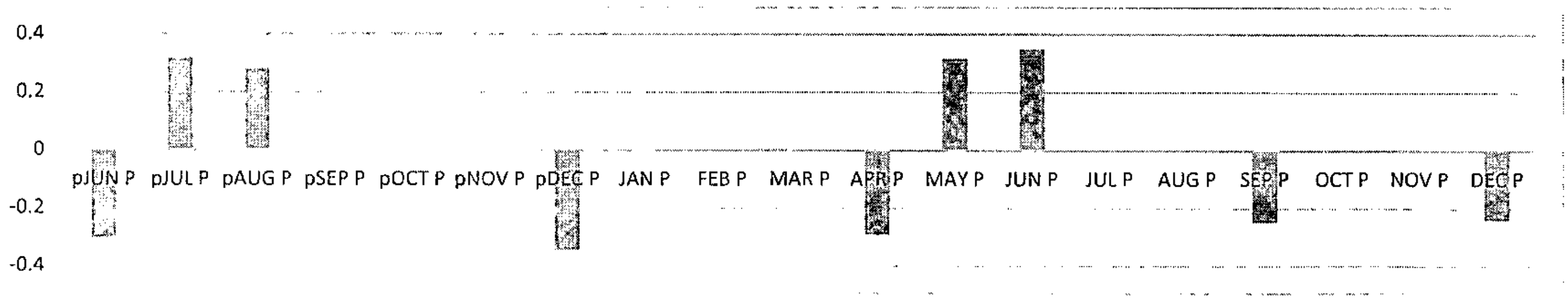

Fig 38 Bootstrapped correlation between rainfall and residual totalwood ring chronologies at Conolly's plot

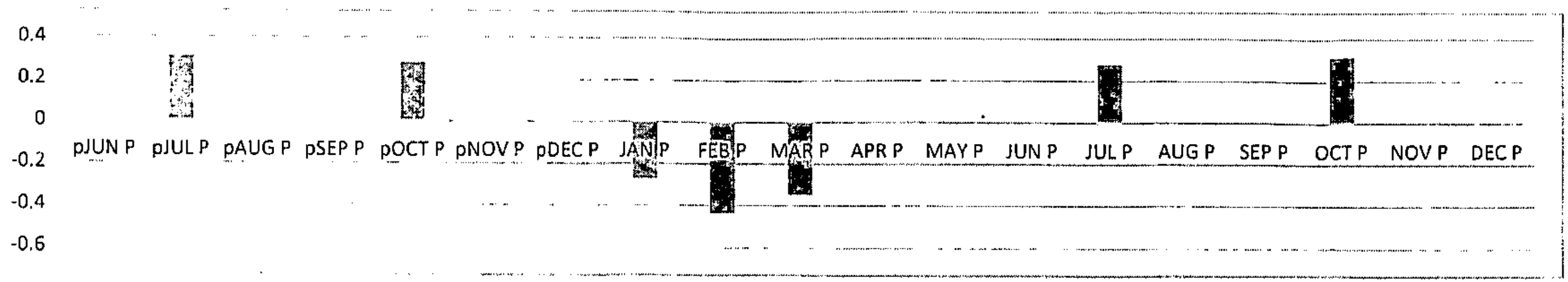

Fig 39 Bootstrapped correlation between rainfall and standard earlywood ring chronologies at Edakkode

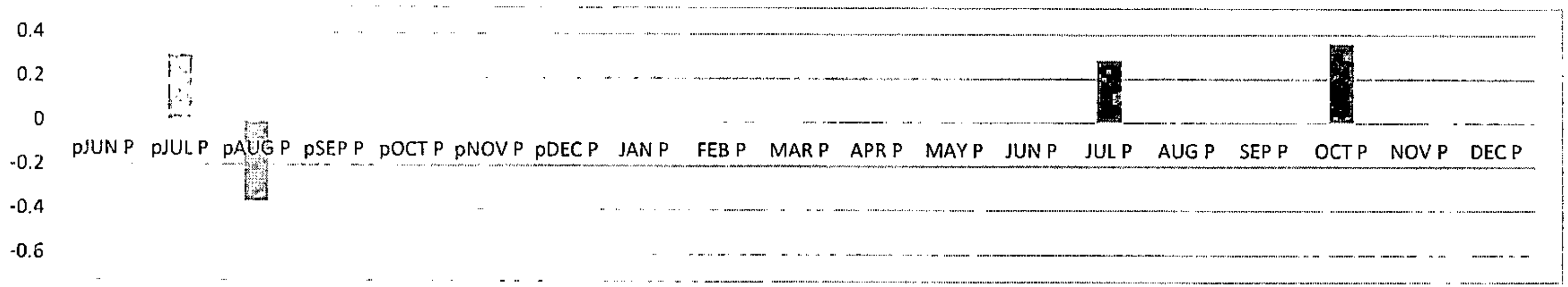

Fig 40 Bootstrapped correlation between rainfall and standard latewood ring chronologies at Edakkode

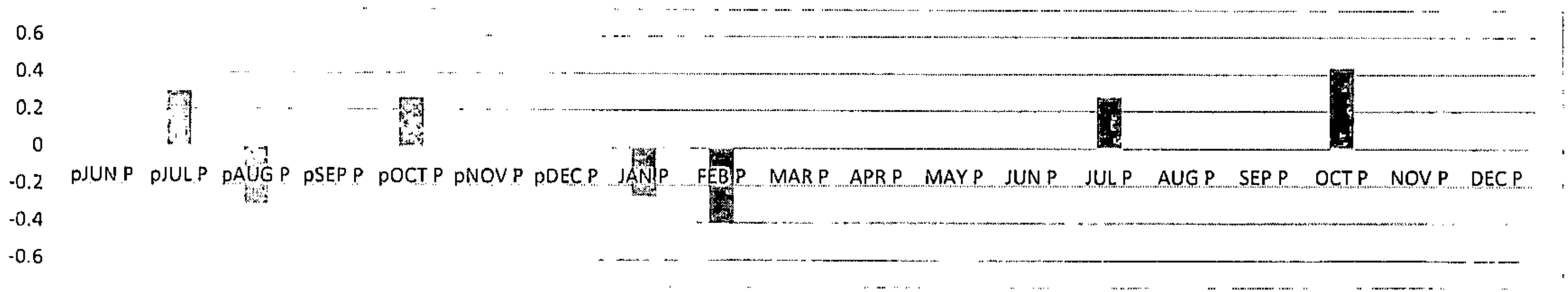

Fig 41 Bootstrapped correlation between rainfall and standard totalwood ring chronologies at Edakkode

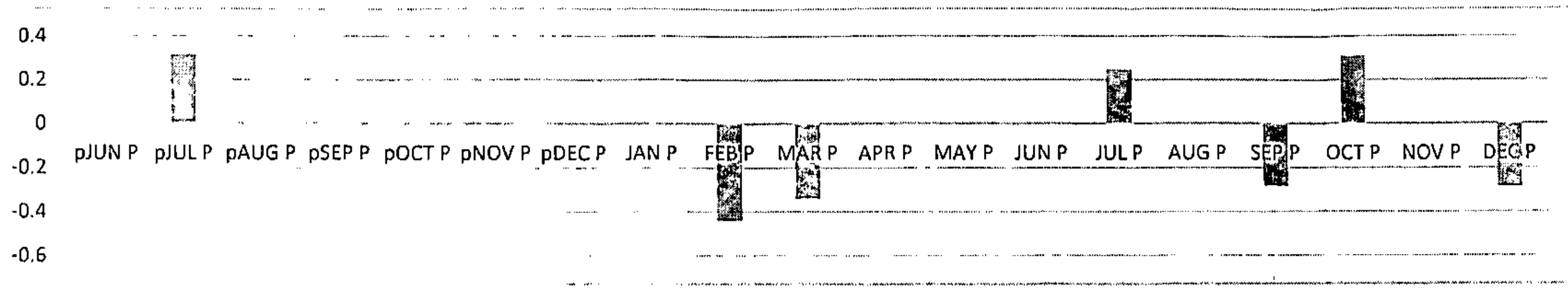

Fig 42 Bootstrapped correlation between rainfall and residual earlywood ring chronologies at Edakkode

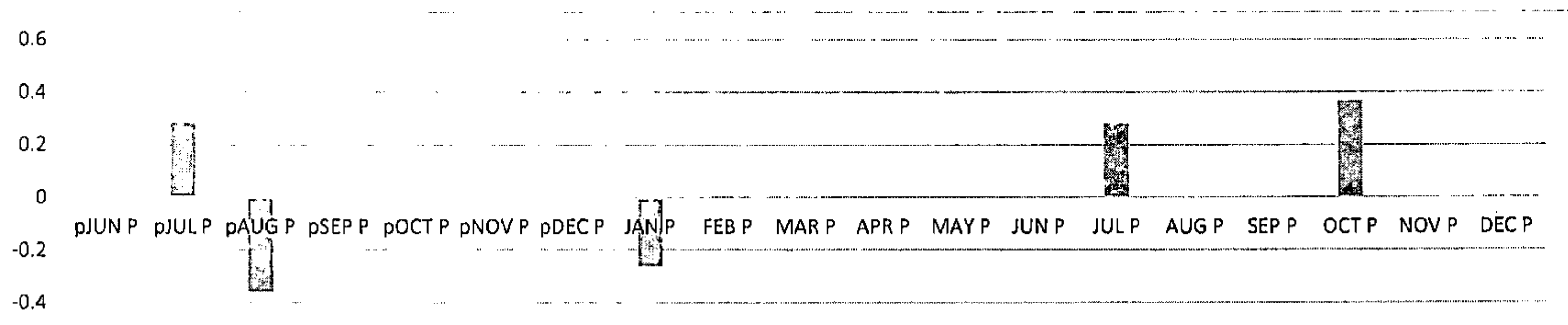

Fig 43 Bootstrapped correlation between rainfall and residual latewood ring chronologies at Edakkode

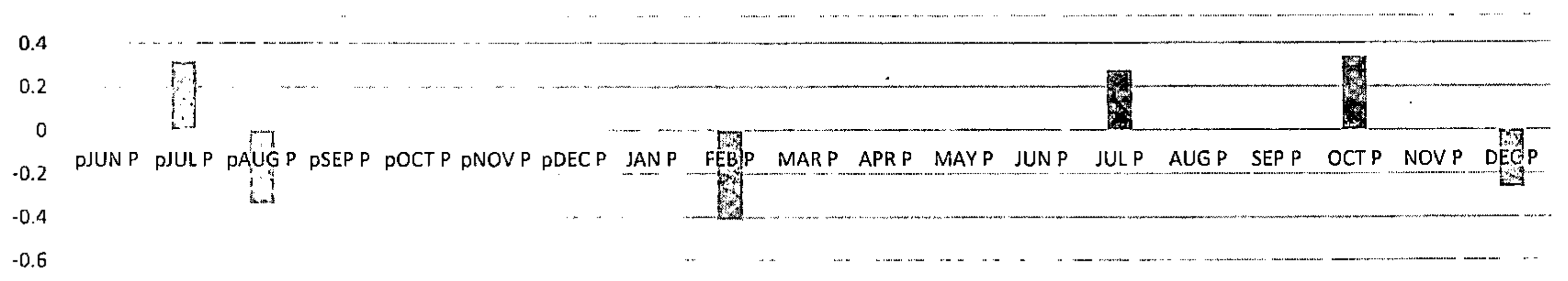

Fig 44 Bootstrapped correlation between rainfall and residual totalwood ring chronologies at Edakkode

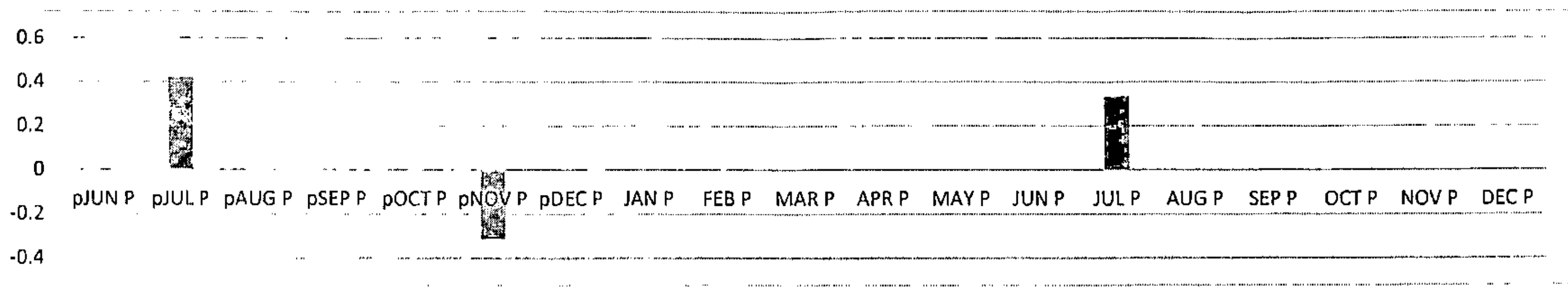

Fig 45 Bootstrapped correlation between rainfall and standard earlywood ring chronologies at Kanakuthu

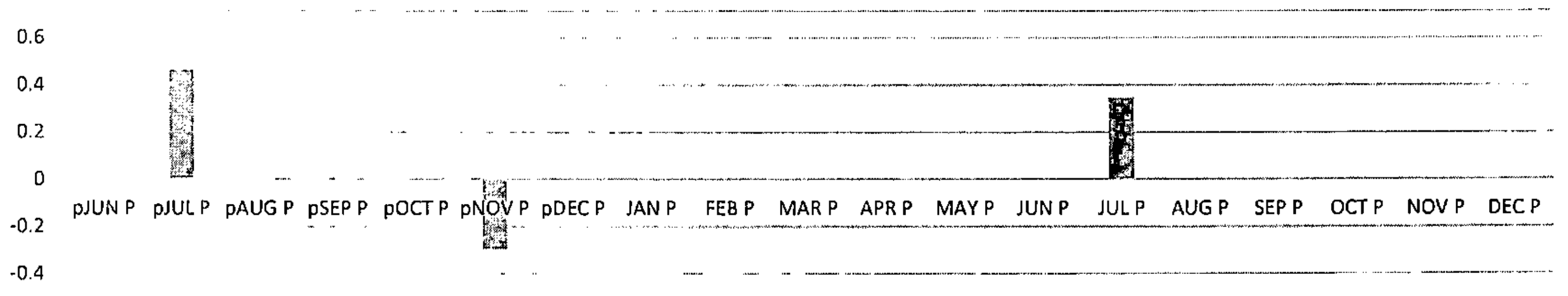

Fig 46 Bootstrapped correlation between rainfall and standard latewood ring chronologies at Kanakuthu

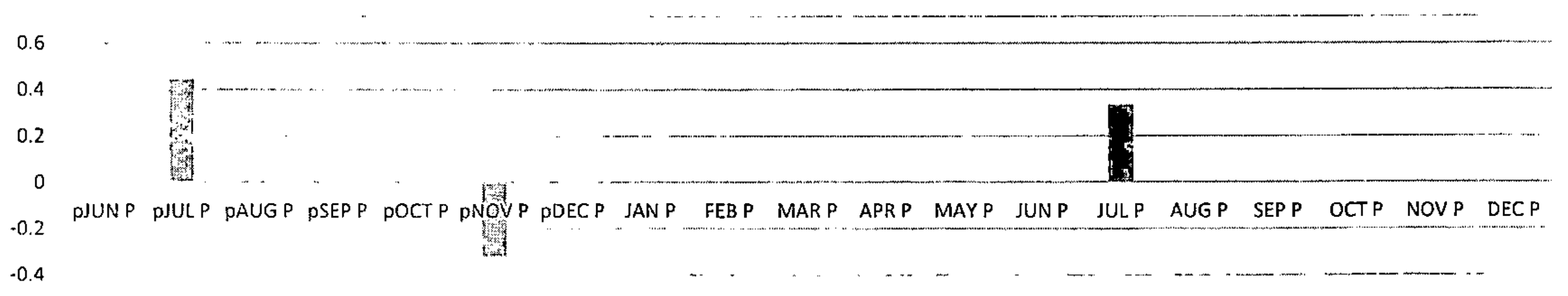

Fig 47 Bootstrapped correlation between rainfall and standard totalwood ring chronologies at Kanakuthu

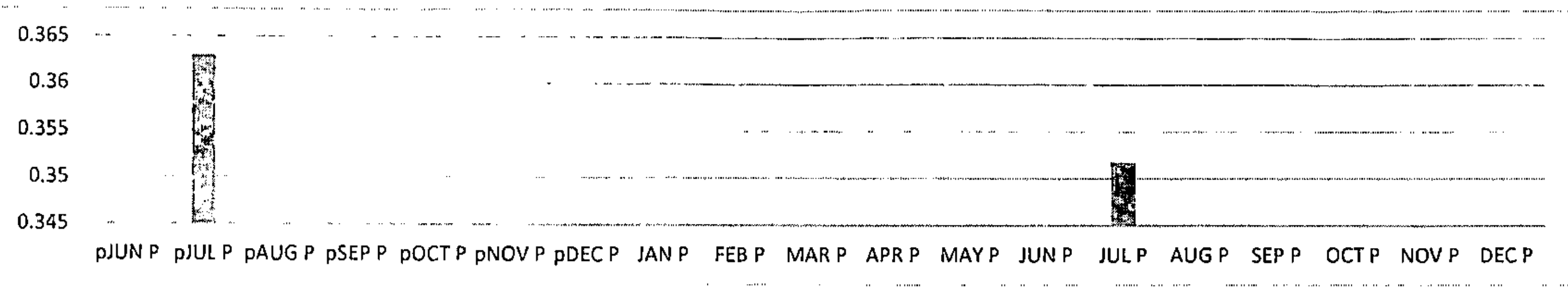

Fig 48 Bootstrapped correlation between rainfall and residual earlywood ring chronologies at Kanakuthu

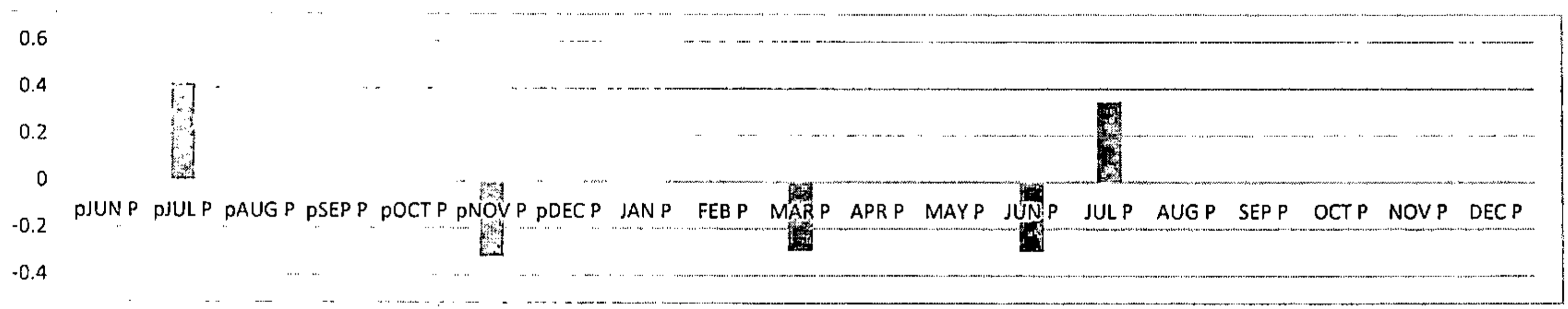

Fig 49 Bootstrapped correlation between rainfall and residual latewood ring chronologies at Kanakuthu

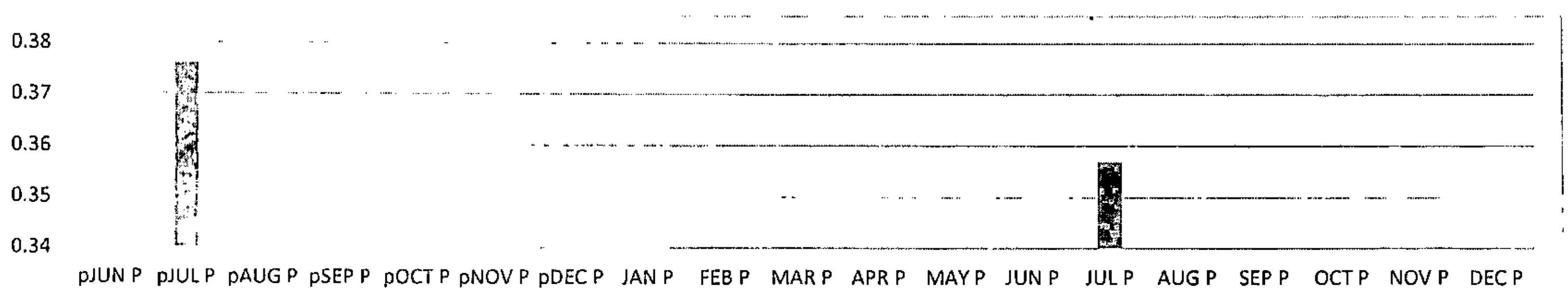

Fig 50 Bootstrapped correlation between rainfall and residual totalwood ring chronologies at Kanakuthu

Table 19 Bootstrapped correlation between seasonal variables and standard ring width chronologies at Conolly's plot

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.286			-0.306	-0.272			0.390	0.321	0.328		0.379		
Late	-0.299			-0.319	-0.304				0.315	-0.293	0.279	0.279		
Total	-0.287			-0.328	-0.285			0.345	0.317	0.298		0.373		

Table 20 Bootstrapped correlation between seasonal variables and residual ring width chronologies at Conolly's plot

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.286			-0.286	-0.272			0.390	0.321	0.328		0.379		
Late	-0.293	-0.298	-0.280	-0.327	-0.315				0.296	-0.329				
Total			-0.299	-0.332	-0.271			0.214	0.289	-0.246		0.299		

Table 21 Bootstrapped correlation between seasonal variables and standard ring width chronologies at Edakkode

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.314		-0.374	-0.392	-0.384					-0.374	0.353	0.331		
Late	-0.479	-0.390	-0.365	-0.357	-0.465			0.374		-0.349		0.420		
Total	-0.372		-0.355	-0.415	-0.416					-0.385	0.347	0.368		

Table 22 Bootstrapped correlation between seasonal variables and residual ring width chronologies at Edakkode

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.359	-0.348	-0.268		-0.340			0.319	0.303	-0.394		0.367		
Late	-0.456	-0.366	-0.353	-0.414	-0.450			0.319	0.2872	-0.359	0.335	0.429		
Total	-0.452	-0.380	-0.293	-0.322	-0.413			0.341		-0.359		0.423		

Table 23 Bootstrapped correlation between seasonal variables and standard ring width chronologies at Kanakuthu

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.349	-0.452			-0.420			0.283				0.270		
Late	-0.355		-0.313	-0.412	-0.452							0.319		
Total	-0.347	-0.447	-0.349	-0.379	-0.436			0.266				0.300		

Table 24 Bootstrapped correlation between seasonal variables and residual ring width chronologies at Kanakuthu

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T		ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.413	-0.360			-0.386				0.267						
Late	-0.299		-0.325	-0.379	-0.437										
Total	-0.384		-0.312	-0.385	-0.421				0.241						

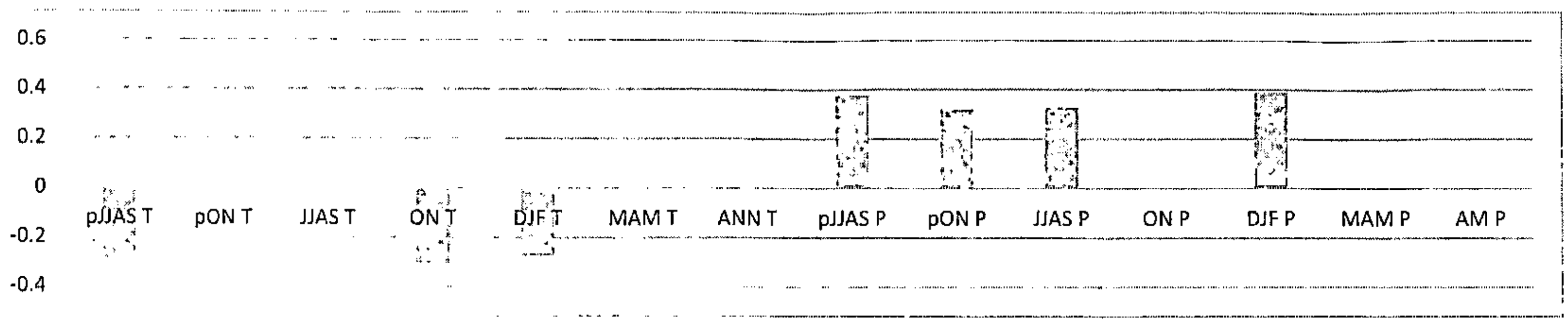

Fig 51 Bootstrapped correlation between seasonal climate and standard earlywood ring chronologies at Conolly's plot

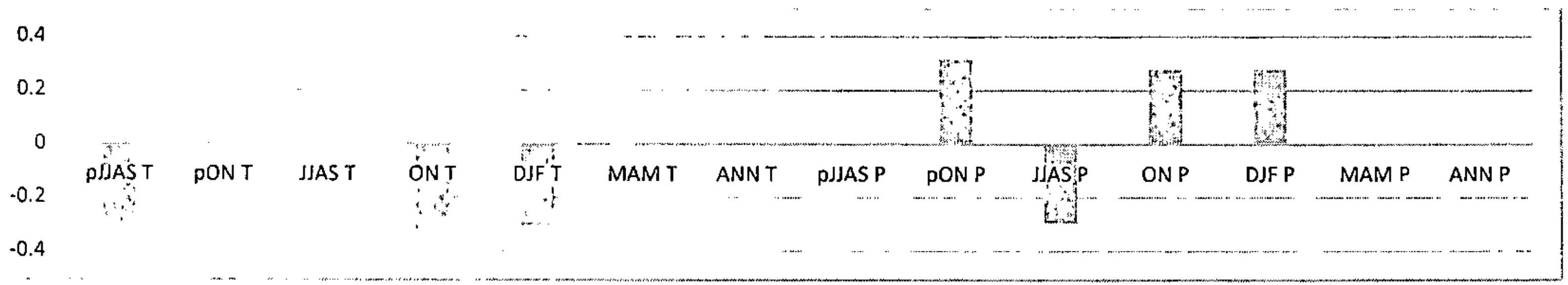

Fig 52 Bootstrapped correlation between seasonal climate and standard latewood ring chronologies at Conolly's plot

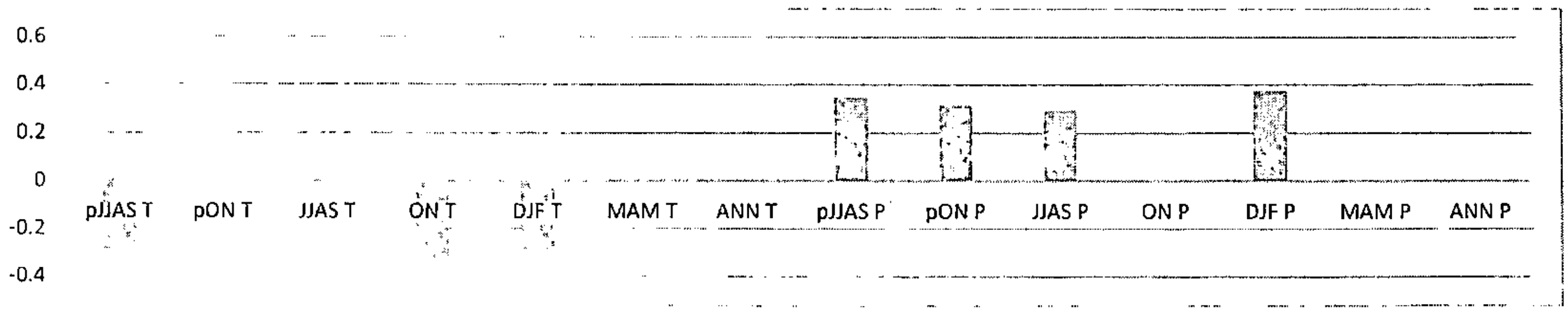

Fig 53 Bootstrapped correlation between seasonal climate and standard totalwood ring chronologies at Conolly's plot

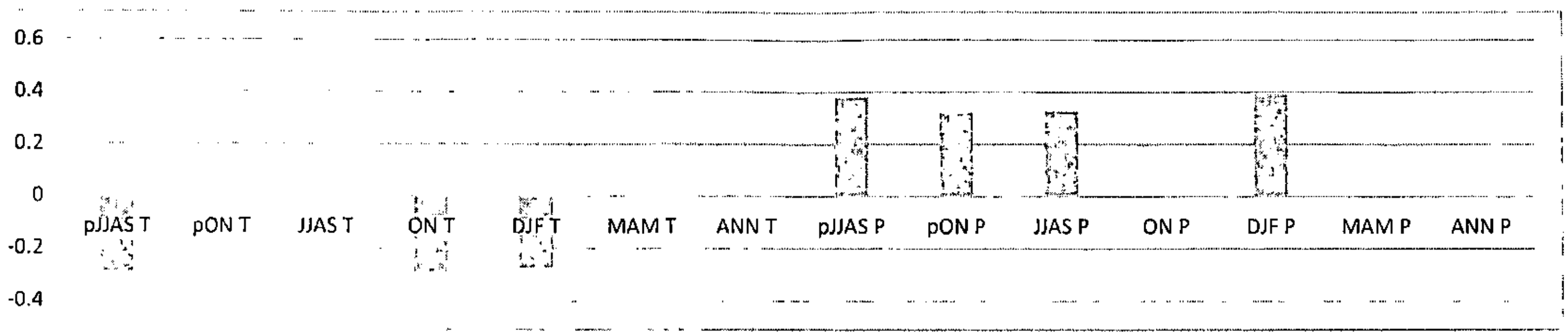

Fig 54 Bootstrapped correlation between seasonal climate and residual earlywood ring chronologies at Conolly's plot

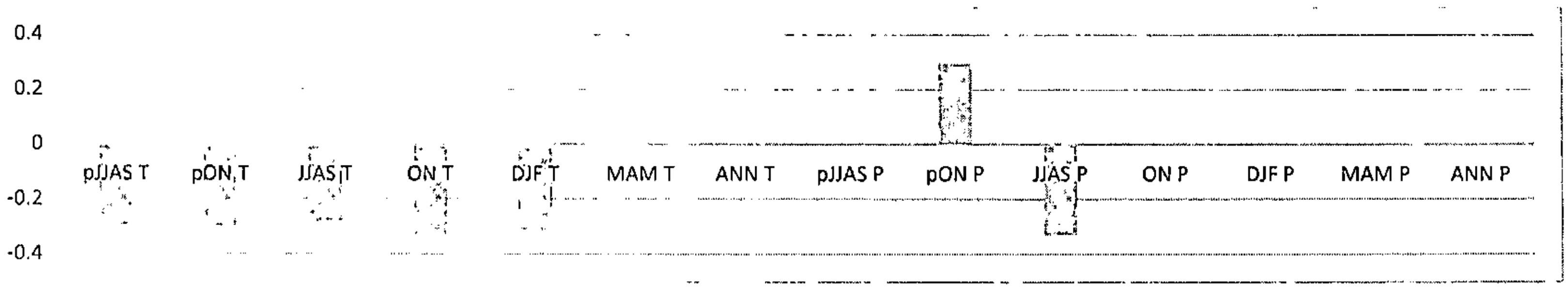

Fig 55 Bootstrapped correlation between seasonal climate and residual latewood ring chronologies at Conolly's plot

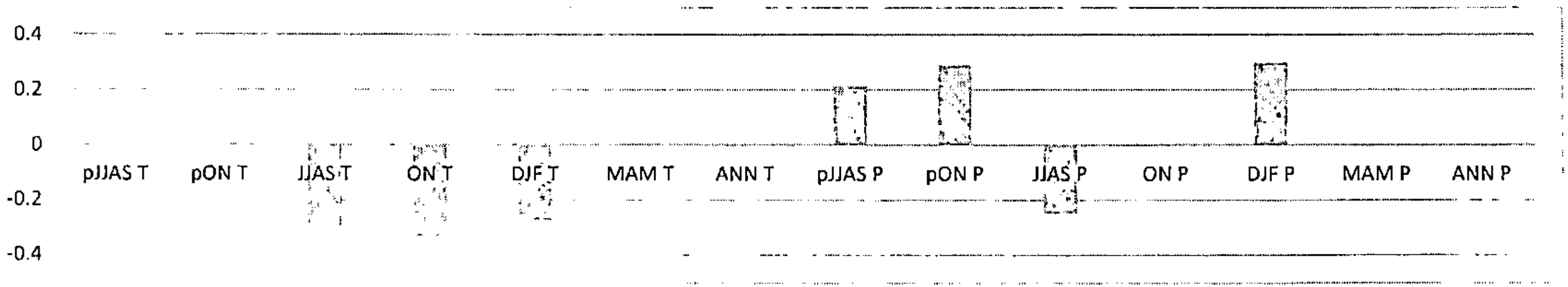

Fig 56 Bootstrapped correlation between seasonal climate and residual totalwood ring chronologies at Conolly's plot

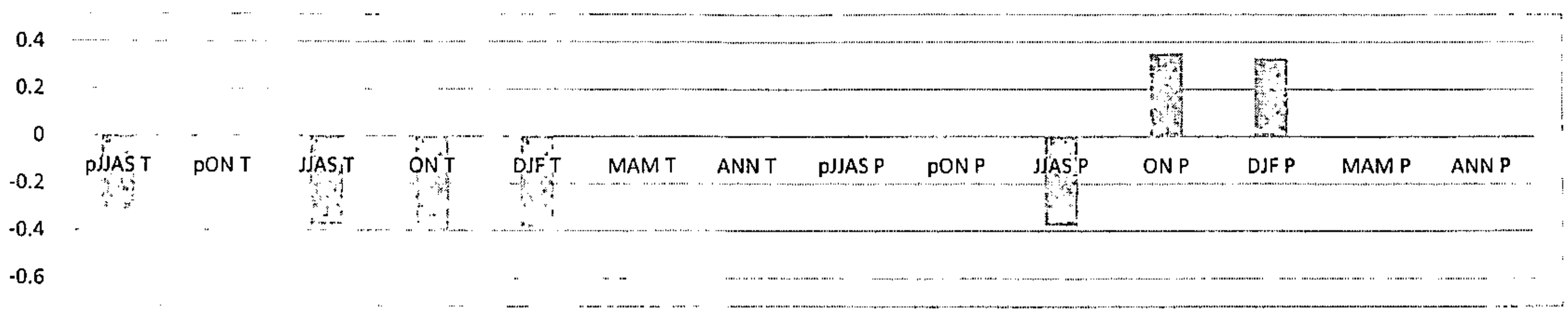

Fig 57 Bootstrapped correlation between seasonal climate and standard earlywood ring chronologies at Edakkode

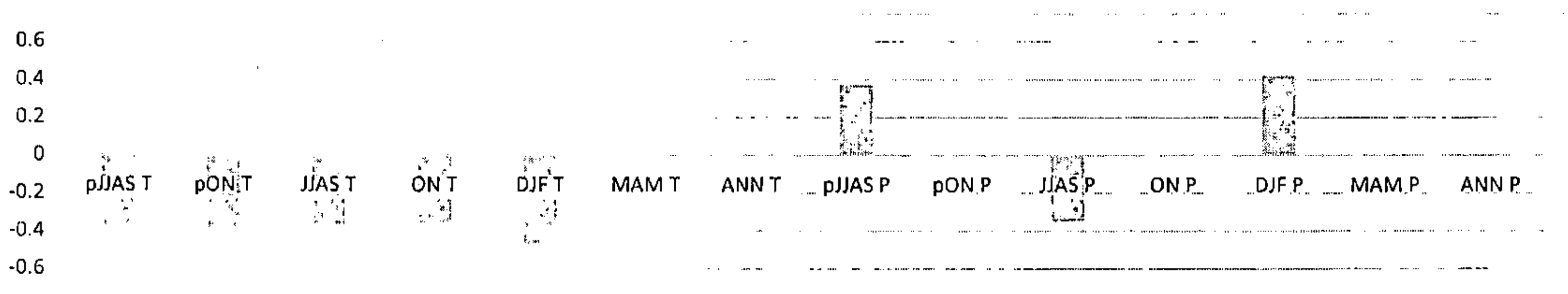

Fig 58 Bootstrapped correlation between seasonal climate and standard latewood ring chronologies at Edakkode

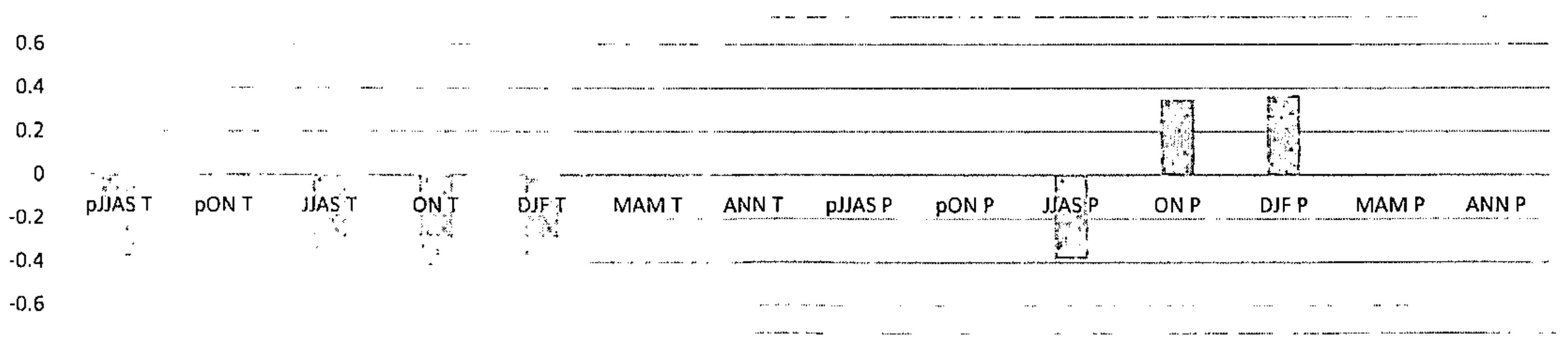

Fig 59 Bootstrapped correlation between seasonal climate and standard totalwood ring chronologies at Edakkode

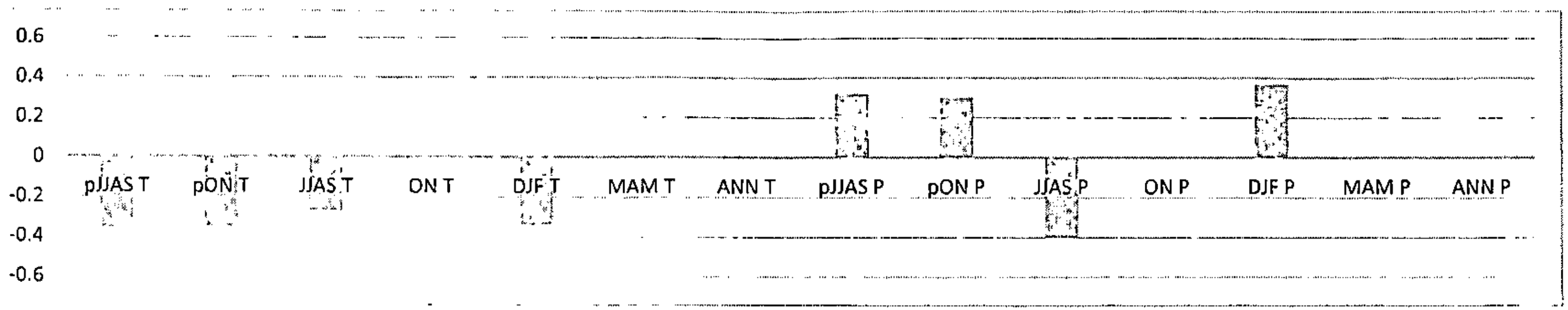

Fig60 Bootstrapped correlation between seasonal climate and residual earlywood ring chronologies at Edakkode

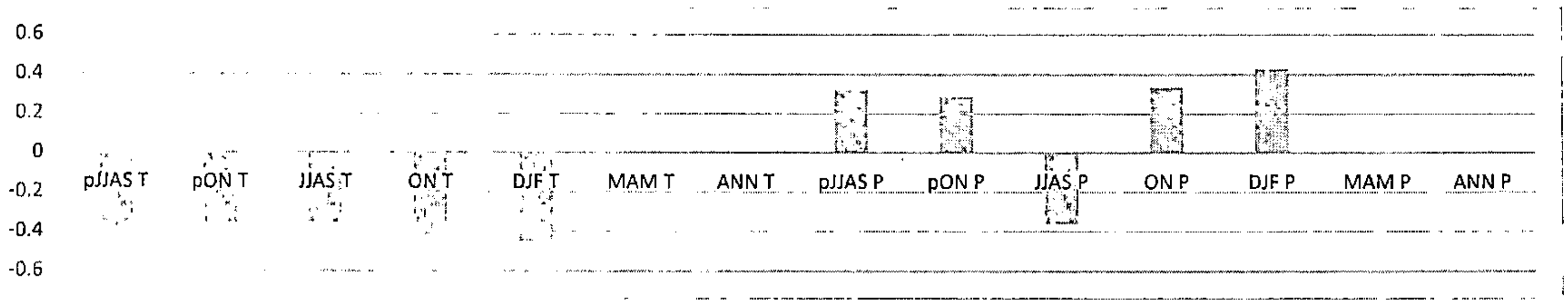

Fig 61 Bootstrapped correlation between seasonal climate and residual latewood ring chronologies at Edakkode

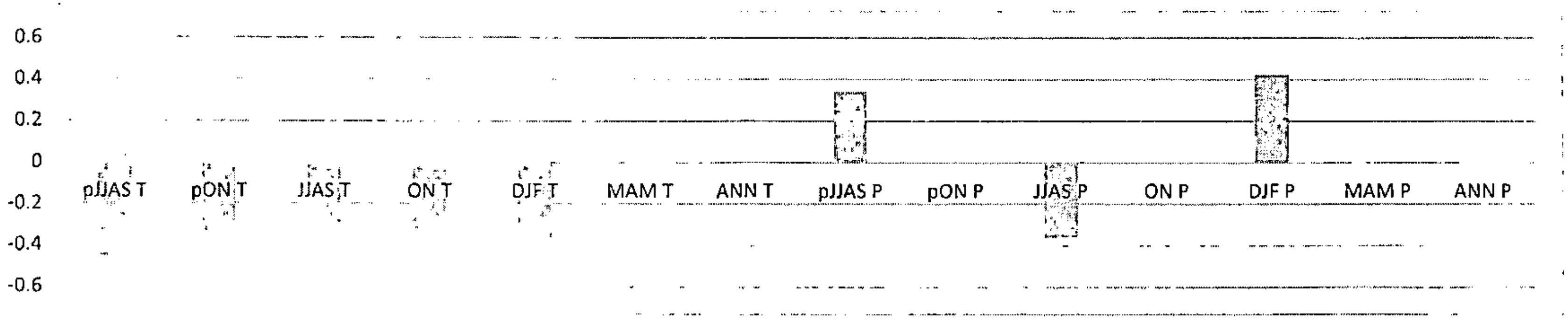

Fig 62 Bootstrapped correlation between seasonal climate and residual totalwood ring chronologies at Edakkode

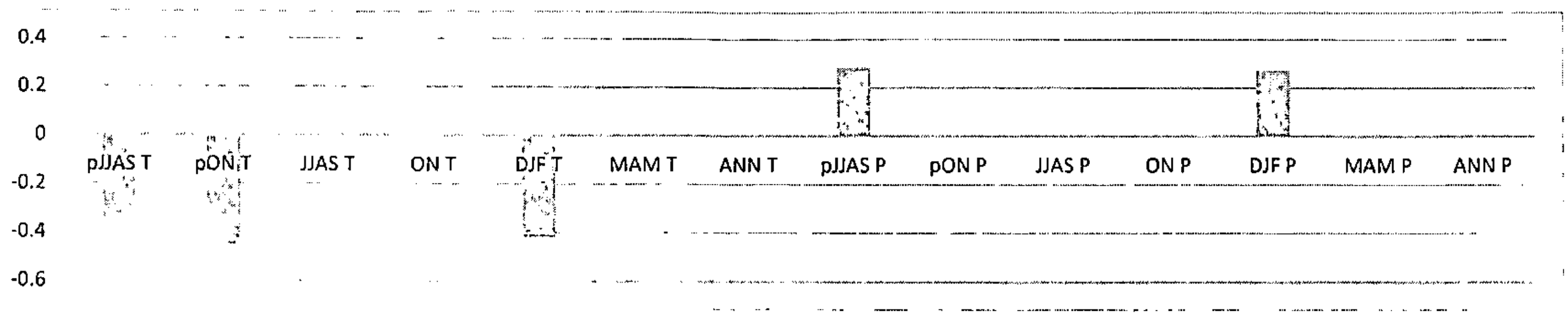

Fig 63 Bootstrapped correlation between seasonal climate and standard earlywood ring chronologies at Kanakuthu

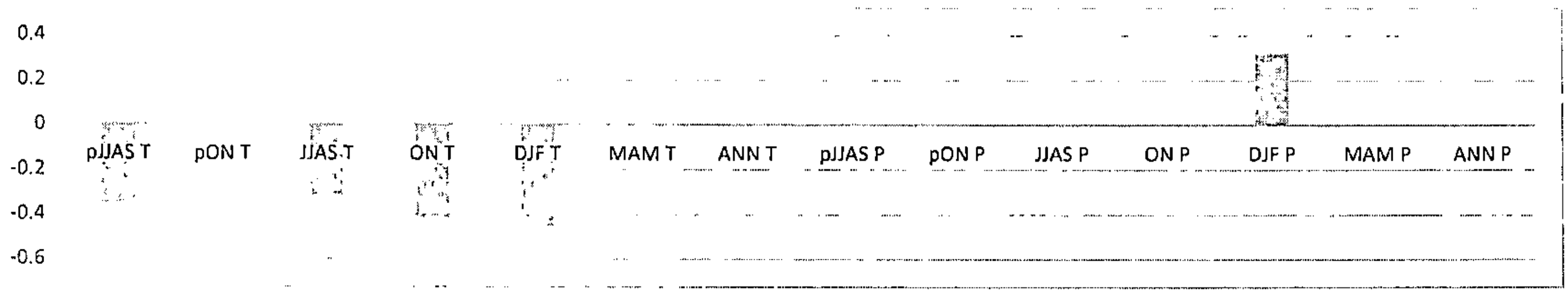

Fig 64 Bootstrapped correlation between seasonal climate and standard latewood ring chronologies at Kanakuthu

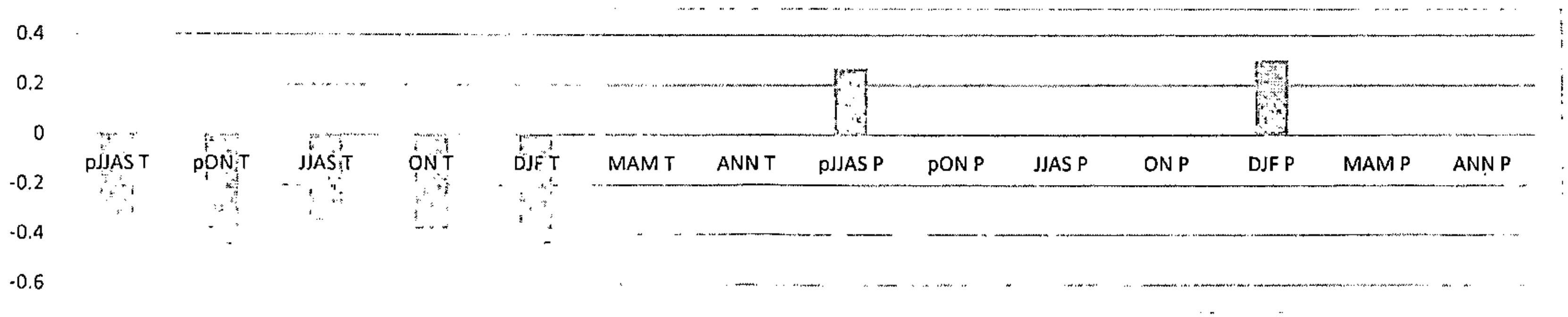

Fig 65 Bootstrapped correlation between seasonal climate and standard totalwood ring chronologies at Kanakuthu

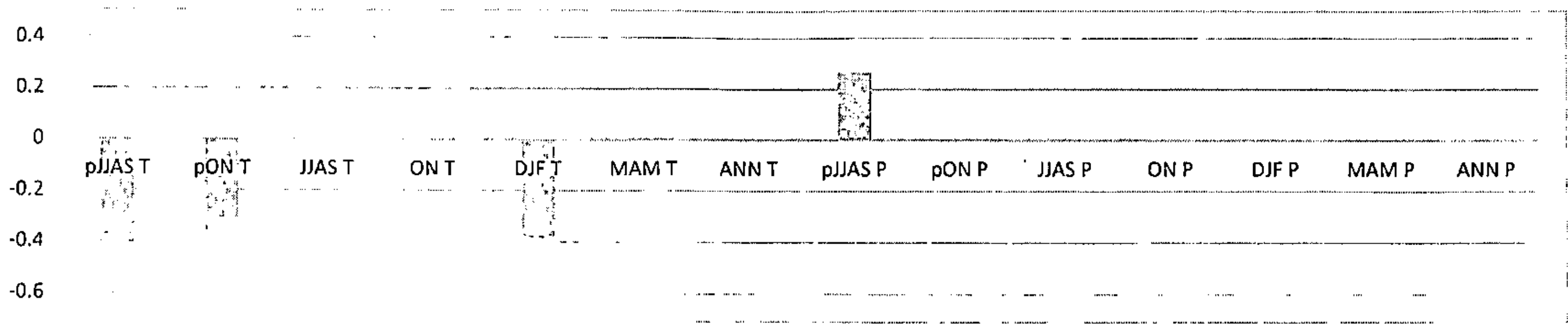

Fig 66 Bootstrapped correlation between seasonal climate and residual earlywood ring chronologies at Kanakuthu

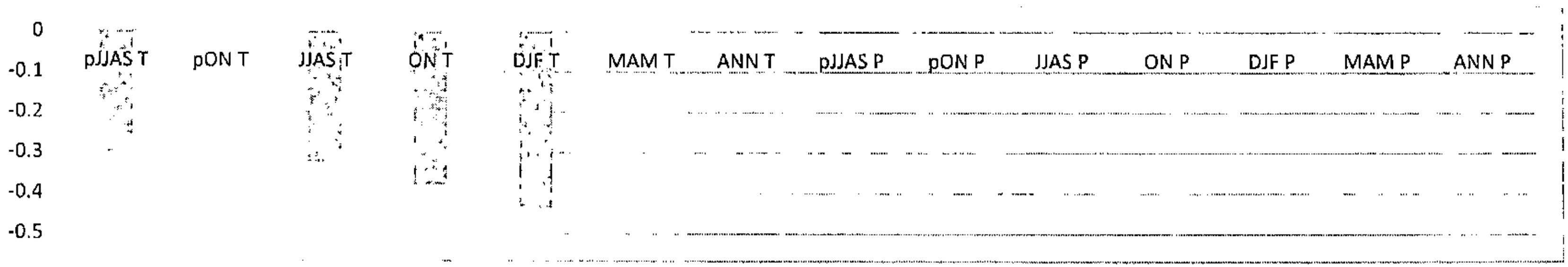

Fig 67 Bootstrapped correlation between seasonal climate and residual latewood ring chronologies at Kanakuthu

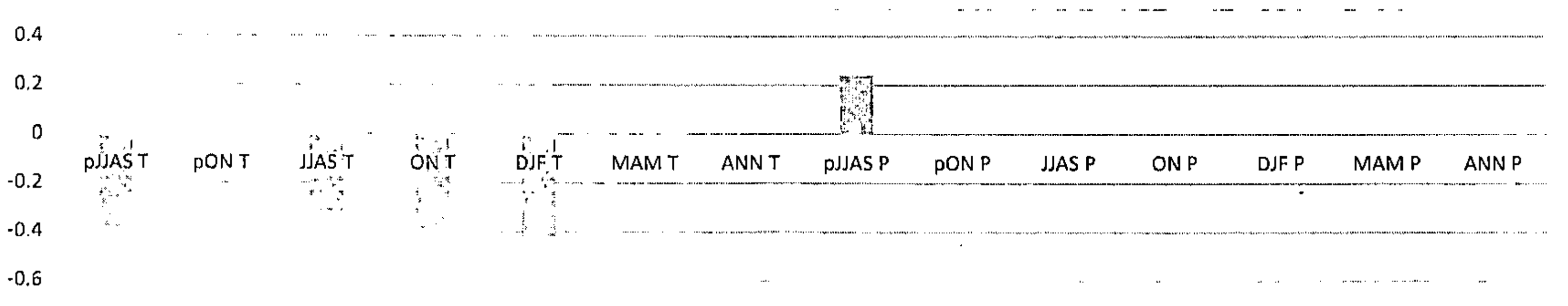

Fig 68 Bootstrapped correlation between seasonal climate and residual totalwood ring chronologies at Kanakuthu

4.8.3 Monthly temperature and ring width

In standard chronologies from Conolly's plot January temperature had negative correlation with earlywood (0.395), latewood (-0.405) as well as totalwood (-0.391). In the residual ringwidth chronology January temperature was negatively correlated with earlywood (-0.395), latewood (-0.424) and totalwood (-0.428). In Edakkode the standard earlywood (-0.333), standard latewood (-0.365) and standard totalwood (-0.372) all were negatively correlated with July temperature of the current year. While in the residual chronologies from Edakkode the latewood showed negative correlation with previous December temperature (-0.361) and July temperature also showed a high negative correlation (-0.420) with latewood chronology. (Table 25-30; Figure 69-86). October temperature was negatively correlated (-0.427) with standard earlywood at Kanakuthu, also December temperature was negatively (-0.399) correlated with standard totalwood chronology. In residual chronologies august temperature (-0.401) and October temperature (-0.397) were the observed correlation with earlywood.

4.8.4 Monthly rainfall and mean vessel area (MVA)

In Conolly's plot the early wood had maximum climatic signals. In standard earlywood chronology was negatively correlated with January rainfall (-0.404) while it has positive correlation with previous June rainfall (0.3660 and previous September rainfall (0.354). In residual earlywood chronology there was negative correlation with January rainfall (-0.409) and positive correlation with previous june precipitation (0.398). In Edakkode May rainfall was negatively correlated with both standard (-0.429) and residual (-0.429) totalwood chronologies. Also the previous November rainfall was positively correlated with standard (0.487) and residual (0.534) totalwood chronologies. May precipitation had negative correlation with earlywood standard chronology (-0.376) and totalwood residual chronology (-0.366) at Kanakuthu. The July rainfall had positive correlations with standard totalwood (0.378) and residual totalwood (0.384) chronology at Kanakuthu. (Table 31-36, Figure 87-104)

Table 25 Bootstrapped correlation between temperature and standard ringwidth chronologies at Conolly's plot

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		-0.301	-0.372	-0.267		-0.259		-0.395		-0.331	-0.341		-0.241	-0.280					
Late		-0.316	-0.227	-0.282	-0.315	-0.312	-0.331	-0.405	-0.291		-0.335	-0.307	-0.319	-0.264	-0.272	-0.287	0.262	-0.259	
Total		-0.302	-0.329	-0.303	-0.290	-0.286	-0.294	-0.391	-0.280	-0.309	-0.345	-0.326		-0.273	-0.248				

Table 26 Bootstrapped correlation between temperature and residual ringwidth chronologies at Conolly's plot

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		-0.301	-0.373	-0.267		-0.259		-0.395		-0.330	-0.341		-0.241	-0.282					
Late		-0.305	-0.221	-0.280		-0.299	-0.324	-0.424	-0.321	-0.332	-0.384	-0.300	-0.309	-0.273	-0.312	-0.272	0.263	-0.328	
Total		-0.309	-0.315	-0.328		-0.315	-0.325	-0.428	-0.288		-0.360	-0.293			-0.271			-0.239	

Table 27 Bootstrapped correlation between temperature and standard ringwidth chronologies at Edakkode

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		-0.333					-0.295	-0.283					0.331	-0.237	-0.259				-0.253
Late		-0.365			-0.246		-0.267	-0.280						-0.364	-0.245	-0.227	-0.359	-0.238	-0.281
Total		-0.372			-0.227		-0.302	-0.276					0.297	-0.320	-0.249	-0.200			-0.252

Table 28 Bootstrapped correlation between temperature and residual ringwidth chronologies at Edakkode

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		-0.331			-0.218		-0.277						0.330	-0.261		-0.190			-0.259
Late		-0.326			-0.249		-0.361							-0.420	-0.256	-0.253	-0.349	-0.300	-0.333
Total		-0.348			-0.242		-0.299							-0.355	-0.257	-0.279	-0.317	-0.262	-0.323

Table 29 Bootstrapped correlation between temperature and standard ringwidth chronologies at Kanakuthu

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.279				-0.285		-0.355				-0.272			-0.263	-0.352		-0.427	-0.332	-0.386
Late					-0.343	-0.256	-0.320	-0.297			-0.313			-0.341	-0.392		-0.324		-0.380
Total					-0.299		-0.295	-0.255			-0.299			-0.295	-0.351		-0.386		-0.399

Table 30 Bootstrapped correlation between temperature and residual ringwidth chronologies at Kanakuthu

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early					-0.292		-0.299				-0.306			-0.237	-0.401		-0.397	-0.296	-0.375
Late					-0.342		-0.299	-0.299			-0.323			-0.282	-0.375		-0.353		-0.390
Total					-0.311		-0.298	-0.240			-0.331			-0.254	-0.363		-0.368		-0.372

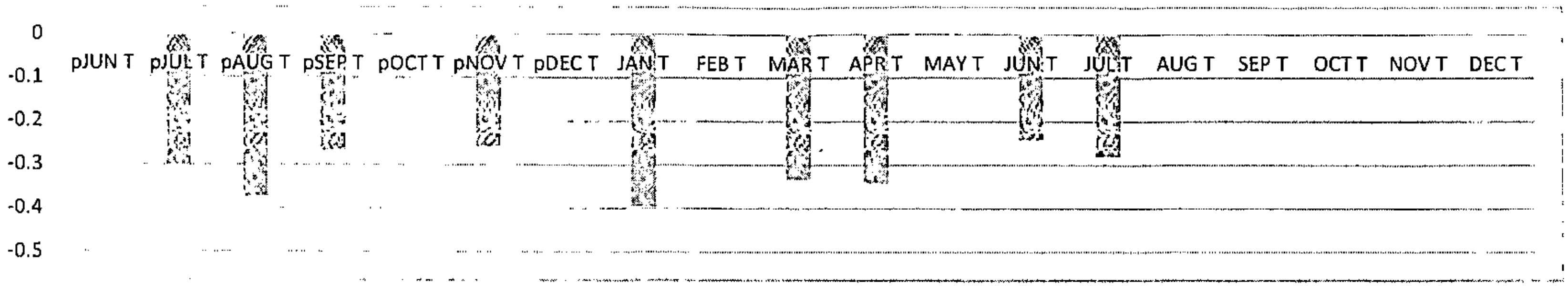

Fig 69 Bootstrapped correlation between temperature and standard earlywood ring width chronologies at Conolly's plot

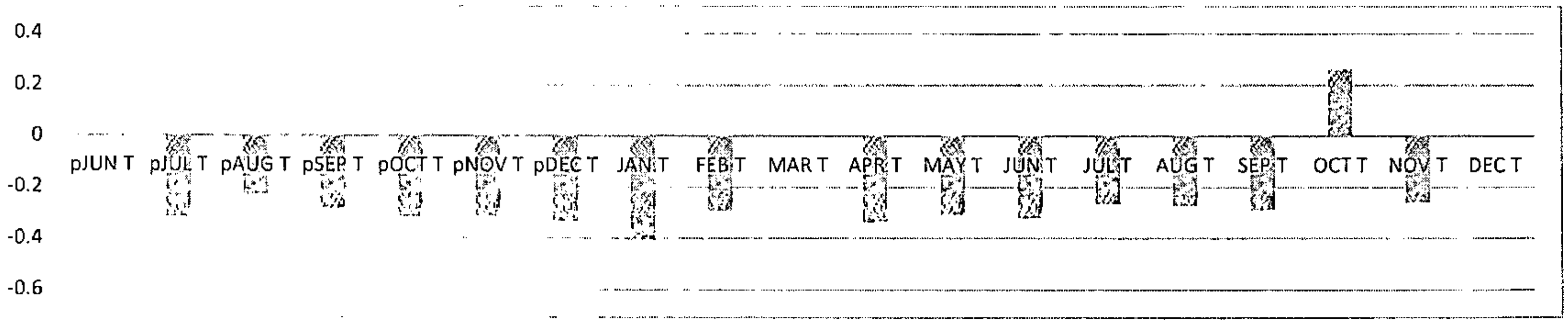

Fig 70 Bootstrapped correlation between temperature and standard latewood ring width chronologies at Conolly's plot

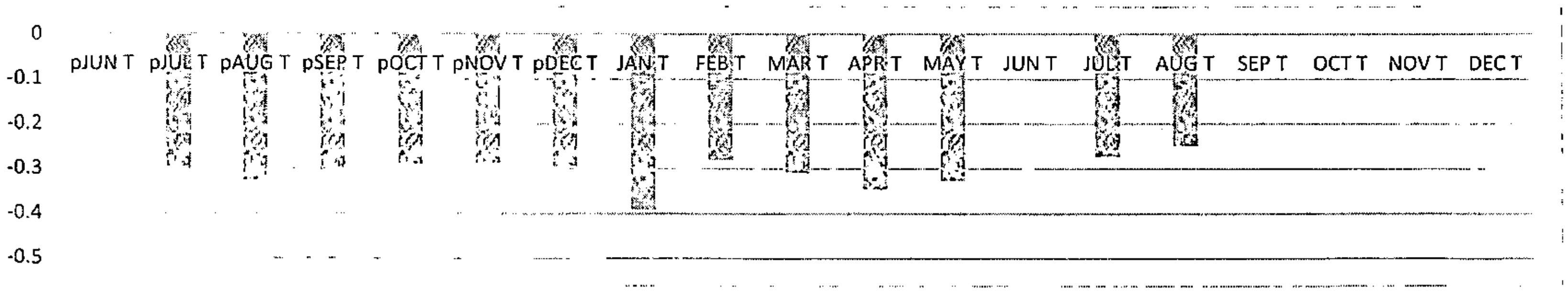

Fig 71 Bootstrapped correlation between temperature and standard totalwood ring width chronologies at Conolly's plot

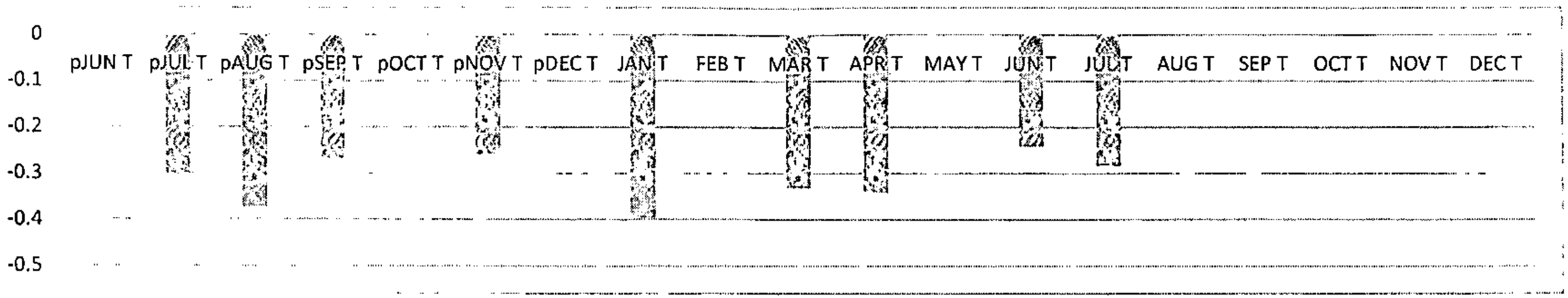

Fig 72 Bootstrapped correlation between temperature and residual earlywood ring width chronologies at Conolly's plot

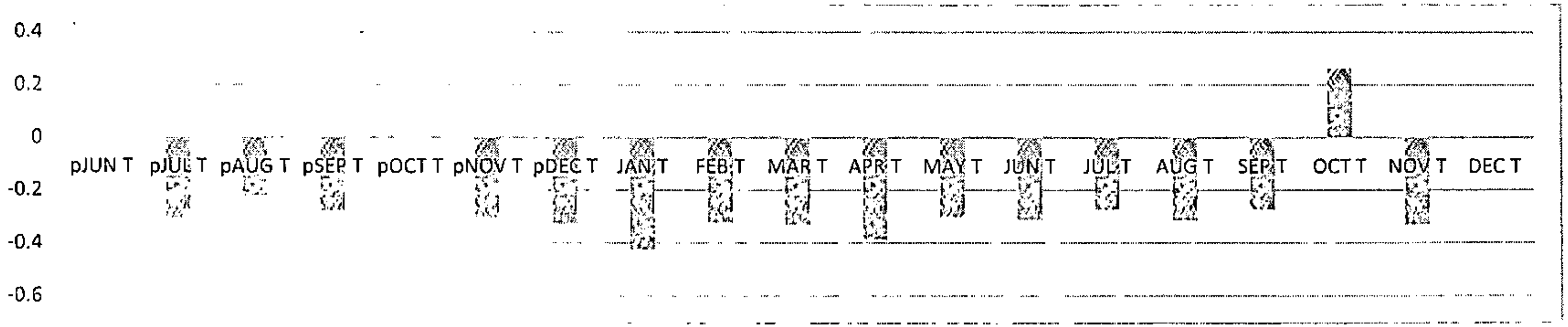

Fig 73 Bootstrapped correlation between temperature and residual latewood ring width chronologies at Conolly's plot

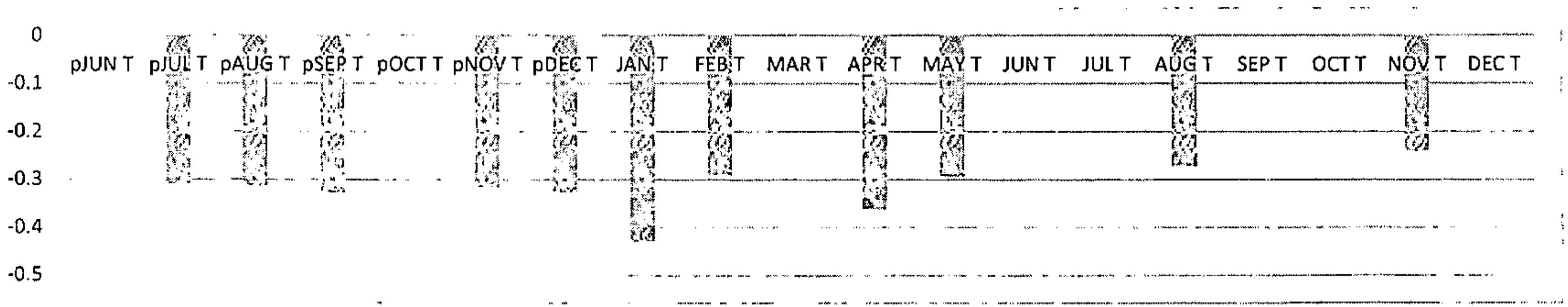

Fig 74 Bootstrapped correlation between temperature and residual totalwood ring width chronologies at Conolly's plot

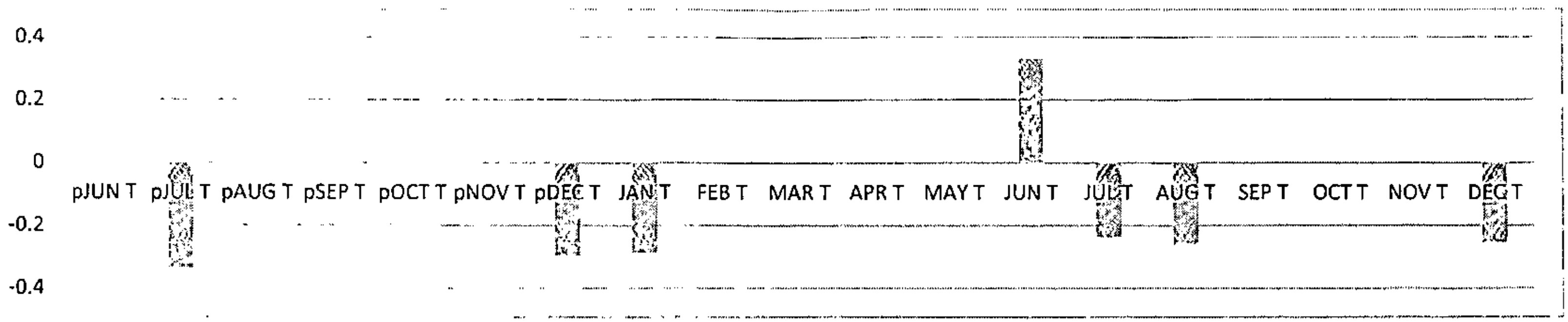

Fig 75 Bootstrapped correlation between temperature and standard earlywood ring width chronologies at Edakkode

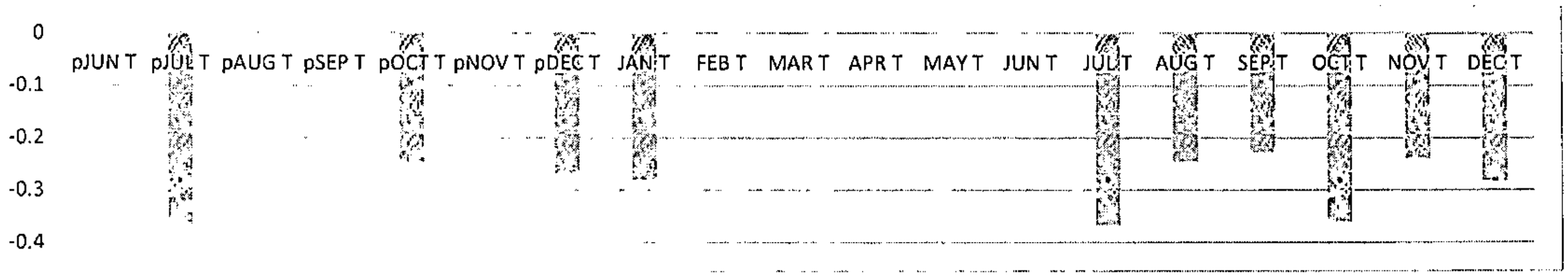

Fig 76 Bootstrapped correlation between temperature and standard latewood ring width chronologies at Edakkode

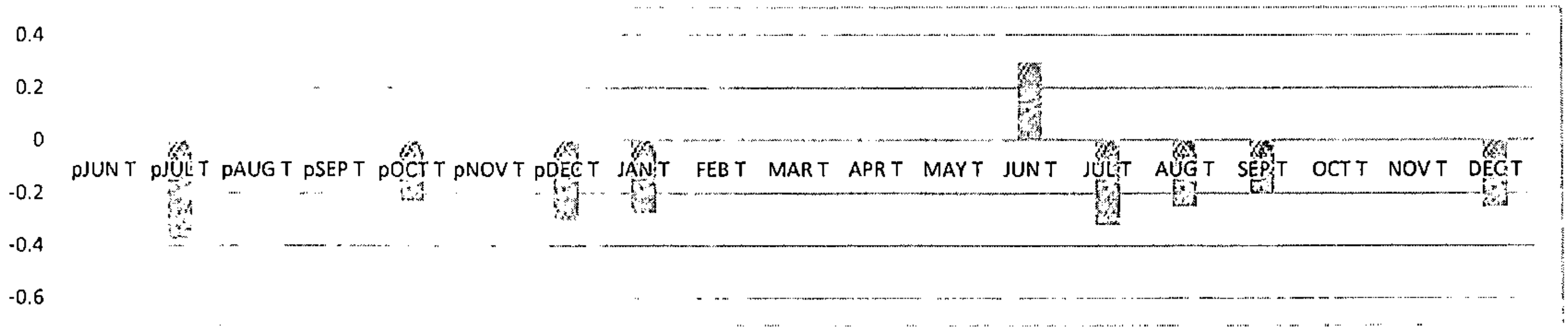

Fig 77 Bootstrapped correlation between temperature and standard totalwood ring width chronologies at Edakkode

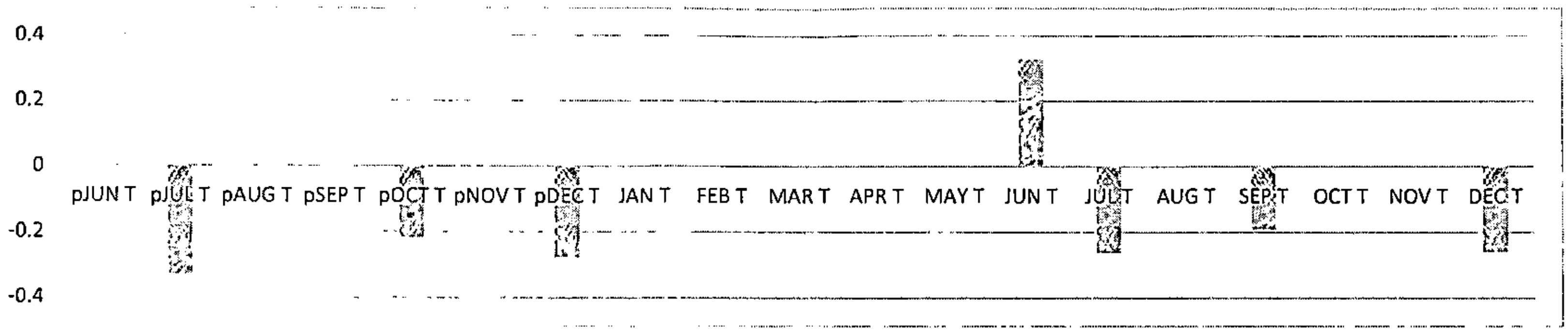

Fig 78 Bootstrapped correlation between temperature and residual earlywood ring width chronologies at Edakkode

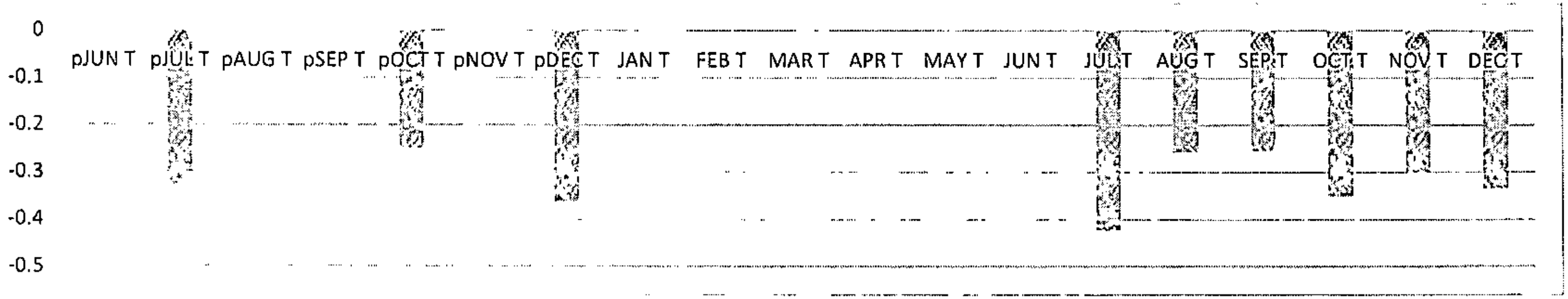

Fig 79 Bootstrapped correlation between temperature and residual latewood ring width chronologies at Edakkode

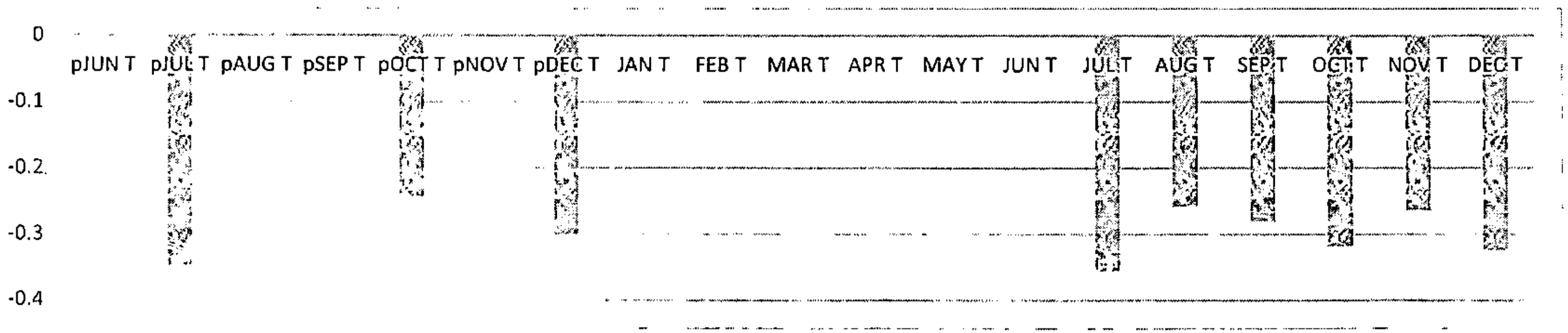

Fig 80 Bootstrapped correlation between temperature and residual totalwood ring width chronologies at Edakkode

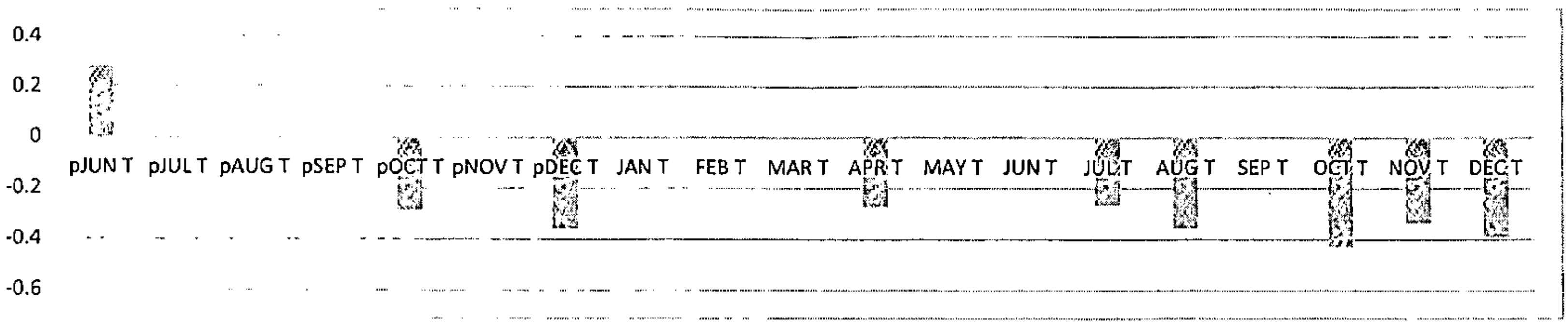

Fig 81 Bootstrapped correlation between temperature and standard earlywood ring width chronologies at Kanakuthu

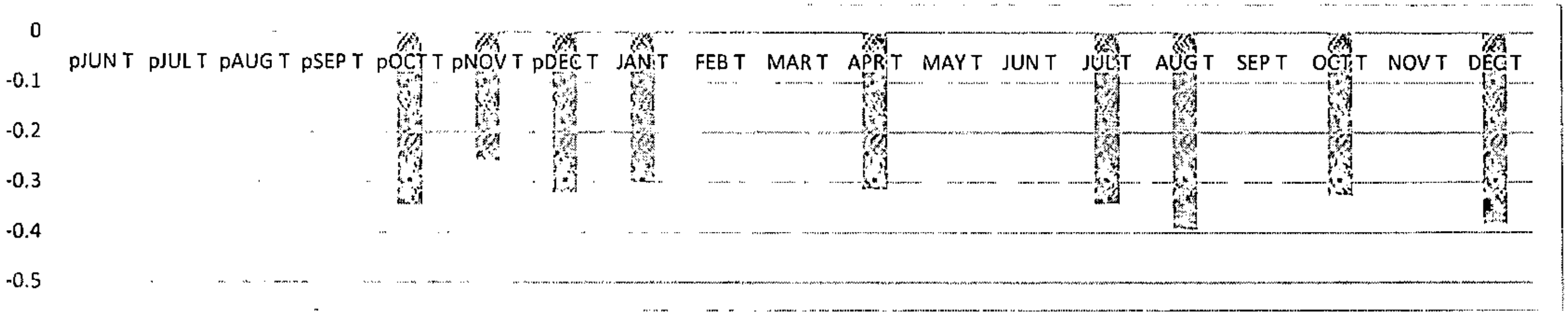

Fig 82 Bootstrapped correlation between temperature and standard latewood ring width chronologies at Kanakuthu

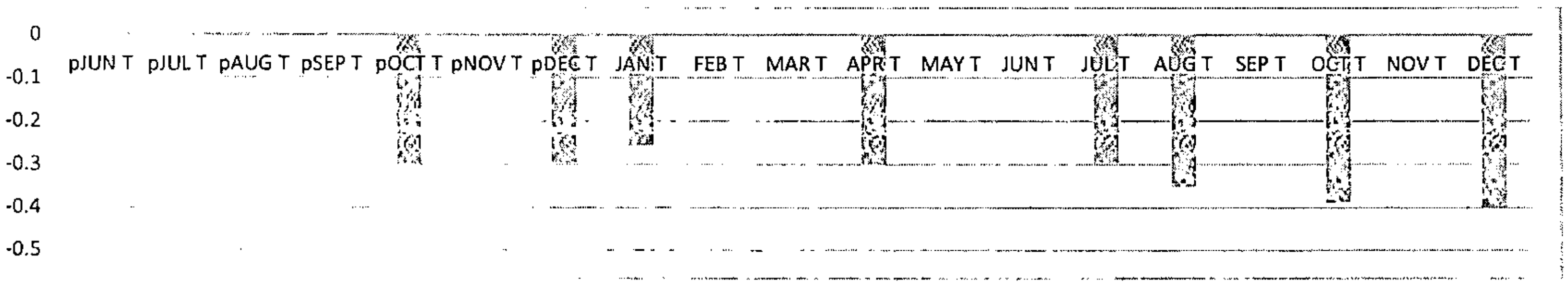

Fig 83 Bootstrapped correlation between temperature and standard totalwood ring width chronologies at Kanakuthu

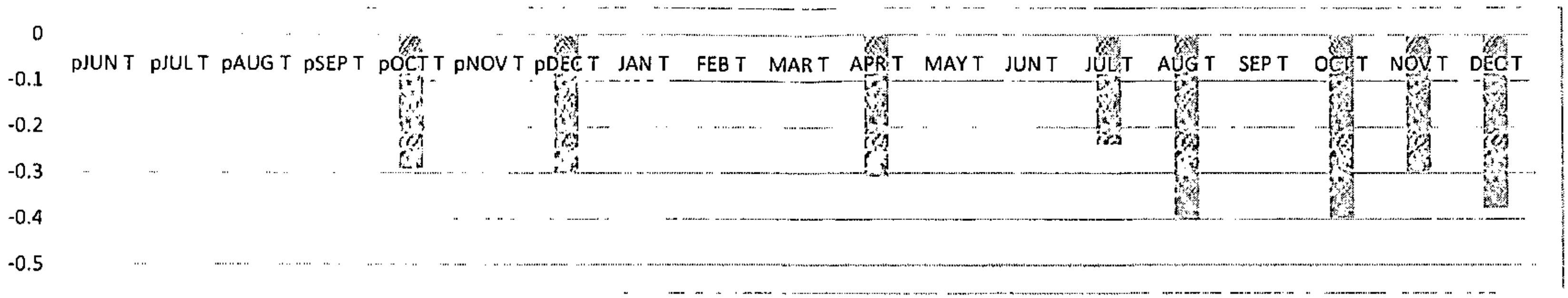

Fig 84 Bootstrapped correlation between temperature and residual earlywood ring width chronologies at Kanakuthu

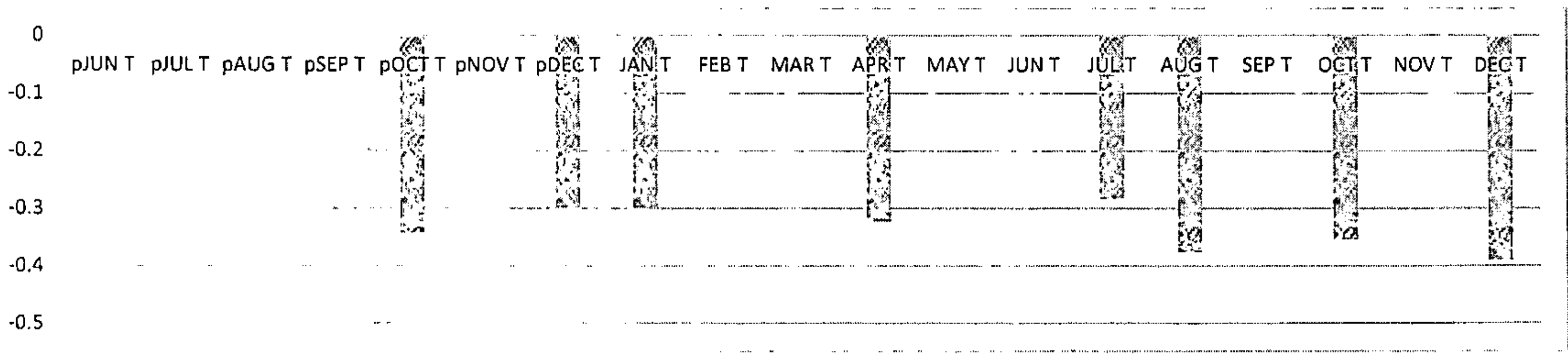

Fig 85 Bootstrapped correlation between temperature and residual latewood ring width chronologies at Kanakuthu

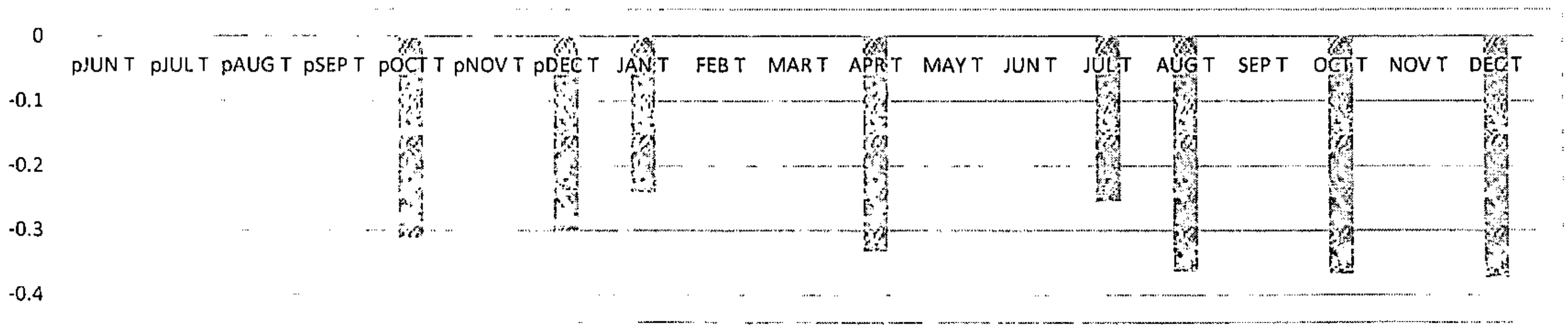

Fig 86 Bootstrapped correlation between temperature and residual totalwood ring width chronologies at Kanakuthu

Table 31 Bootstrapped correlation between precipitation and standard MVA chronologies at Conolly's plot

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early	0.366	0.283		0.354			-0.334	-0.404			0.314	-0.293	-0.311				0.323		0.334
late	-0.372	-0.274		-0.371			0.332	0.316	-0.295	0.335	-0.319	0.252	0.301				-0.272		
total	-0.311			-0.289	0.319	0.302			-0.249	0.317	0.229					-0.314		0.343	-0.268

Table 32 Bootstrapped correlation between precipitation and residual MVA chronologies at Conolly's plot

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early	0.398	0.284		0.335			-0.334	-0.409	0.285		0.314	-0.290	-0.311				0.322		0.353
late	-0.344			-0.397	0.346		0.331		-0.310	0.366	-0.318		-0.293				-0.212		
total	-0.303			-0.346		0.284			-0.253	0.033	0.262				-0.283	-0.273		0.267	-0.280

Table 33 Bootstrapped correlation between precipitation and standard MVA chronologies at Edakkode

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early		-0.242			-0.311		-0.291		0.219			0.229		-0.371		0.321			
late	0.315		-0.336	-0.306		0.487				-0.235		-0.331	0.299					0.359	
total	0.230					0.534			0.307			-0.429		-0.263					0.255

Table 34 Bootstrapped correlation between precipitation and residual MVA chronologies at Edakkode

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early					-0.312		-0.255				-0.242			-0.339	0.387				
late	0.320		-0.318	-0.289		0.385				-0.313	-0.340	-0.281						0.394	
total	0.230					0.534			0.307			-0.429		-0.263					0.255

Table 35 Bootstrapped correlation between precipitation and standard MVA chronologies at Kanakuthu

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early		0.324	0.275				0.301		0.325	0.342		-0.376		0.377					
late				-0.254				-0.354											
total							0.276				0.356	-0.369		0.378	0.297				

Table 36 Bootstrapped correlation between precipitation and residual MVA chronologies at Kanakuthu

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early		0.204	0.281		0.285		0.322	-0.257		0.248		-0.334		0.383	0.272				
late				-0.307	-0.263														
total							0.277	-0.188			0.357	-0.366		0.384	0.301				

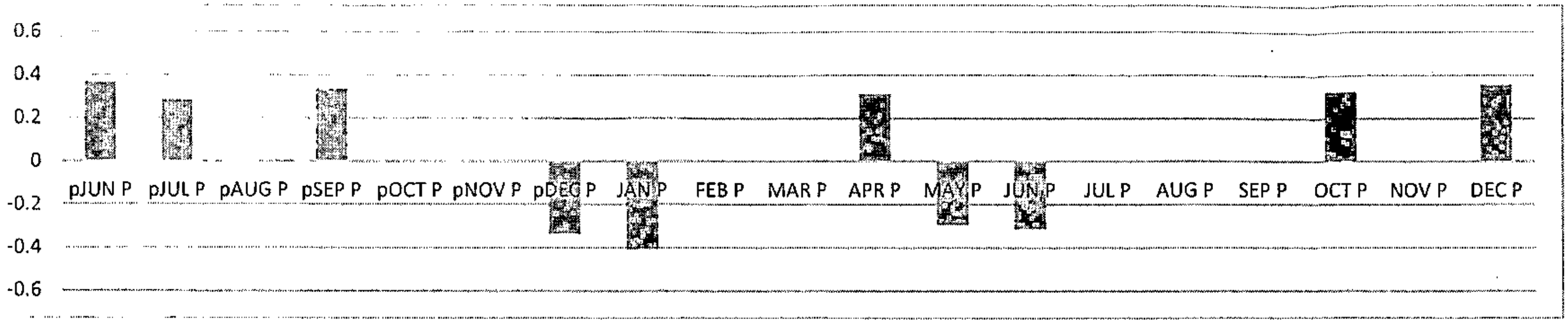

Fig 87 Bootstrapped correlation between rainfall and standard earlywood MVA chronologies at Conolly's plot

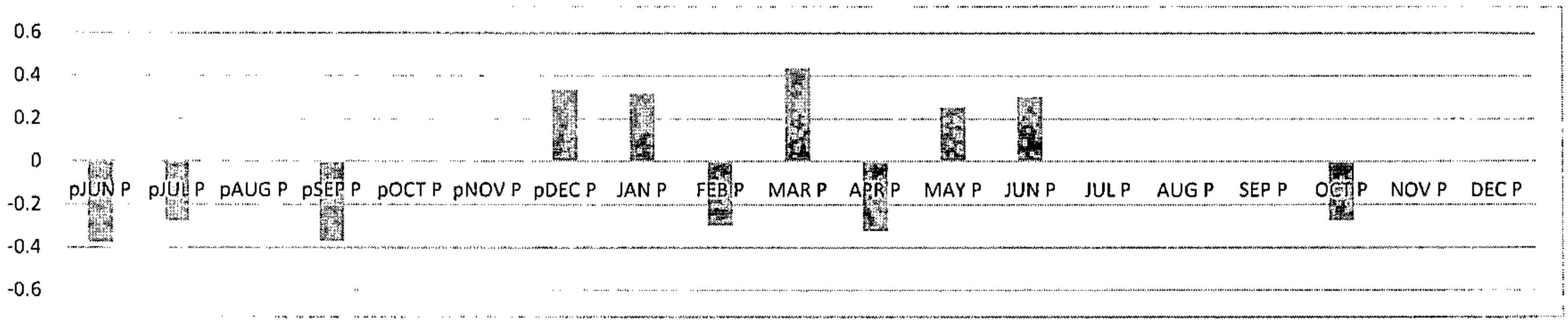

Fig 88 Bootstrapped correlation between rainfall and standard latewood MVA chronologies at Conolly's plot

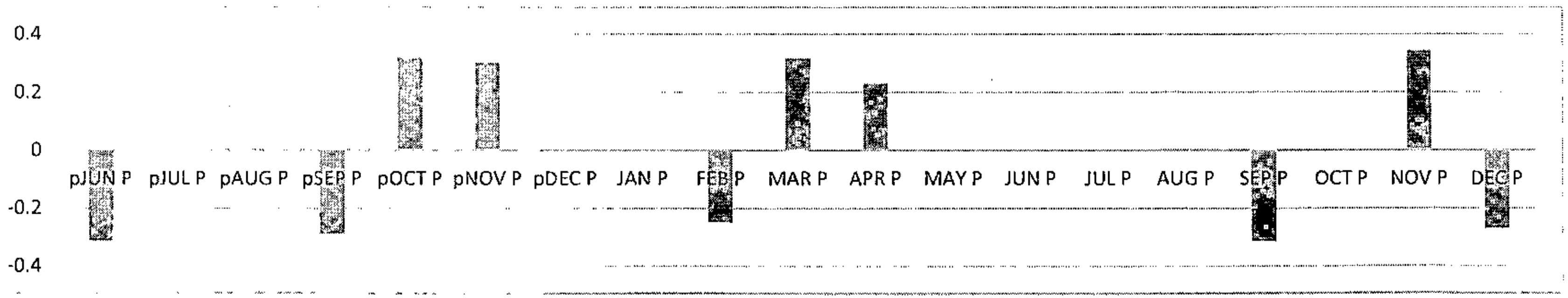

Fig 89 Bootstrapped correlation between rainfall and standard totalwood MVA chronologies at Conolly's plot

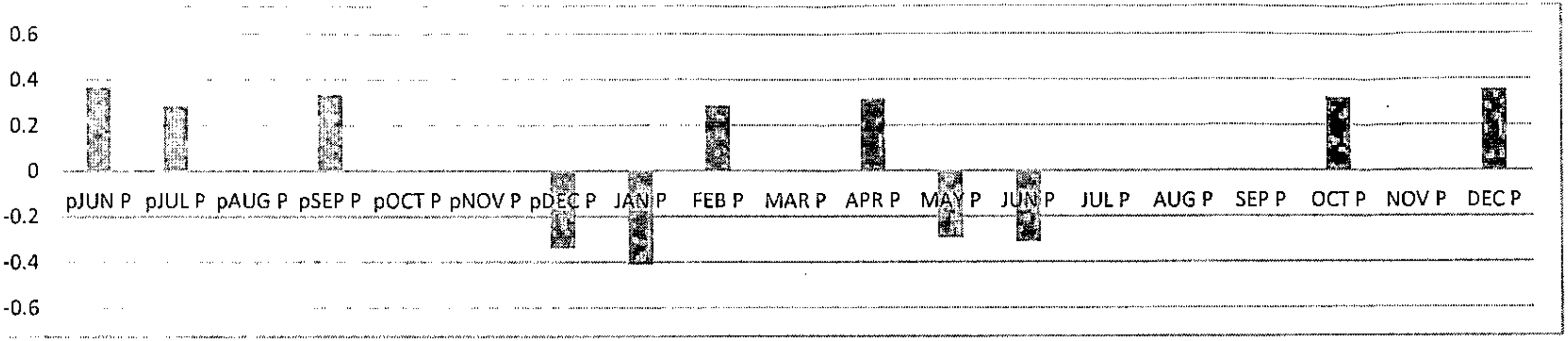

Fig 90 Bootstrapped correlation between rainfall and residual earlywood MVA chronologies at Conolly's plot

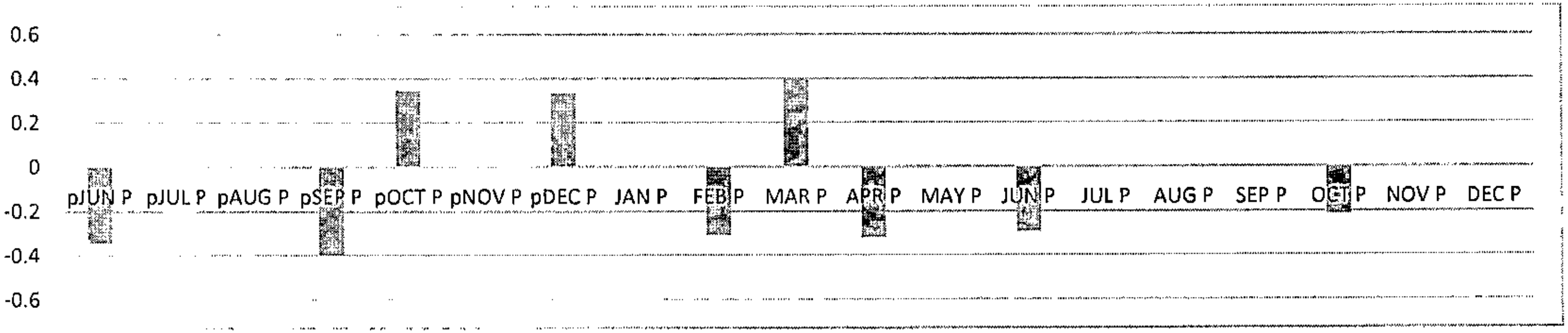

Fig 91 Bootstrapped correlation between rainfall and residual latewood MVA chronologies at Conolly's plot

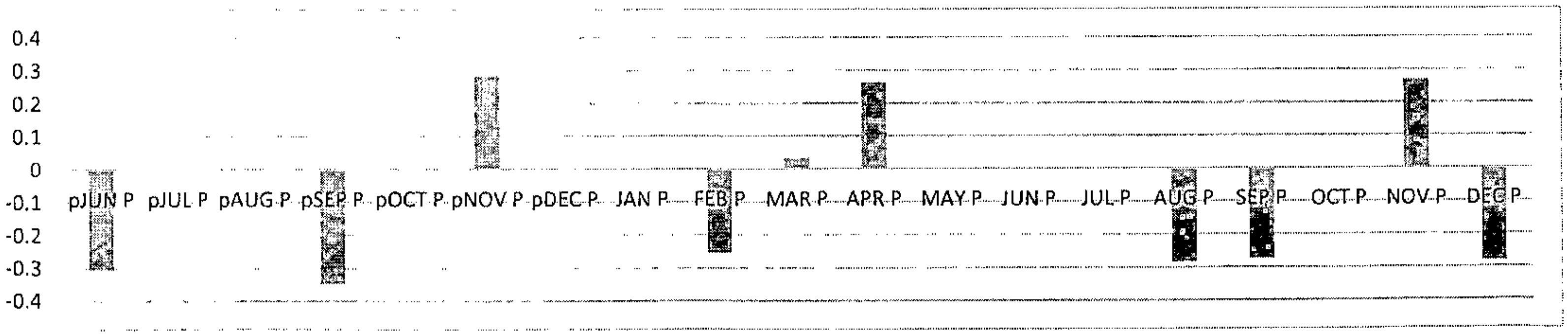

Fig 92 Bootstrapped correlation between rainfall and residual latewood MVA chronologies at Conolly's plot

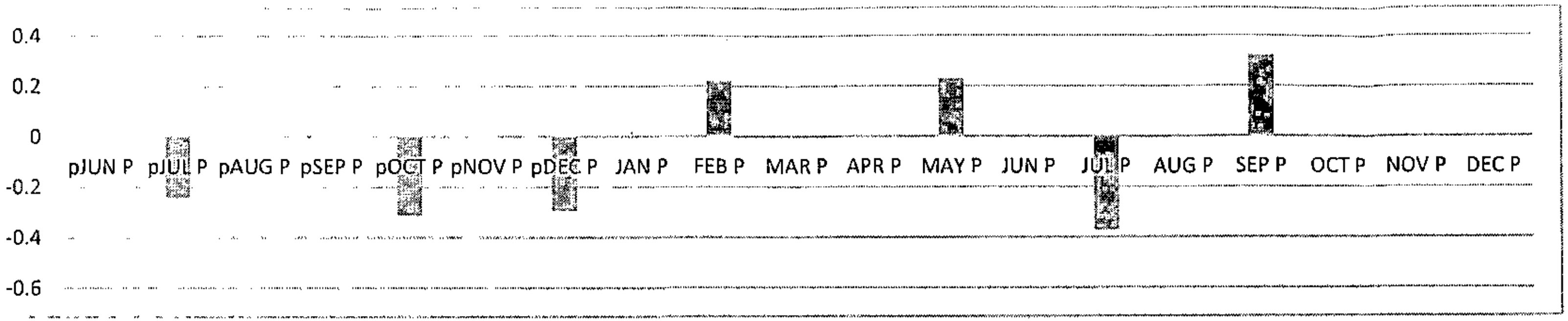

Fig 93 Bootstrapped correlation between rainfall and standard earlywood MVA chronologies at Edakkode

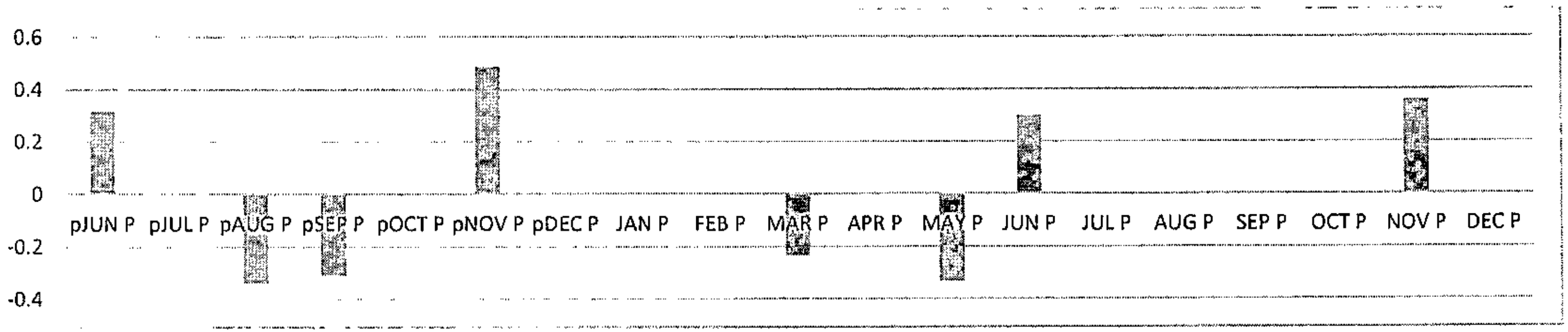

Fig 94 Bootstrapped correlation between rainfall and standard latewood MVA chronologies at Edakkode

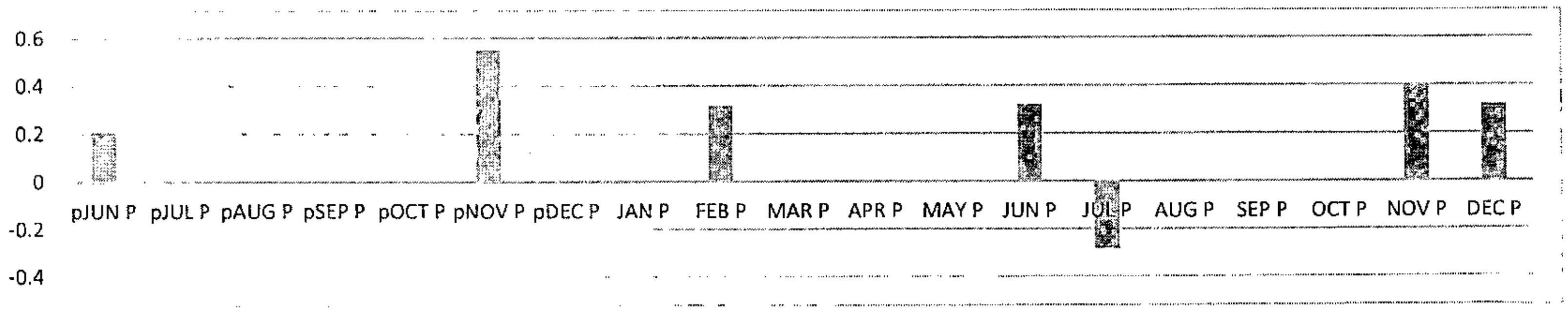

Fig 95 Bootstrapped correlation between rainfall and standard totalwood MVA chronologies at Edakkode

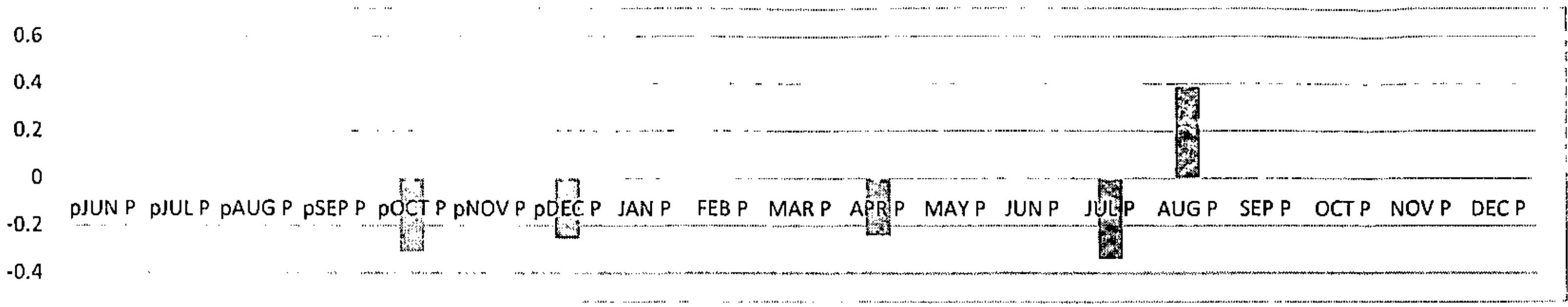

Fig 96 Bootstrapped correlation between rainfall and residual earlywood MVA chronologies at Edakkode

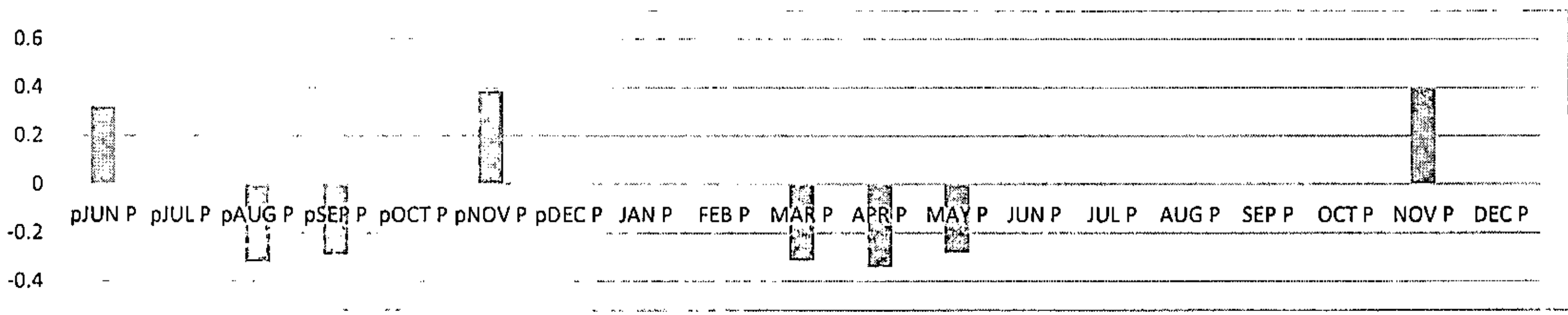

Fig 97 Bootstrapped correlation between rainfall and residual latewood MVA chronologies at Edakkode

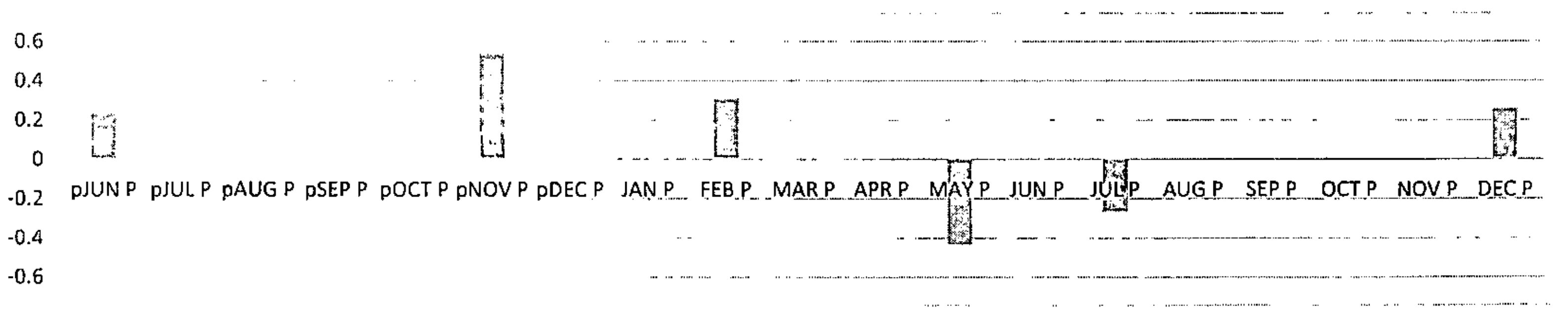

Fig 98 Bootstrapped correlation between rainfall and residual totalwood MVA chronologies at Edakkode

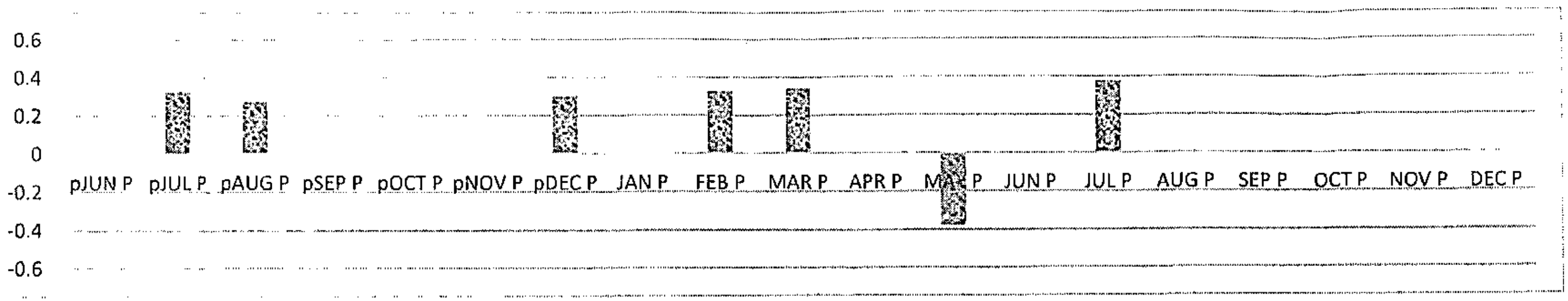

Fig 99 Bootstrapped correlation between rainfall and standard earlywood MVA chronologies at Kanakuthu

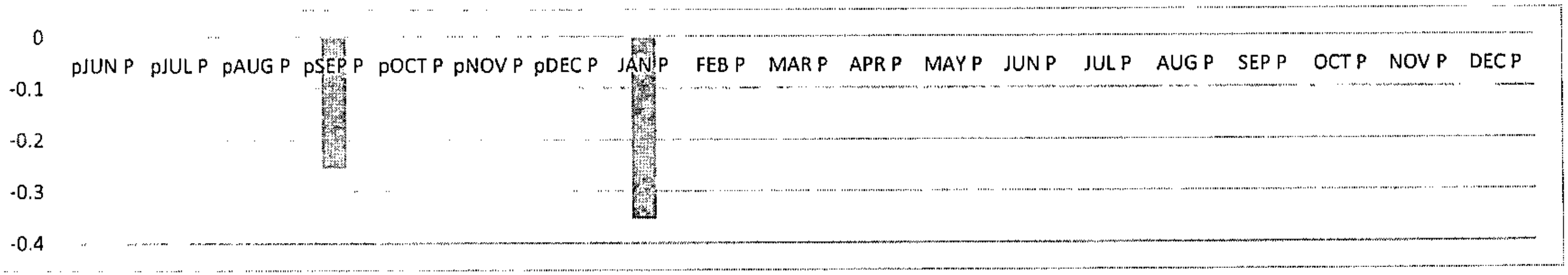

Fig 100 Bootstrapped correlation between rainfall and standard latewood MVA chronologies at Kanakuthu

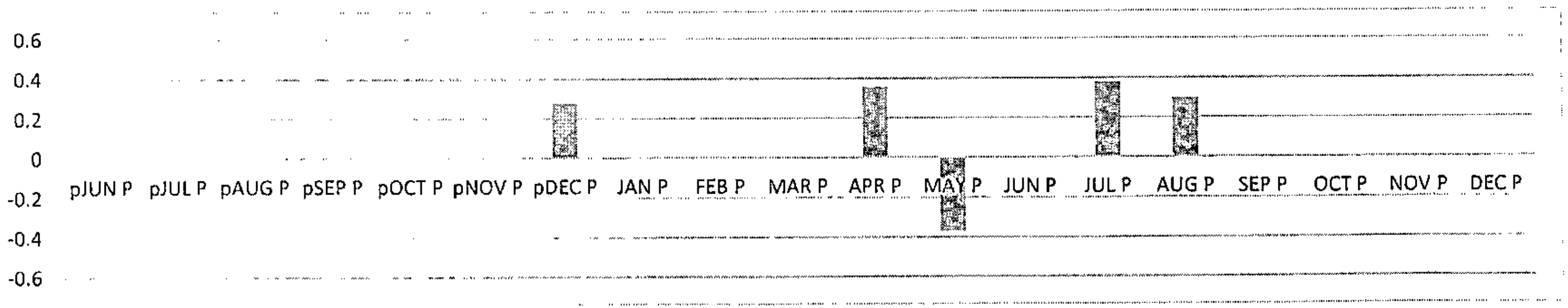

Fig 101 Bootstrapped correlation between rainfall and standard totalwood MVA chronologies at Kanakuthu

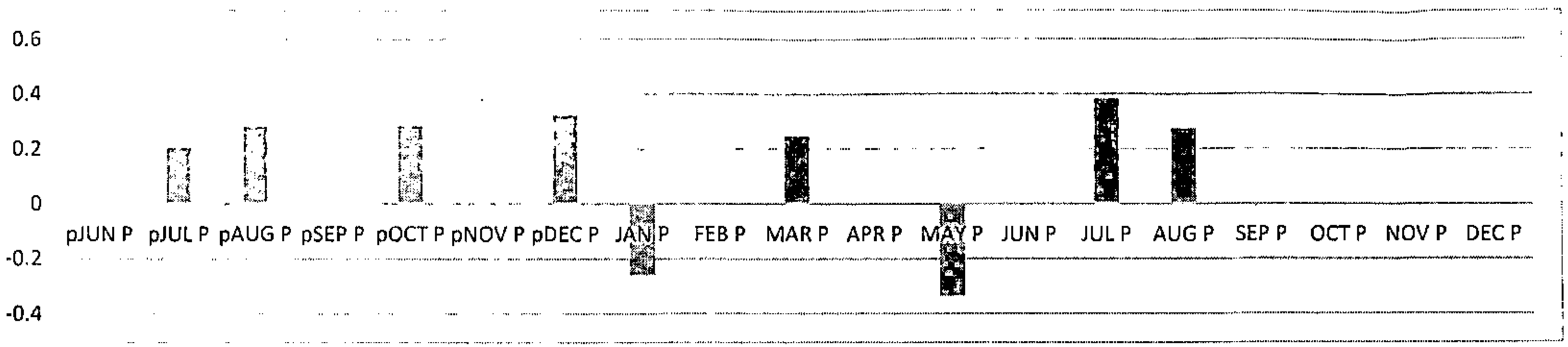

Fig 102 Bootstrapped correlation between rainfall and residual earlywood MVA chronologies at Kanakuthu

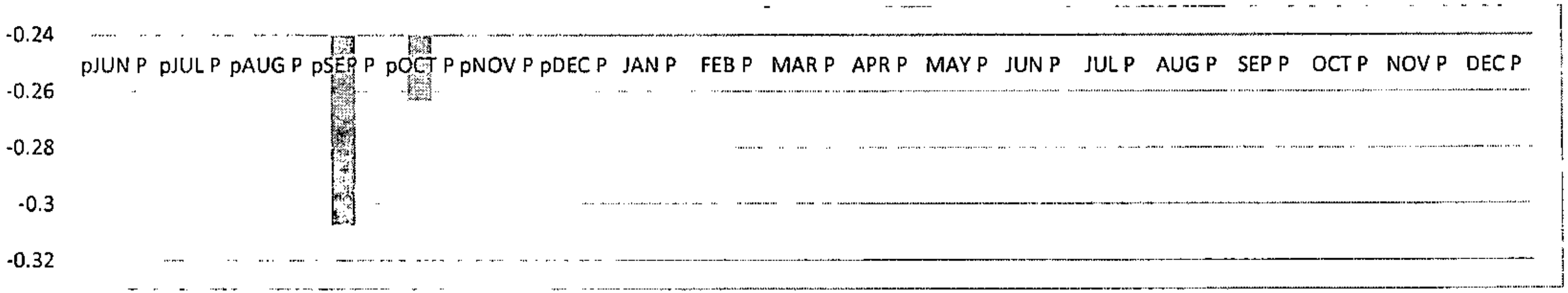

Fig 103 Bootstrapped correlation between rainfall and residual latewood MVA chronologies at Kanakuthu

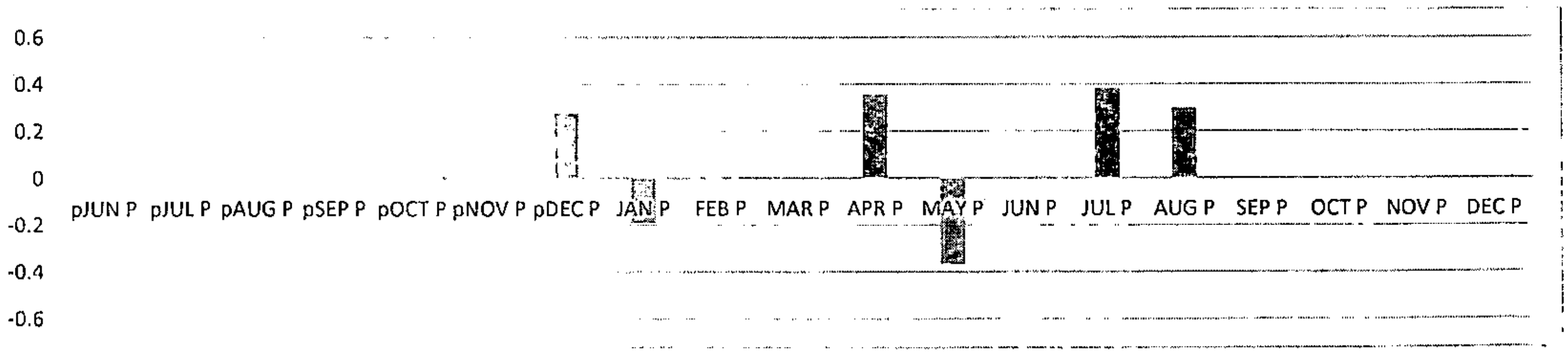

Fig 104 Bootstrapped correlation between rainfall and residual totalwood MVA chronologies at Kanakuthu

4.8.5 Seasonal climate and mean vessel area

The March-May temperature had negative correlation (-0.465) with standard totalwood MVA and October-November temperature had positive correlation with standard latewood MVA at Edakkode. Previous October-November precipitation had positive influence (0.335) on standard latewood MVA. The residual totalwood chronology at Edakkode had negative correlation with March-May temperature (-0.462) while the residual latewood chronology had positive correlation with June-September temperature (0.402) and previous October-November rainfall (0.377).

At Kanakuthu standard totalwood chronology was negatively correlated with March-May temperature (-0.419) and positively correlated with October-November temperature (0.450) and previous June-September rainfall (0.365). In case of residual chronologies at Kanakuthu the totalwood was negatively correlated with March-May temperature (-0.409) and positively correlated with October-November temperature (0.435) while the earlywood chronology was positively correlated with previous June-September rainfall (0.379). In Conolly's plot the standard and residual totalwood MVA chronologies were positivel correlated with June-September rainfall with values of 0.330 and 0.326 respectively. Negative correlations were observed between latewood standard (-0.394) October-November temperature and totalwood residual and June-September temperature (-0.345). (Table 37-42, Figure 105-122).

4.8.6 Monthly temperature and mean vessel area

In Conolly's plot previous Novemeber temperature was negatively correlated (-0.422) with standard latewood chronology and previous June temperature was positively correlated with the same (0.379). In the residual version there was negative correlation between November temperature and totalwood (-0.383), positive correlation with previous June temperature and latewood (0.377). At Edakkode standard and residual earlywood chronologies were negatively correlated with June temperature with values -0.381 and -0.407 respectively. The November temperature was positively correlated with standard latewood (0.367) and residual earlywood chronologies (0.392). There were negative correlations between previous June temperature and standard (-0.374) and residual (-0.351) latewood chronologies at Kanakuthu. While May temperature was positively correlated with standard earlywood (0.392) and March temperature was positively correlated (0.349) with residual latewood chronology. Table 43-48; Figure 123-14.

Table 37 Bootstrapped correlation between seasonal variables and standard MVA chronologies at Edakkode

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.377		0.404					0.306			0.283			
Late	0.365	0.474	0.487	0.488	0.504	-0.445			0.335					
Total			0.370	0.304	0.284	-0.465			0.319	0.276				

Table 38 Bootstrapped correlation between seasonal variables and residual MVA chronologies at Edakkode

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early	-0.423							0.306				0.287		
Late		0.362	0.402	0.391	0.418	-0.438			0.377					
Total			0.363	0.307		-0.462				0.276				

Table 39 Bootstrapped correlation between seasonal variables and standard MVA chronologies at Kanakuthu

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early			0.353	0.355		-0.377		0.361	-0.341					
Late	-0.351	-0.286	-0.408	-0.342	-0.251						0.322			
Total			0.355	0.450	0.336	-0.419		0.365	-0.290			0.291		

Table 40 Bootstrapped correlation between seasonal variables and residual MVA chronologies at Kanakuthu

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early			0.301			-0.339		0.379	-0.313			0.312		
Late			0.294	0.292								0.305		
Total			0.365	0.435	0.324	-0.409		0.367	-0.289			0.291		

Table 41 Bootstrapped correlation between seasonal variables and standard MVA chronologies at Conolly's plot

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early			-0.308					-0.246	0.303	0.315	-0.270			
Late		-0.303	-0.362	-0.394	-0.362				-0.313		0.271			
Total	-0.365	-0.343	-0.355		-0.318				0.282	0.330	-0.239			

Table 42 Bootstrapped correlation between seasonal variables and standard MVA chronologies at Conolly's plot

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early			-0.306					-0.246	0.304	0.315	-0.267			
Late	0.329		-0.315	-0.304	-0.309				-0.287					
Total	-0.339	-0.340	-0.345		-0.298				0.267	0.326	-0.240			

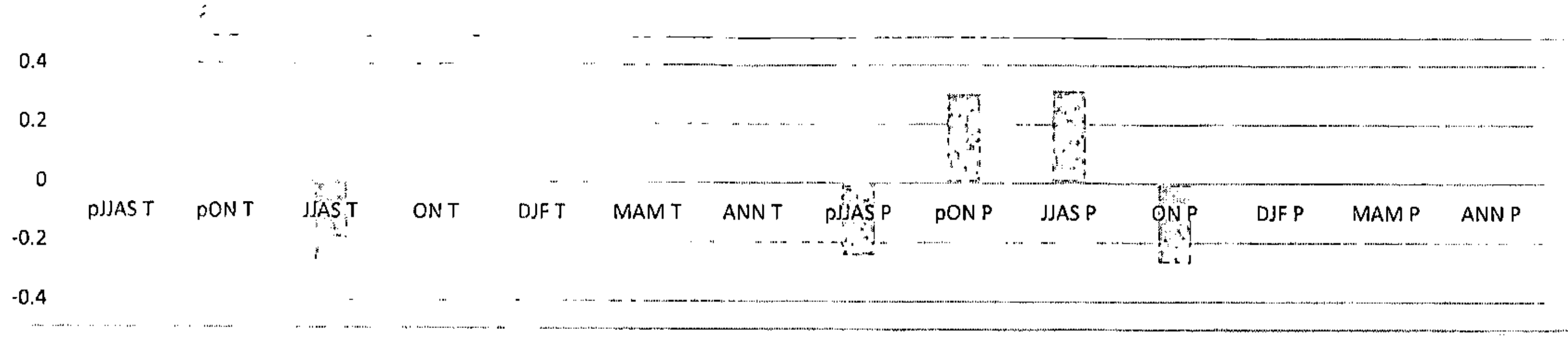

Fig 105 Bootstrapped correlation between seasonal climate and standard earlywood MVA chronologies at Conolly's plot

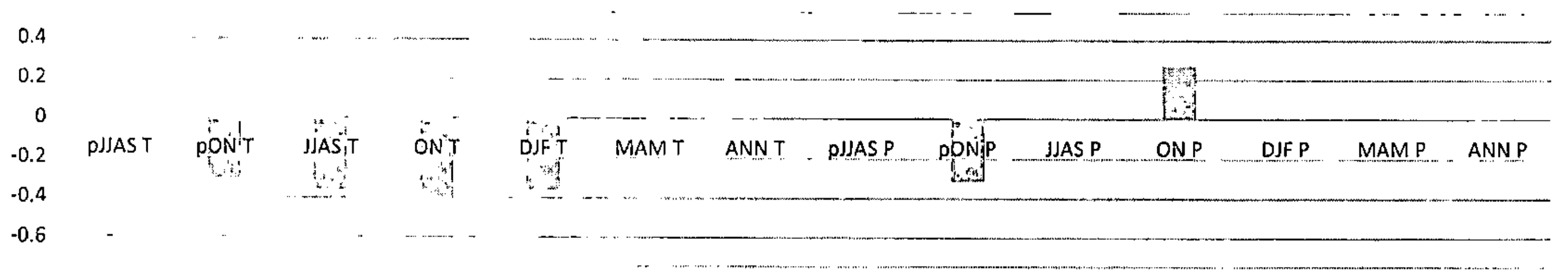

Fig 106 Bootstrapped correlation between seasonal climate and standard latewood MVA chronologies at Conolly's plot

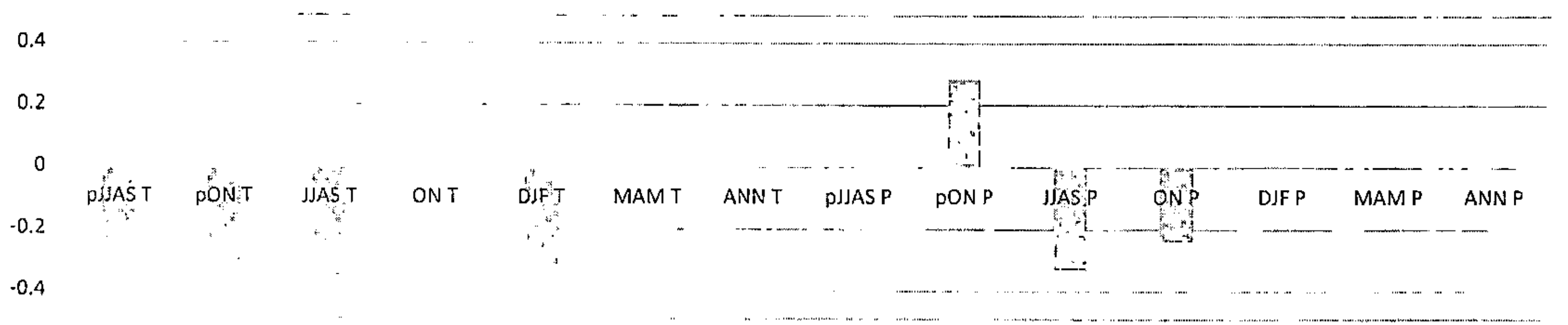

Fig 107 Bootstrapped correlation between seasonal climate and standard totalwood MVA chronologies at Conolly's plot

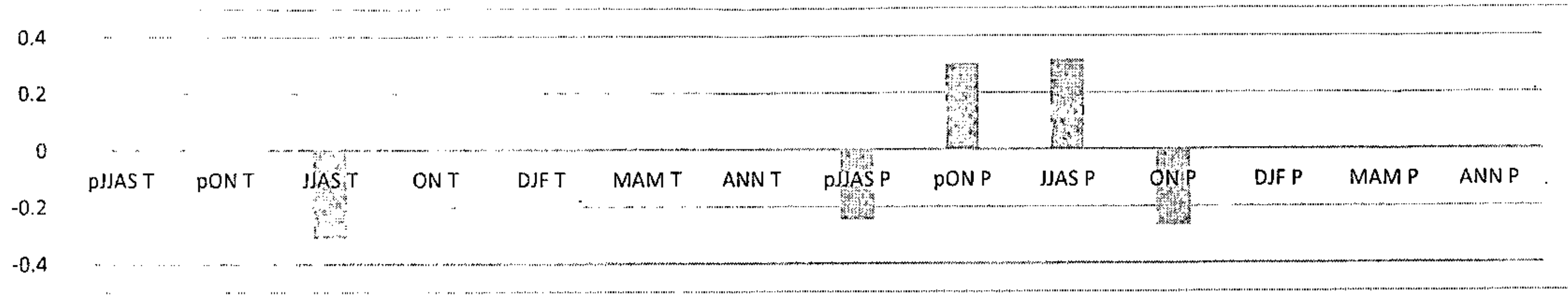

Fig 108 Bootstrapped correlation between seasonal climate and residual earlywood MVA chronologies at Conolly's plot

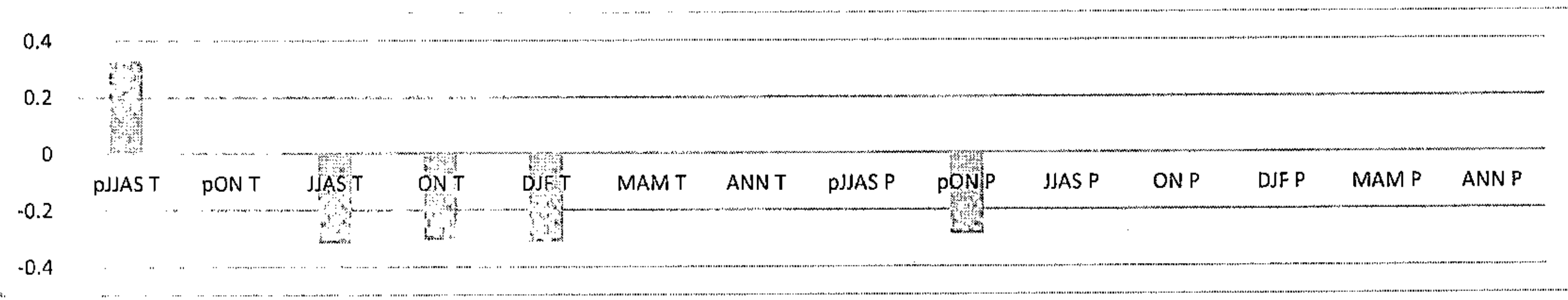

Fig 109 Bootstrapped correlation between seasonal climate and residual latewood MVA chronologies at Conolly's plot

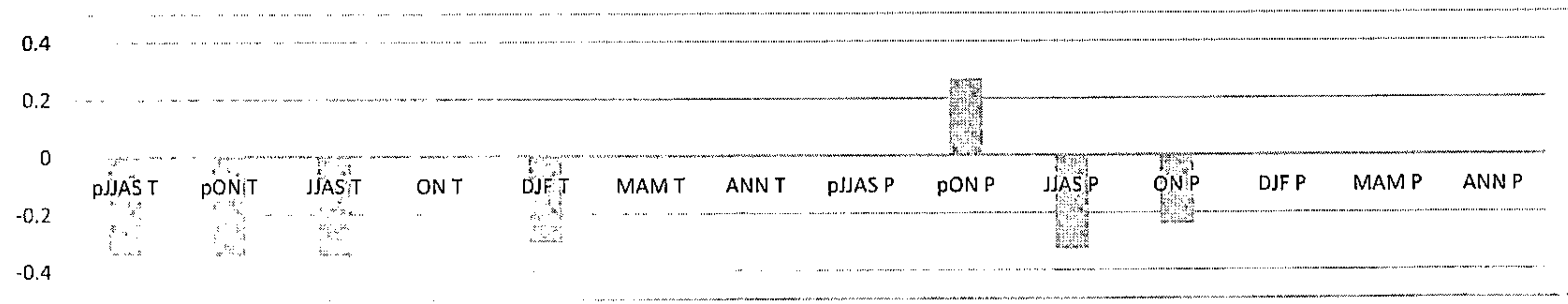

Fig 110 Bootstrapped correlation between seasonal climate and residual totalwood MVA chronologies at Conolly's plot

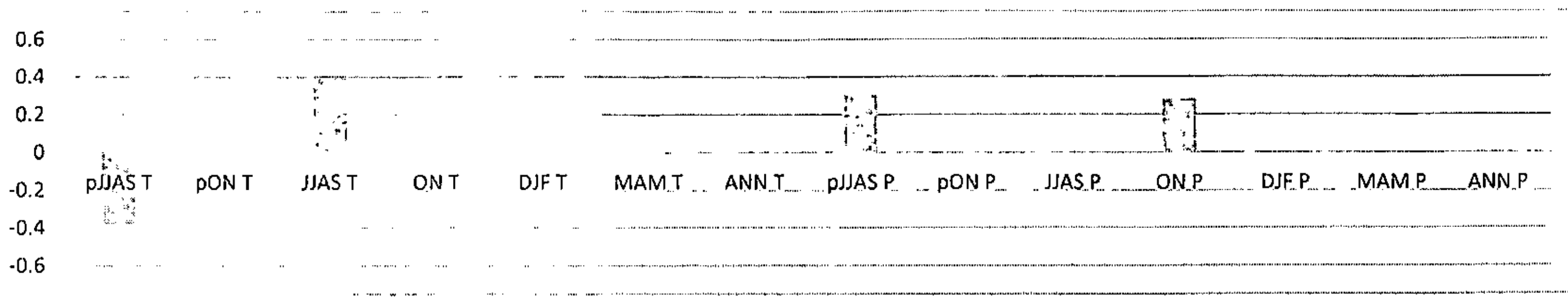

Fig 111 Bootstrapped correlation between seasonal climate and standard earlywood MVA chronologies at Edakkode

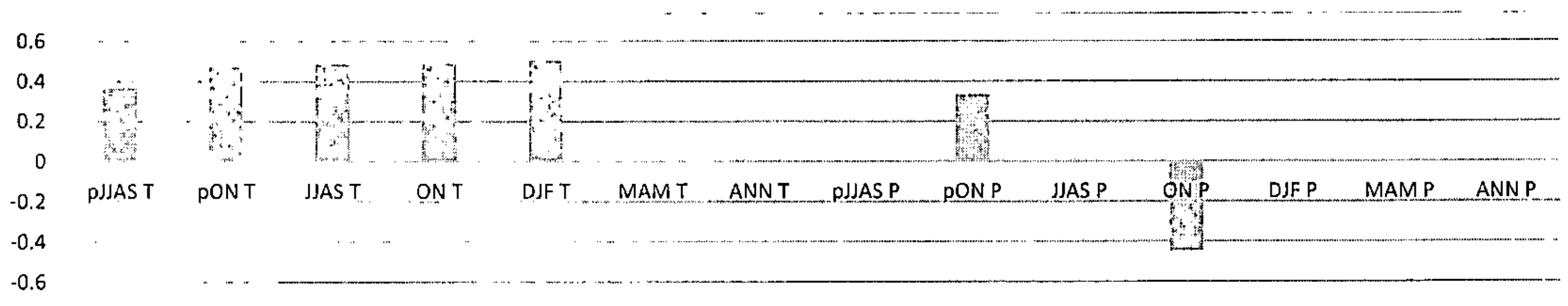

Fig 112 Bootstrapped correlation between seasonal climate and standard latewood MVA chronologies at Edakkode

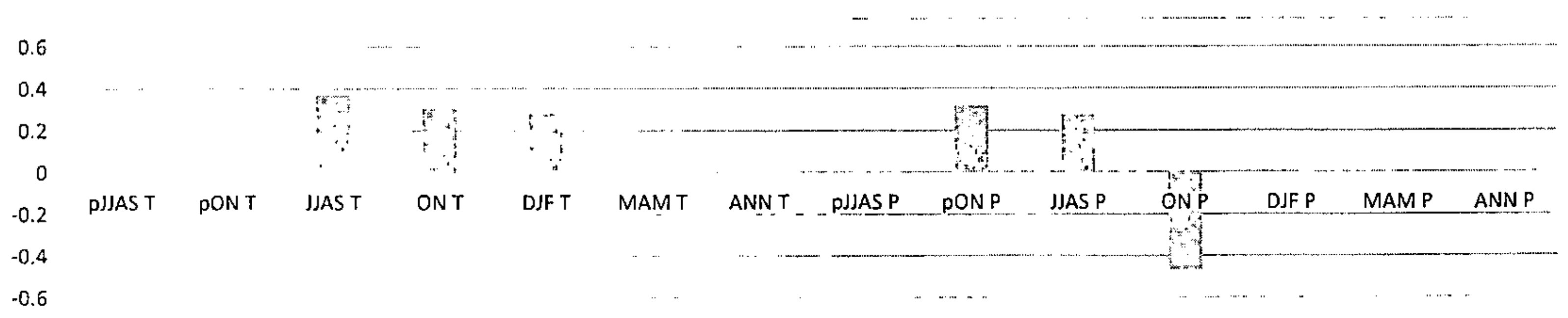

Fig 113 Bootstrapped correlation between seasonal climate and standard totalwood MVA chronologies at Edakkode

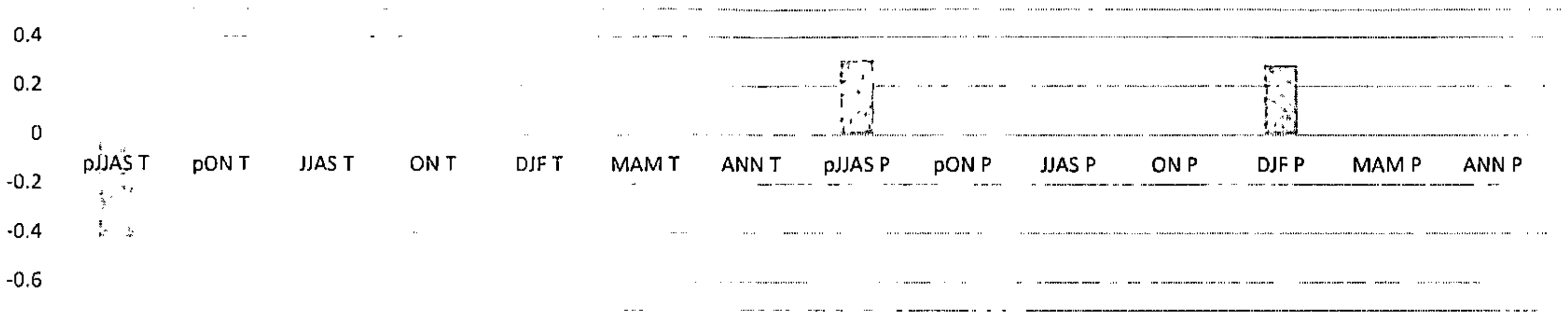

Fig 114 Bootstrapped correlation between seasonal climate and residual earlywood MVA chronologies at Edakkode

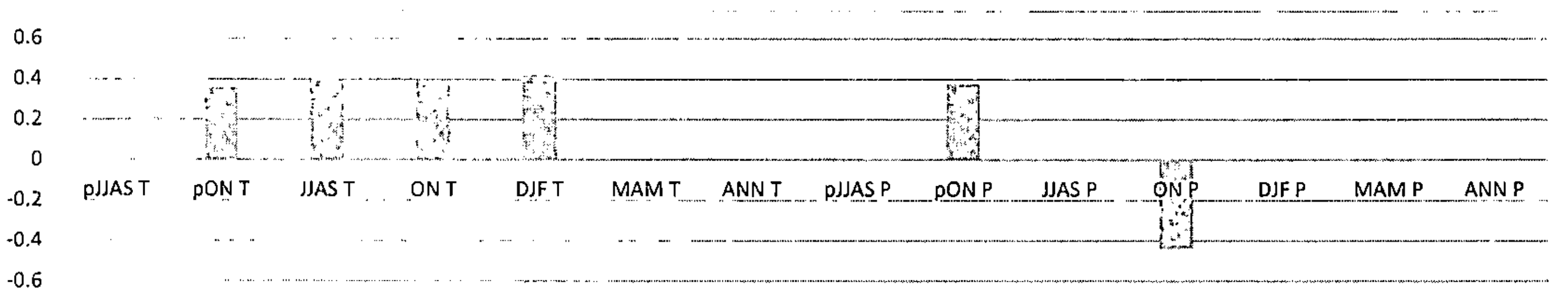

Fig 115 Bootstrapped correlation between seasonal climate and residual latewood MVA chronologies at Edakkode

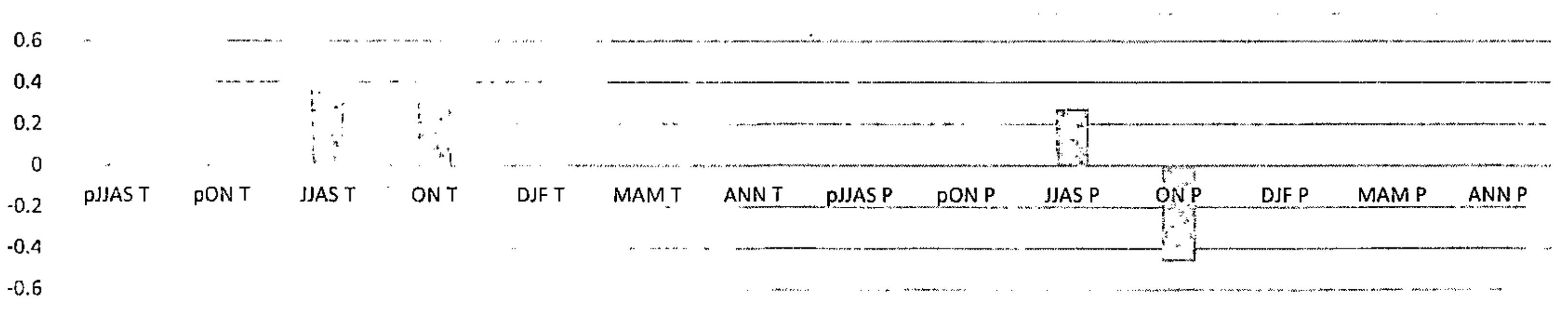

Fig 1116 Bootstrapped correlation between seasonal climate and residual totalwood MVA chronologies at Edakkode

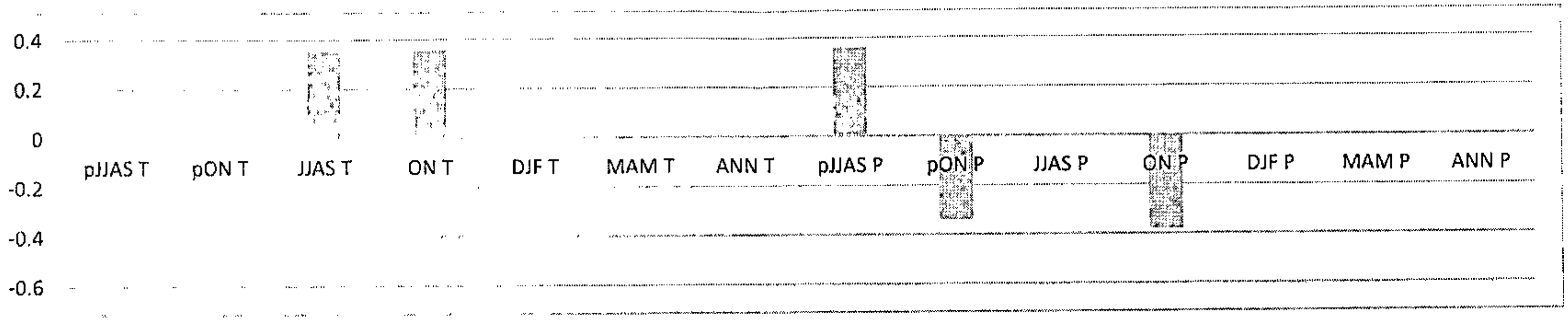

Fig 117 Bootstrapped correlation between seasonal climate and standard earlywood MVA chronologies at Kanakuthu

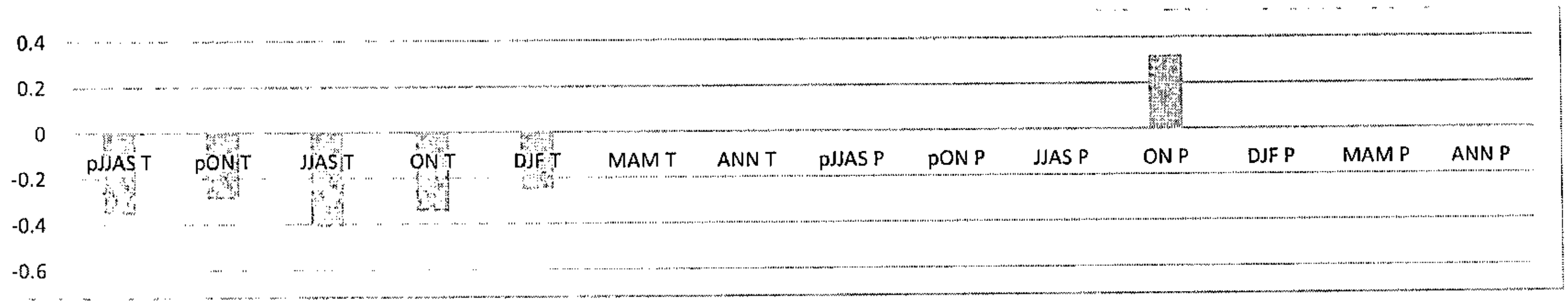

Fig 118 Bootstrapped correlation between seasonal climate and standard latewood MVA chronologies at Kanakuthu

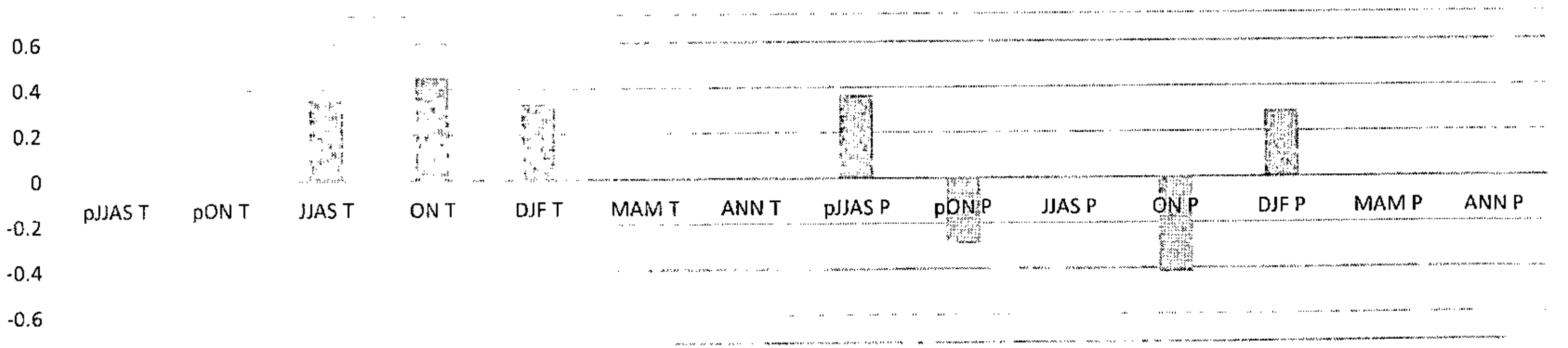

Fig 119 Bootstrapped correlation between seasonal climate and standard totalwood MVA chronologies at Kanakuthu

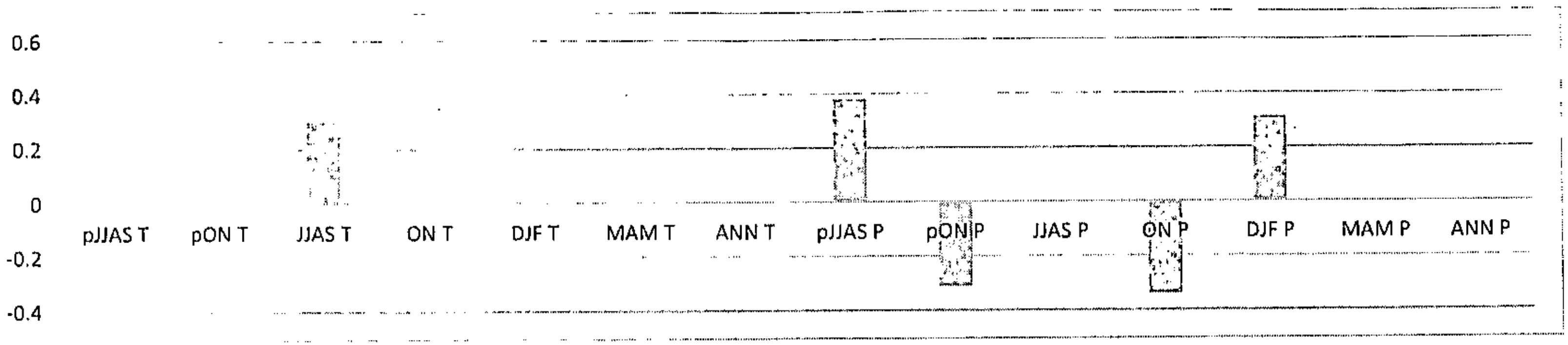

Fig 120 Bootstrapped correlation between seasonal climate and residual earlywood MVA chronologies at Kanakuthu

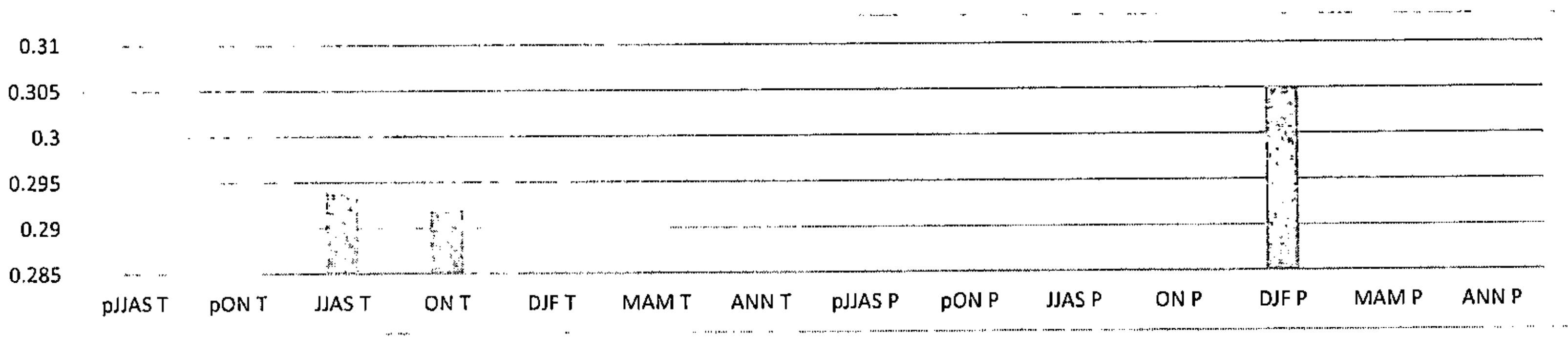

Fig 121 Bootstrapped correlation between seasonal climate and residual latewood MVA chronologies at Kanakuthu

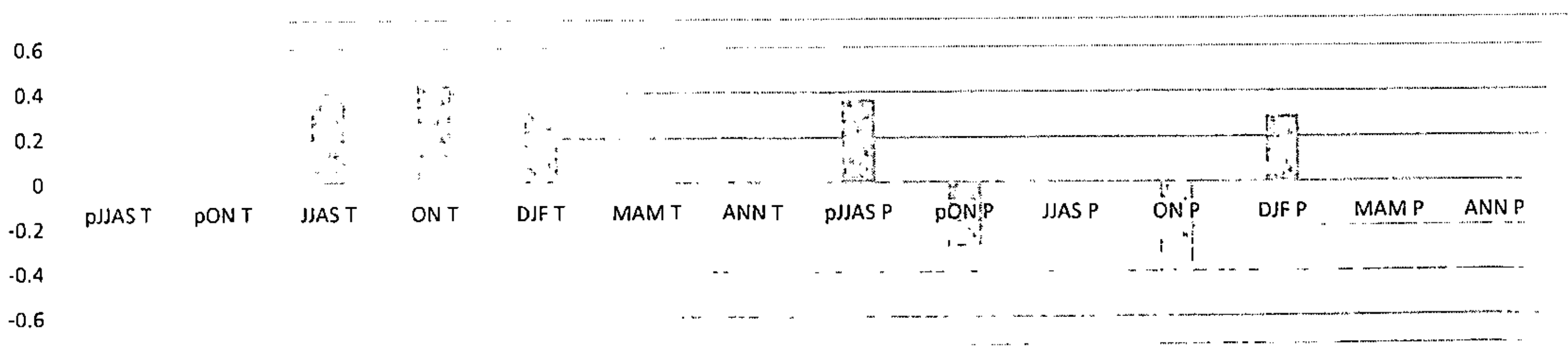

Fig 122 Bootstrapped correlation between seasonal climate and residual totalwood MVA chronologies at Kanakuthu

Table 43 Bootstrapped correlation between temperature and standard MVA chronologies at Conolly's plot

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		0.310	0.234			0.337		-0.341	-0.316					-0.306		-0.325			-0.319
Late	0.379	0.278	-0.281	-0.349	-0.277	-0.422	-0.305	-0.269	-0.287	-0.303	-0.315	-0.373		0.31	-0.325	0.319		-0.309	-0.354
Total	0.268	-0.279	-0.308	-0.295		-0.281	-0.237	-0.339	-0.342	-0.281			-0.318	-0.305	-0.347	-0.300		-0.407	-0.302

Table 44 Bootstrapped correlation between temperature and residual MVA chronologies at Conolly's plot

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		0.309	0.236			0.336		-0.338	-0.314					-0.305		-0.325			-0.319
Late	0.377	0.292		-0.325		-0.346	-0.267	-0.114	-0.295	-0.249	-0.272	-0.324		0.319	-0.319	0.339		-0.275	-0.295
Total	0.270	-0.286	-0.296	-0.279		-0.260	-0.242	-0.329	-0.342	-0.267			-0.325	-0.301	-0.350	-0.281	-0.287	-0.383	-0.288

Table 45 Bootstrapped correlation between temperature and standard MVA chronologies at Edakkode

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	-0.307								0.376		0.334		-0.381			-0.292			
Late		-0.314	0.334	0.307		0.337	0.395	0.399	0.327	0.378	0.346	0.3552			0.343			0.445	0.419
Total						0.254		0.306			0.251	0.312						0.232	0.302

Table 46 Bootstrapped correlation between temperature and residual MVA chronologies at Edakkode

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early											0.294		-0.407			-0.317			
Late	-0.294	-0.285									0.320	0.340						0.367	0.362
Total								0.309				0.311							0.254

Table 47 Bootstrapped correlation between temperature and standard MVA chronologies at Kanakuthu

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.335		0.295	-0.308				0.291	0.327			0.392	0.335	-0.337	0.313	-0.308			
Late	-0.372	-0.287	-0.374			-0.344		-0.345		-0.303			-0.304		-0.331	-0.302	-0.236	-0.293	
Total										0.354				-0.326					

Table 48 Bootstrapped correlation between temperature and residual MVA chronologies at Kanakuthu

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early		0.284						0.236	0.288			0.321	0.241	-0.267		-0.296			
Late	-0.320		-0.351																
Total										0.349				-0.327					

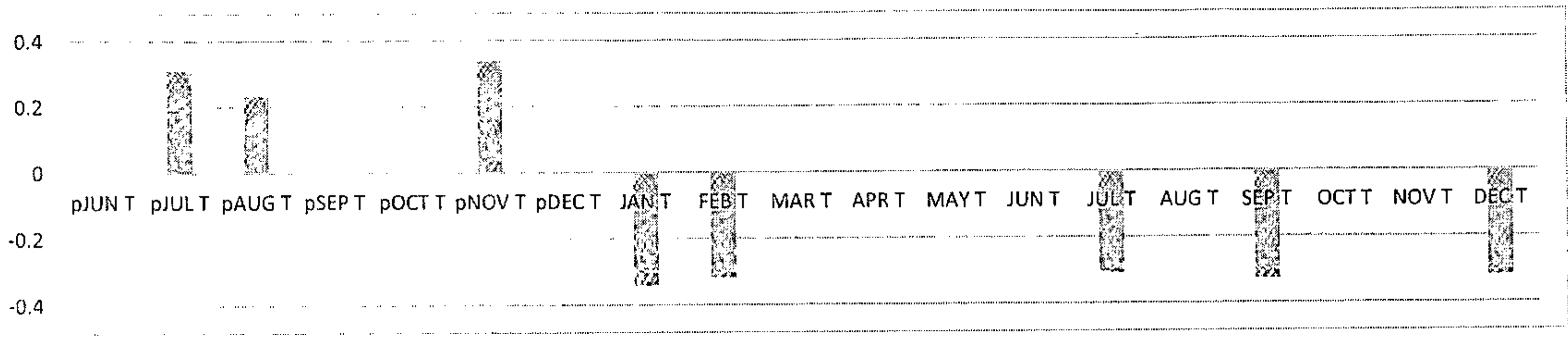

Fig 123 Bootstrapped correlation between temperature and standard earlywood MVA chronologies at Conolly's plot

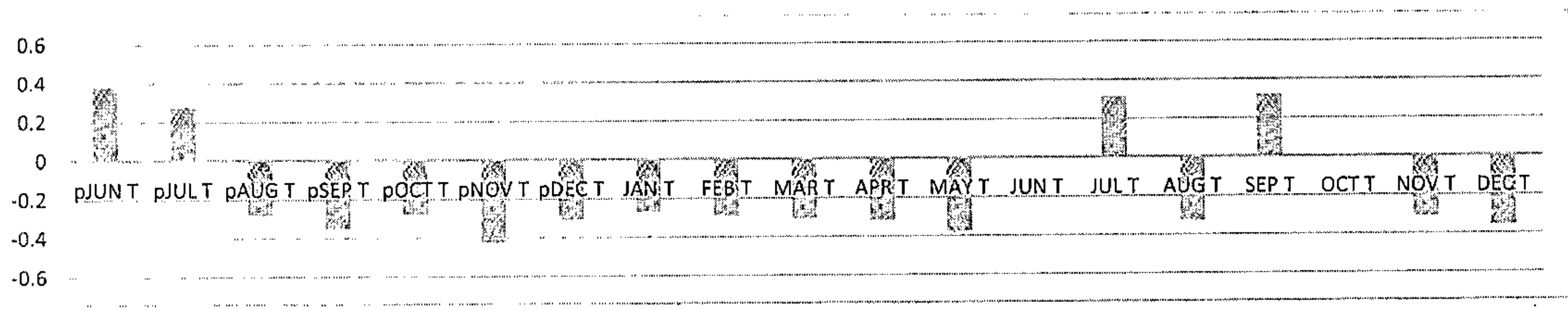

Fig 124 Bootstrapped correlation between temperature and standard latewood MVA chronologies at Conolly's plot

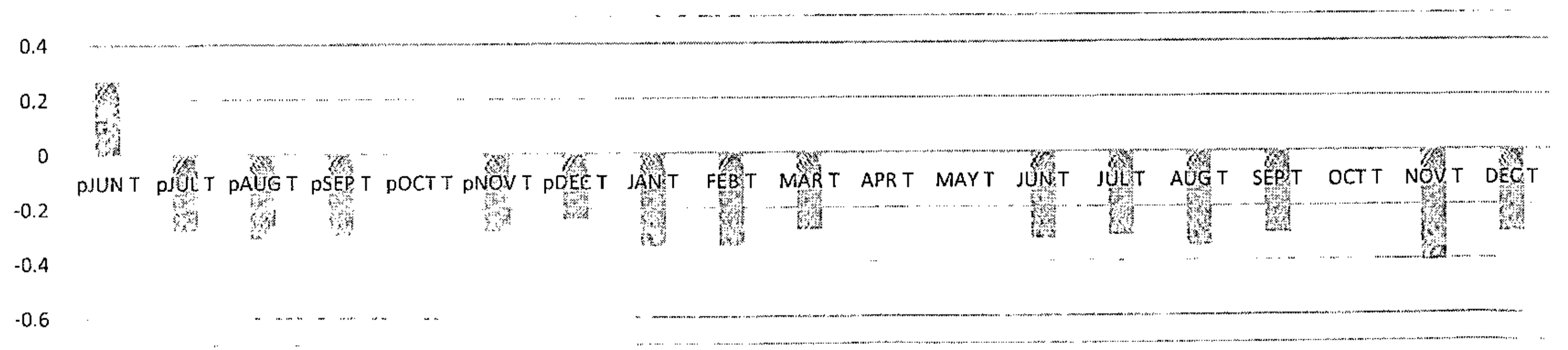

Fig 125 Bootstrapped correlation between temperature and standard totalwood MVA chronologies at Conolly's plot

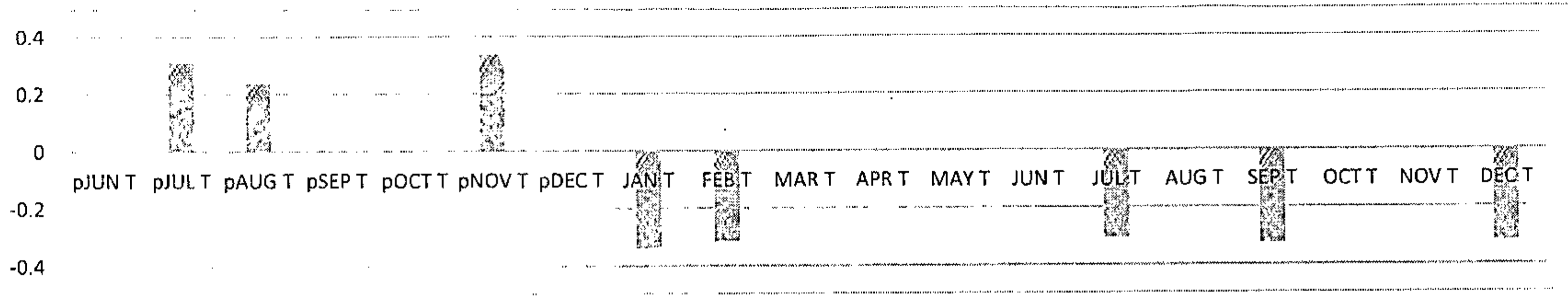

Fig 126 Bootstrapped correlation between temperature and residual earlywood MVA chronologies at Conolly's plot

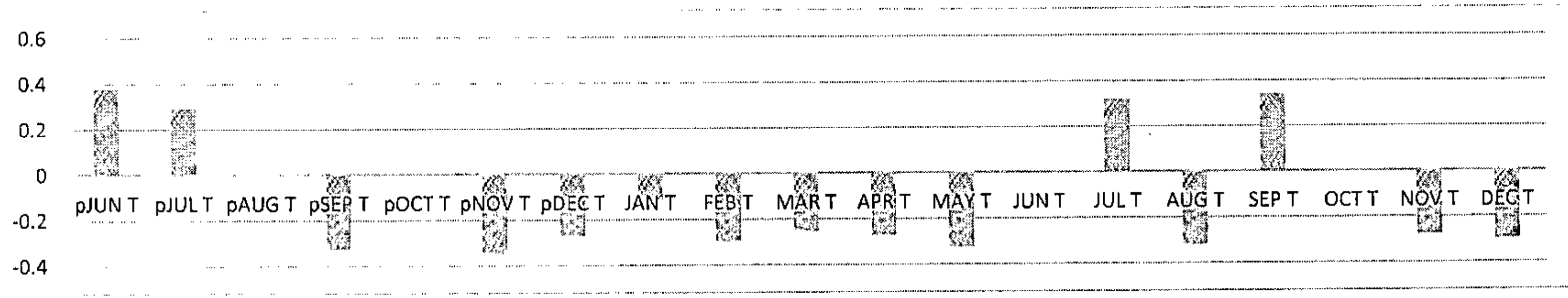

Fig 127 Bootstrapped correlation between temperature and residual latewood MVA chronologies at Conolly's plot

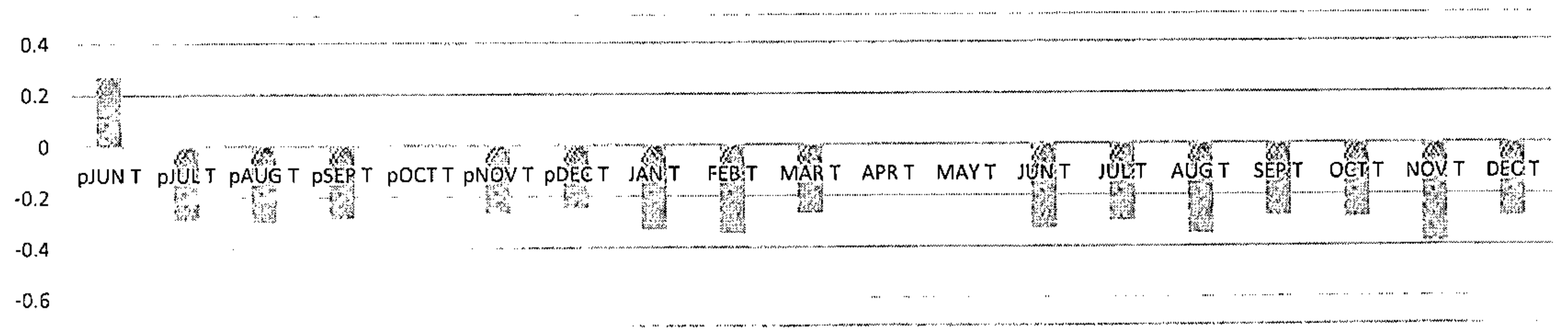

Fig 128 Bootstrapped correlation between temperature and residual totalwood MVA chronologies at Conolly's plot

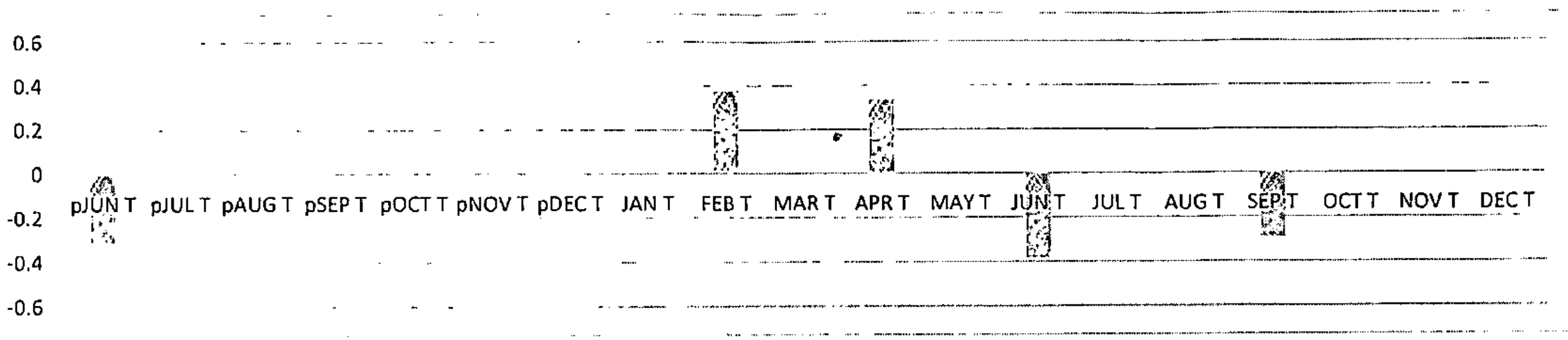

Fig 129 Bootstrapped correlation between temperature and standard earlywood MVA chronologies at Edakkode

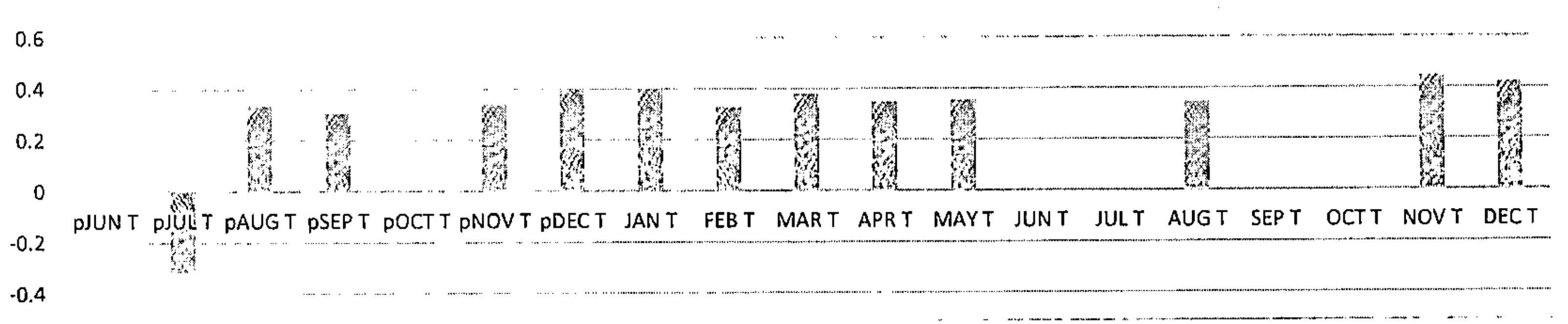

Fig 130 Bootstrapped correlation between temperature and standard latewood MVA chronologies at Edakkode

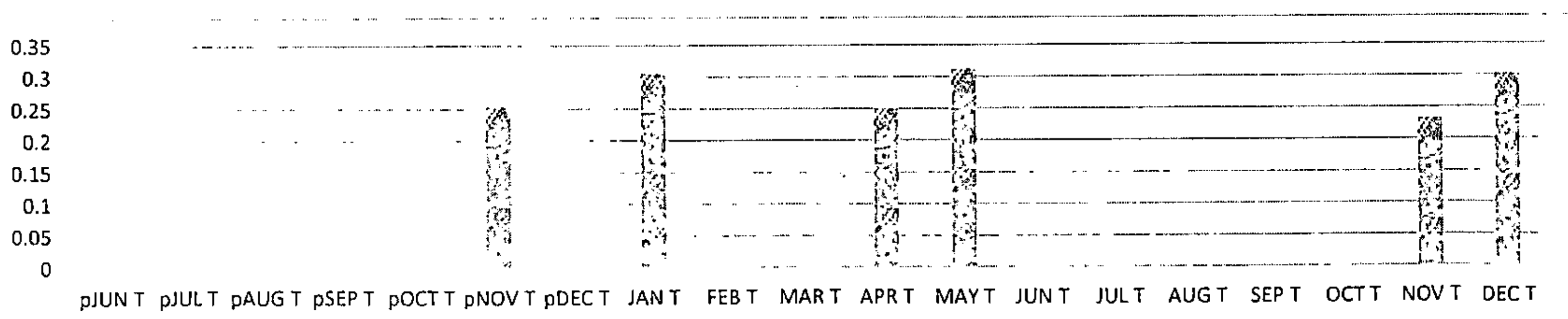

Fig 131 Bootstrapped correlation between temperature and standard totalwood MVA chronologies at Edakkode

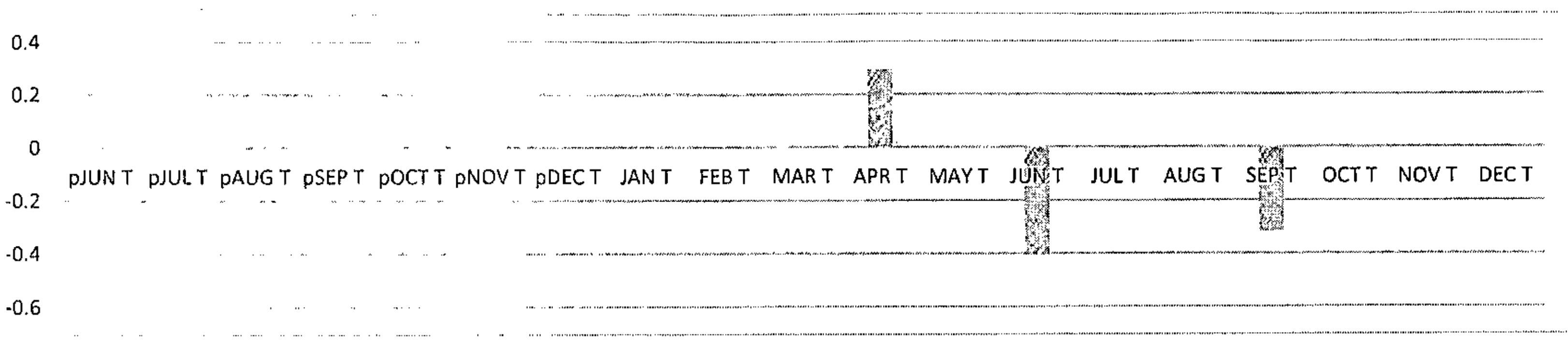

Fig 132 Bootstrapped correlation between temperature and residual earlywood MVA chronologies at Edakkode

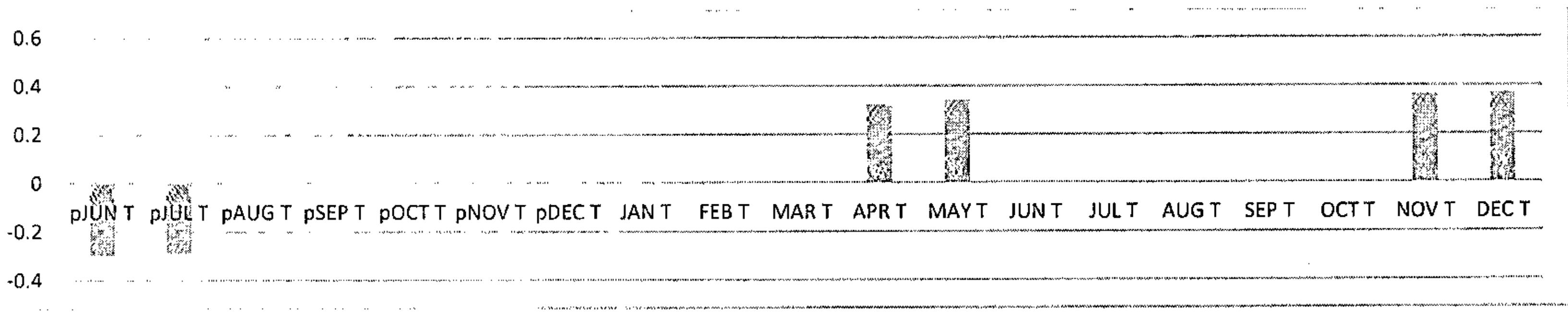

Fig 133 Bootstrapped correlation between temperature and residual latewood MVA chronologies at Edakkode

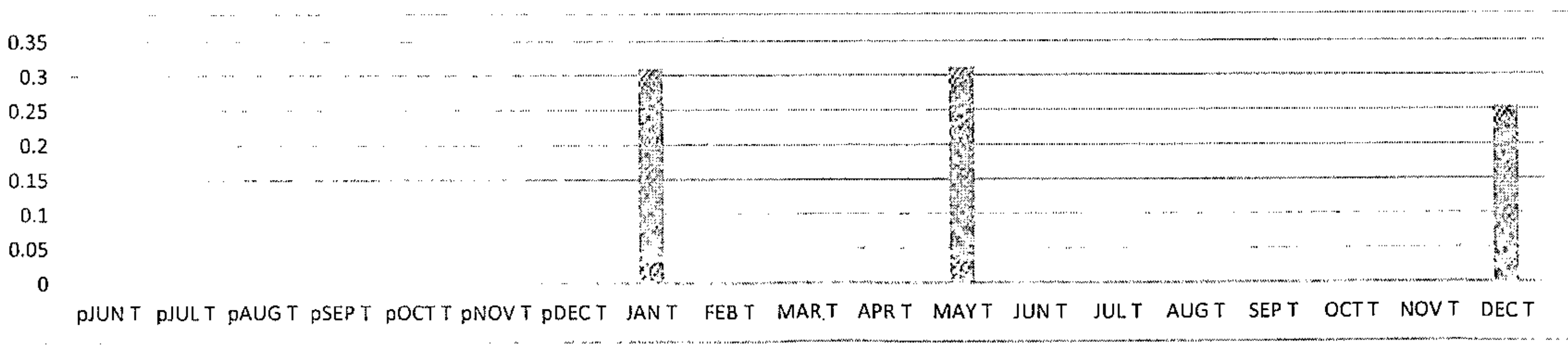

Fig 134 Bootstrapped correlation between temperature and residual totalwood MVA chronologies at Edakkode

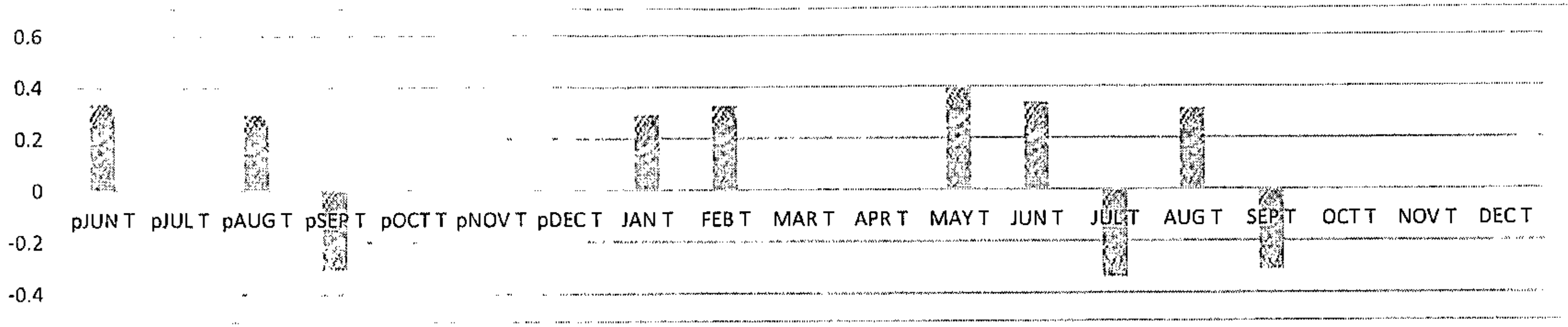

Fig 135 Bootstrapped correlation between temperature and standard earlywood MVA chronologies at Kanakuthu

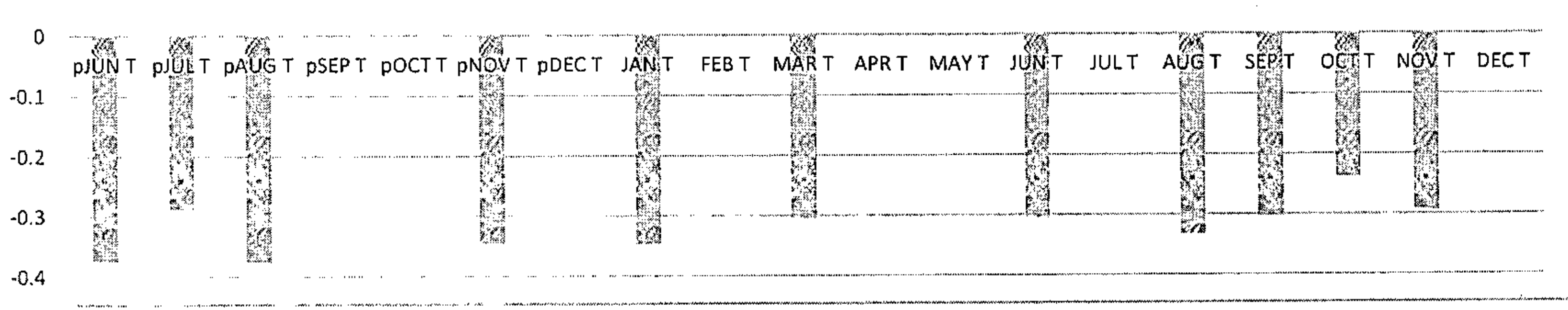

Fig 136 Bootstrapped correlation between temperature and standard latewood MVA chronologies at Kanakuthu

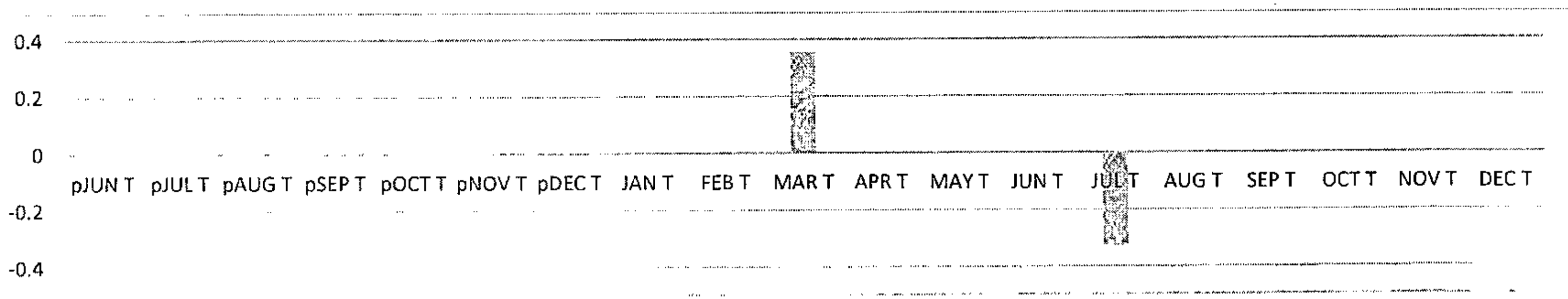

Fig 137 Bootstrapped correlation between temperature and standard totalwood MVA chronologies at Kanakuthu

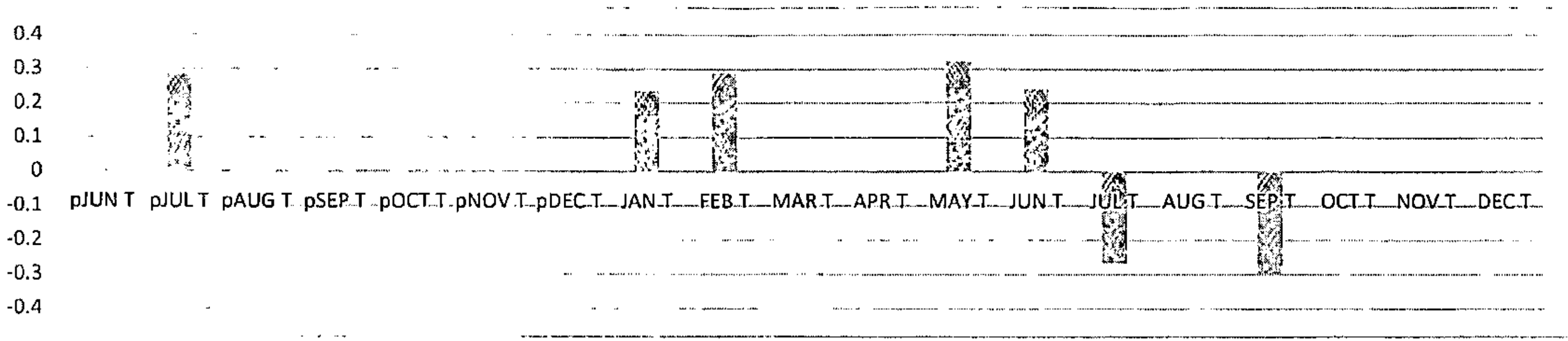

Fig 138 Bootstrapped correlation between temperature and residual earlywood MVA chronologies at Kanakuthu

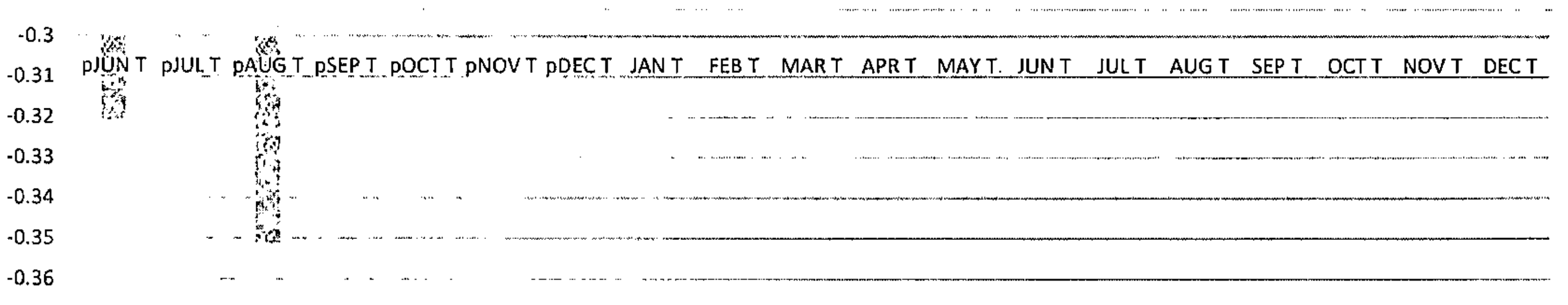

Fig 139 Bootstrapped correlation between temperature and residual latewood MVA chronologies at Kanakuthu

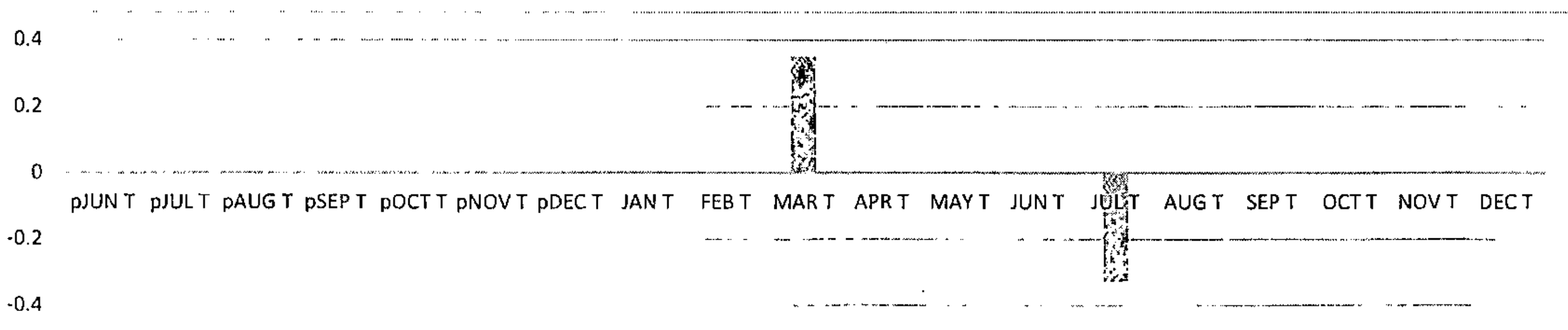

Fig 140 Bootstrapped correlation between temperature and residual totalwood MVA chronologies at Kanakuthu

4.9 Response function analysis between climate and tree rings

4.9.1 Response between monthly rainfall and ringwidth

In Conolly's plot, the standard totalwood ringwidth index chronology had responded negatively with previous December rainfall (-0.318) and positively responded with previous July rainfall (0.335). In case of residual chronology the latewood was again negatively related with previous December rainfall (-0.290) and earlywood was positively associated with June rainfall (0.317). In the case of standard chronology at Edakkode the latewood showed negative response with previous August rainfall (-0.355) and positive response with October precipitation (0.290). The residual latewood chronology at Edakkode was positively related with October rainfall (0.312) while earlywood negatively responded with May precipitation (-0.316). The standard latewood chronology from Kanakuthu showed negative response with previous November rainfall (-0.250), while totalwood had positive response with previous July rainfall (0.456). Residual chronology for latewood showed the same trend that of standard at Kanakuthu responding to previous November rainfall (-0.252) and previous July rainfall (0.421). (Table 49-54; Figure 141-158).

4.9.2 Response between seasonal climate and ringwidth

In Conolly's plot, with respect to standard chronology the highest negative response was between December-February temperature and latewood (-0.277) and positive response was between June-September rainfall and earlywood (0.320). In residual chronology October-November temperature was showing high negative response with latewood (-0.244) while June-September was positively related with earlywood (0.320). The chronologies of Edakkode showed positive response to June-September rainfall (0.528 for standard totalwood and 0.501 for residual latewood). While negative response was observed between December-February and latewood (-0.258 for standard and -0.247 for residual). The ringwidths of Kanakuthu responded to December-February temperature negatively (-0.139 for latewood standard and -0.124 for latewood residual) and standard latewood was positively related with previous June-September rainfall. (Table 55-60; Figure 159-177).

Table 49 Bootstrapped response between precipitation and standard ring width chronologies at Conolly's plot

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.309	0.262	-0.292			-0.288						0.317		0.278	-0.307			0.266
Late		0.311					-0.304				-0.272	0.250						0.318	-0.289
Total		0.335		-0.312			-0.318				-0.277								

Table 50 Bootstrapped response between precipitation and residual ring width chronologies at Conolly's plot

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.309	0.264	-0.292			-0.288						0.317		0.278	-0.277			0.266
Late		0.315					-0.290				-0.285					-0.253			-0.309
Total		0.308		-0.251			-0.276				-0.265								

Table 51 Bootstrapped response between precipitation and standard ring width chronologies at Edakkode

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early								-0.219	-0.284	-0.286		-0.290		0.219			0.290		
Late			-0.355									-0.279					0.280		
Total							-0.219				-0.295		0.221			0.284			

Table 52 Bootstrapped response between precipitation and residual ring width chronologies at Edakkode

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early									-0.290	-0.264		-0.316		0.199			0.276		
Late			-0.304									-0.260					0.312		
Total			-0.299									-0.305		0.220			0.288		

Table 53 Bootstrapped response between precipitation and standard ring width chronologies at Kanakuthu

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.404												0.284					
Late		0.456												0.293					
Total		0.434				-0.250								0.288					

Table 54 Bootstrapped response between precipitation and residual ring width chronologies at Kanakuthu

Ring width	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
Early		0.394												0.307					
Late		0.421				-0.252								0.298					
Total		0.374												0.308					

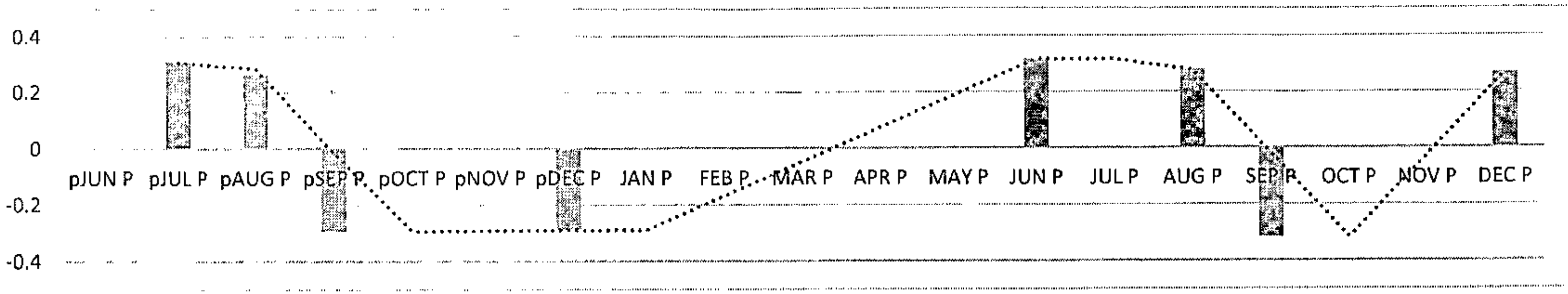

Fig 141 Bootstrapped response between rainfall and standard earlywood ring chronologies at Conolly's plot

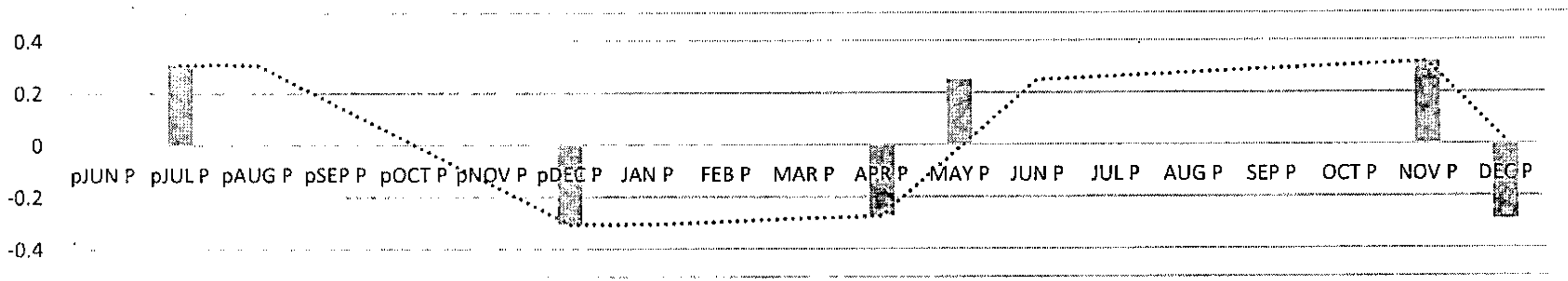

Fig 142 Bootstrapped response between rainfall and standard latewood ring chronologies at Conolly's plot

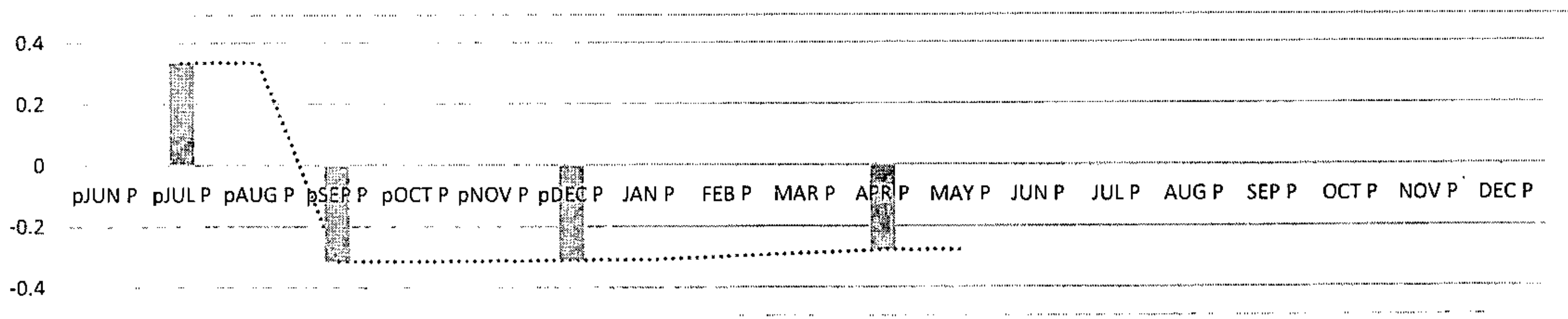

Fig 143 Bootstrapped response between rainfall and standard totalwood ring chronologies at Conolly's plot

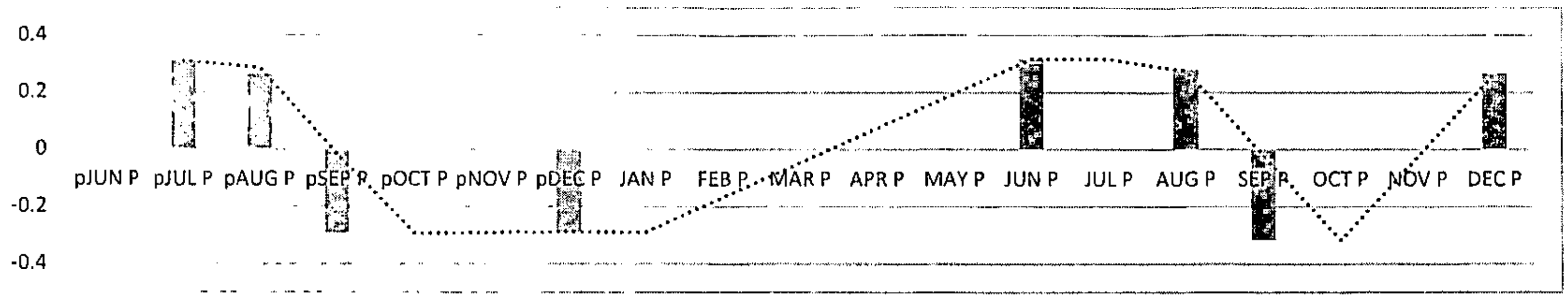

Fig 144 Bootstrapped response between rainfall and residual earlywood ring chronologies at Conolly's plot

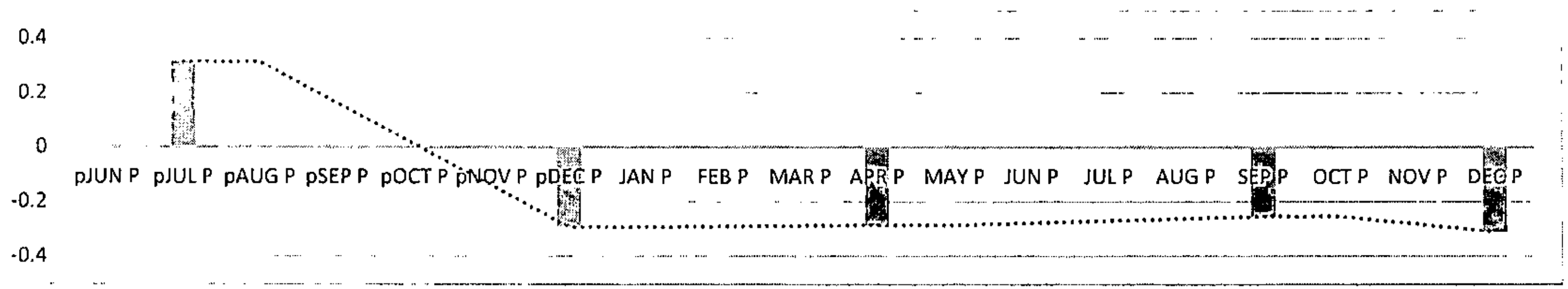

Fig 145 Bootstrapped response between rainfall and residual latewood ring chronologies at Conolly's plot

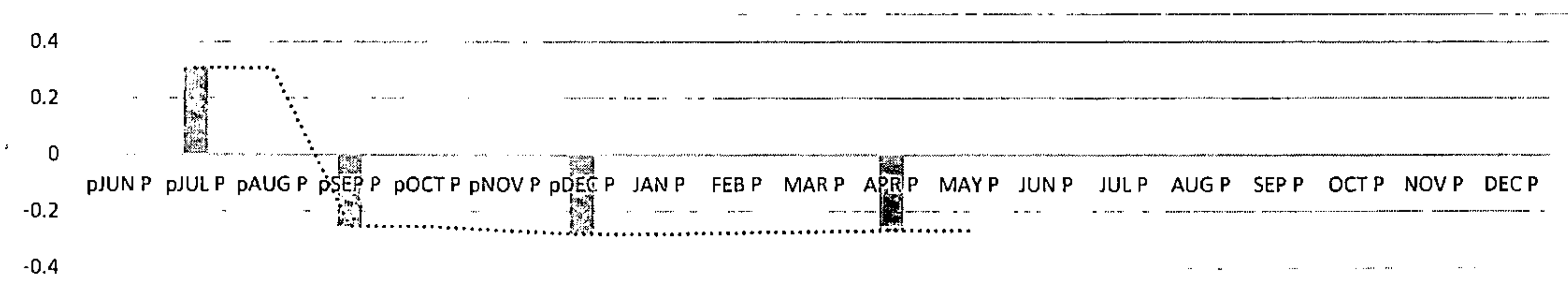

Fig 146 Bootstrapped response between rainfall and residual totalwood ring chronologies at Conolly's plot

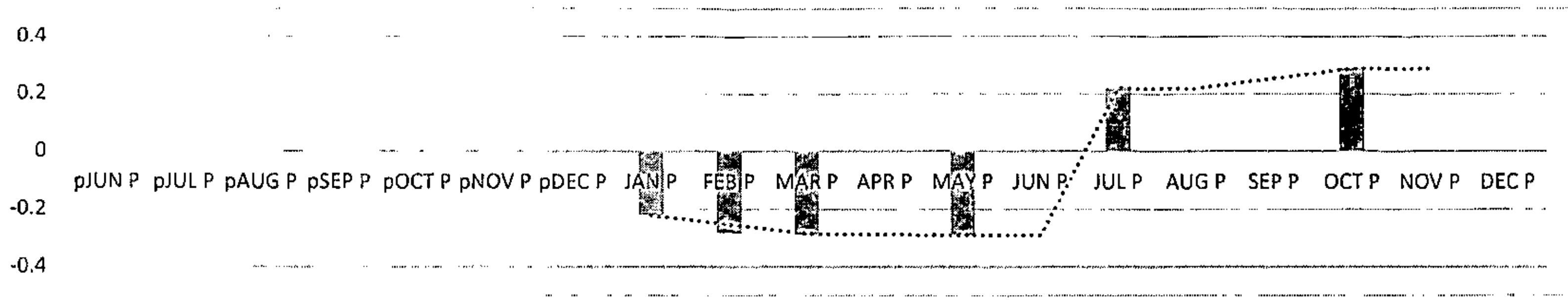

Fig 147 Bootstrapped response between rainfall and standard earlywood ring chronologies at Edakkode

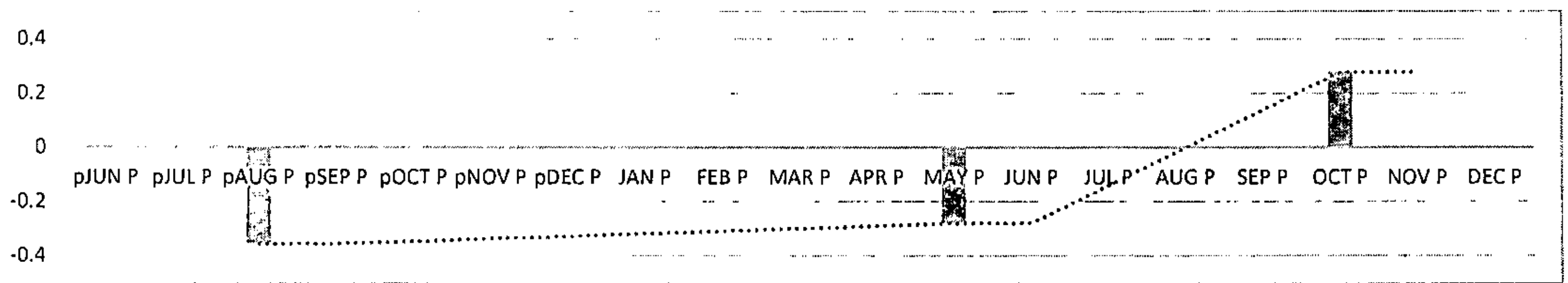

Fig 148 Bootstrapped response between rainfall and standard latewood ring chronologies at Edakkode

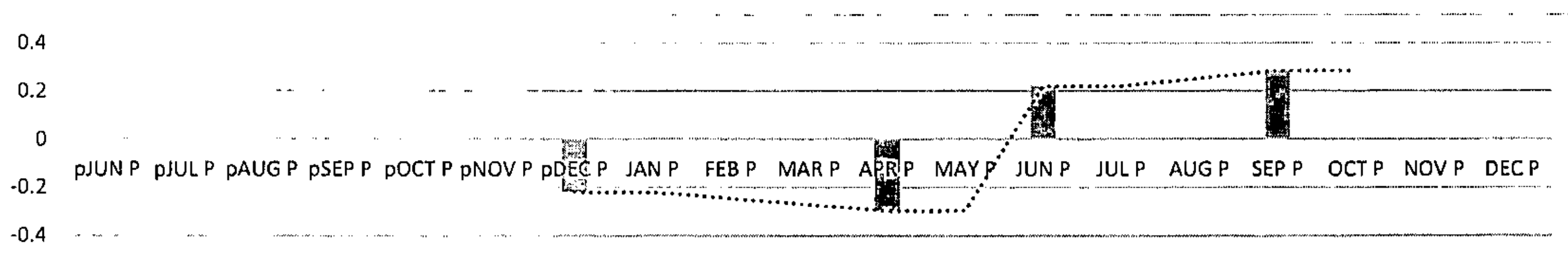

Fig 149 Bootstrapped response between rainfall and standard totalwood ring chronologies at Edakkode

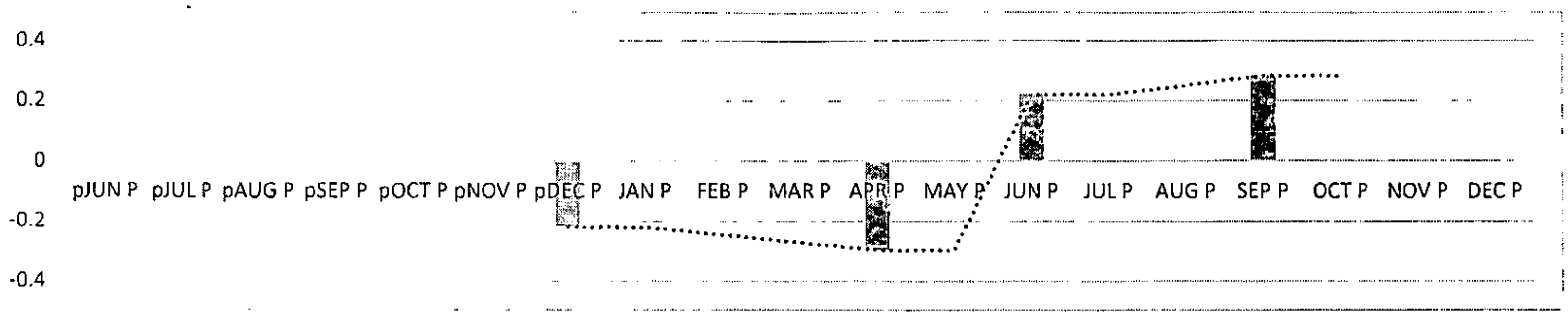

Fig 150 Bootstrapped response between rainfall and residual earlywood ring chronologies at Edakkode

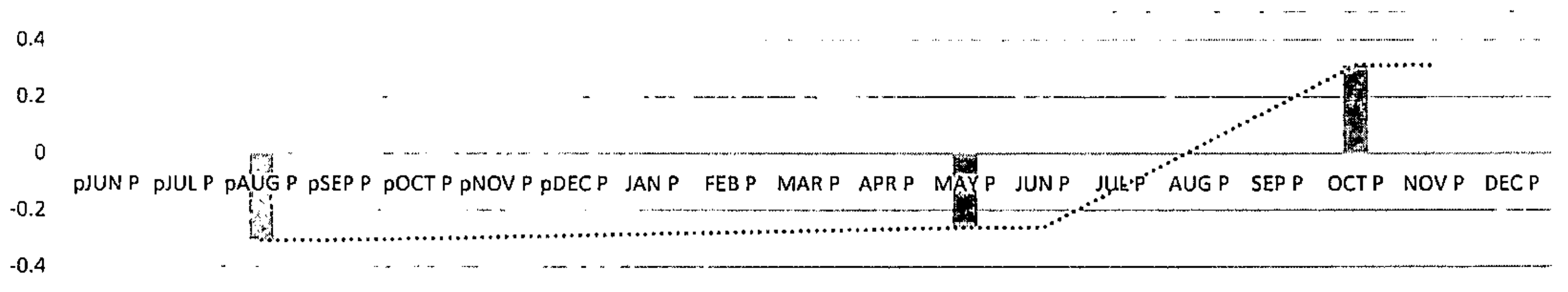

Fig 151 Bootstrapped response between rainfall and residual latewood ring chronologies at Edakkode

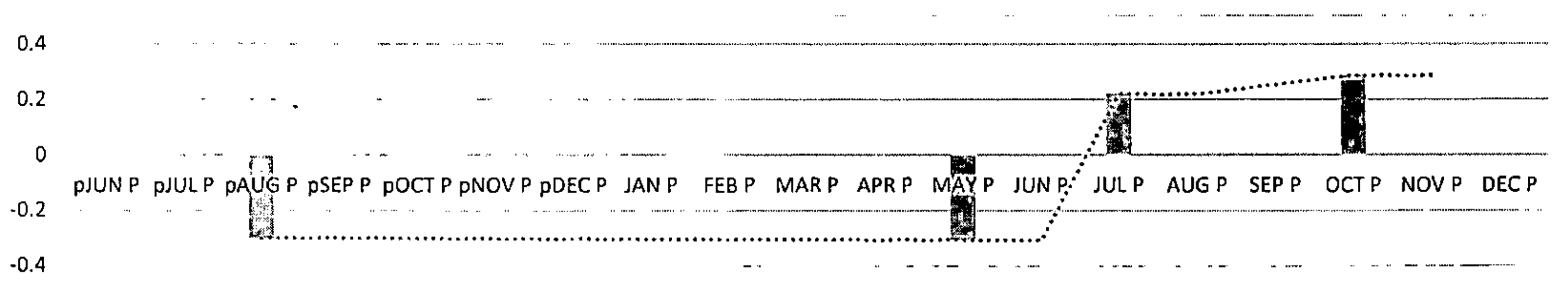

Fig 152 Bootstrapped response between rainfall and residual totalwood ring chronologies at Edakkode

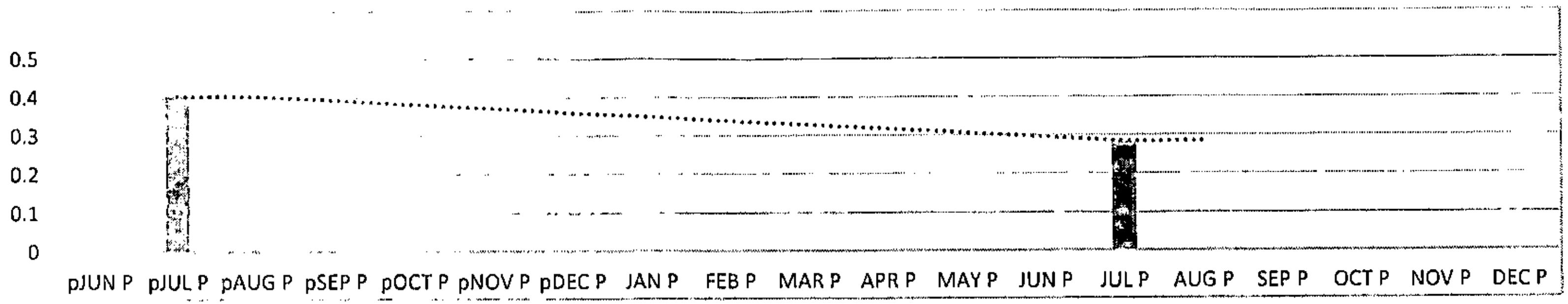

Fig 153 Bootstrapped response between rainfall and standard earlywood ring chronologies at Kanakuthu

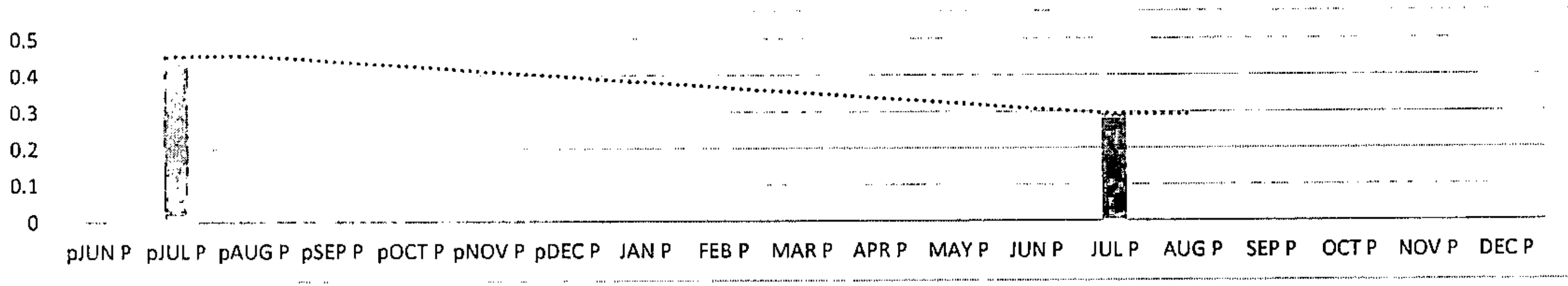

Fig 154 Bootstrapped response between rainfall and standard latewood ring chronologies at Kanakuthu

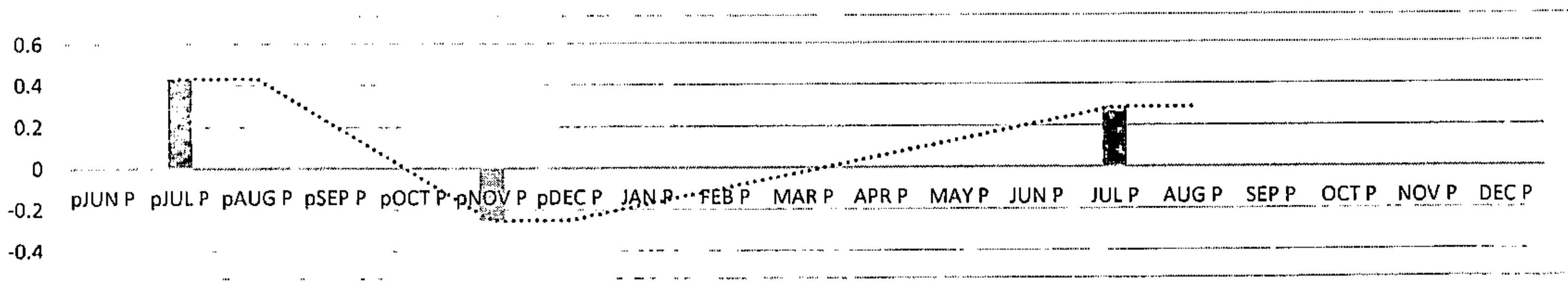

Fig 155 Bootstrapped response between rainfall and standard totalwood ring chronologies at Kanakuthu

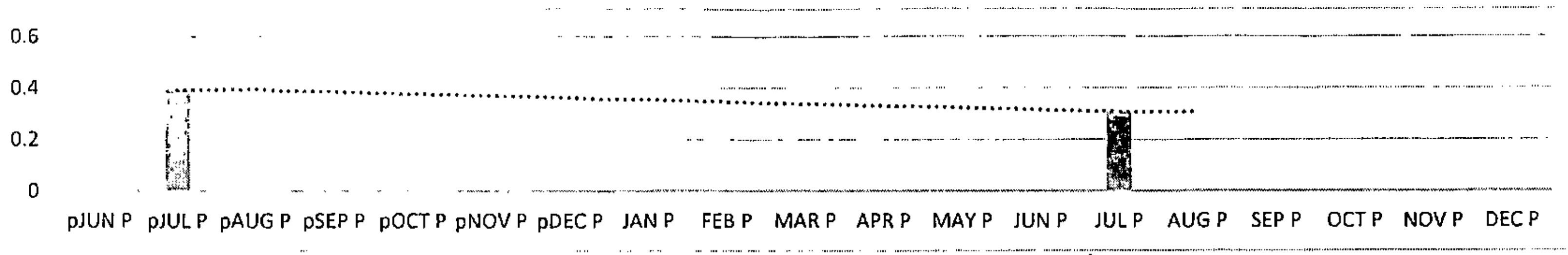

Fig 156 Bootstrapped response between rainfall and residual earlywood ring chronologies at Kanakuthu

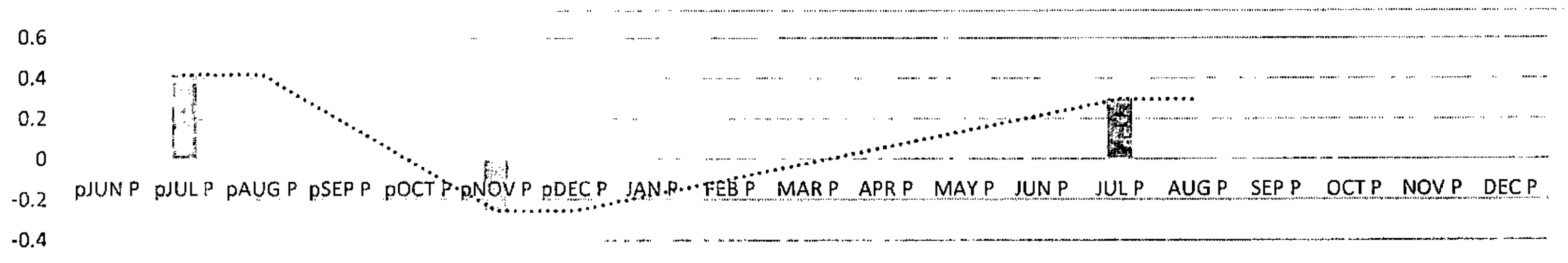

Fig 157 Bootstrapped response between rainfall and residual latewood ring chronologies at Kanakuthu

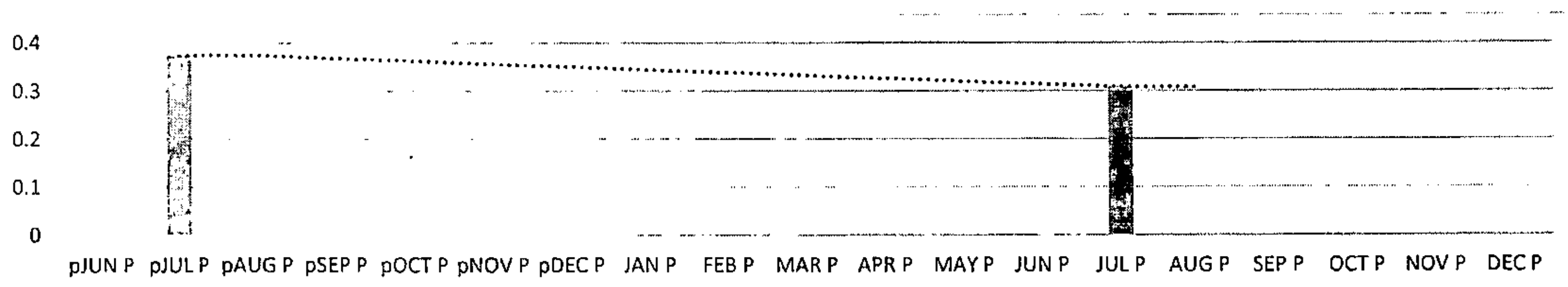

Fig 158 Bootstrapped response between rainfall and residual totalwood ring chronologies at Kanakuthu

Table 55 Bootstrapped response between seasonal climatic variables and standard ring width chronologies at Conolly's plot

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.277			0.230		0.320		0.182		
Late					-0.105				0.345			0.128		
Total					-0.104			0.222				0.174		

Table 56 Bootstrapped response between seasonal climatic variables and residual ring width chronologies at Conolly's plot

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.106			0.259		0.320		0.182		
Late				-0.244	-0.110				0.318	0.315				
Total					-0.115			0.215				0.133		

Table 57 Bootstrapped response between seasonal climatic variables and standard ring width chronologies at Edakkode

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early				-0.173	-0.128					-0.184	0.378	0.207		
Late					-0258			0.226		0.502	0.314	-0.248		
Total					-0.137				0.283	0.528	0.380	0.213		

Table 58 Bootstrapped response between seasonal climatic variables and residual ring width chronologies at Edakkode

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.115					0.437	0.352	0.013		
Late					-0.247				0.312	0.501	0.346	0.252		
Total					-0.139					0.466	0.351	0.068		

Table 59 Bootstrapped response between seasonal climatic variables and standard ring width chronologies at Kanakuthu

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.117									
Late					-0.139			0.213						
Total					-0.133									

Table 60 Bootstrapped response between seasonal climatic variables and residual ring width chronologies at Kanakuthu

Ring width	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.112									
Late					-0.124									
Total					-0.12									

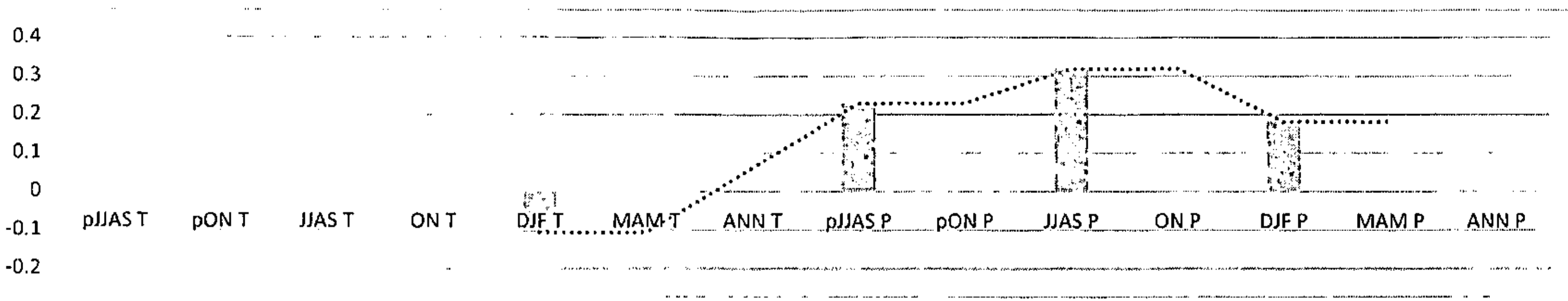

Figure 159 Bootstrapped response between seasonal climate and standard earlywood ring chronologies at Conolly's plot

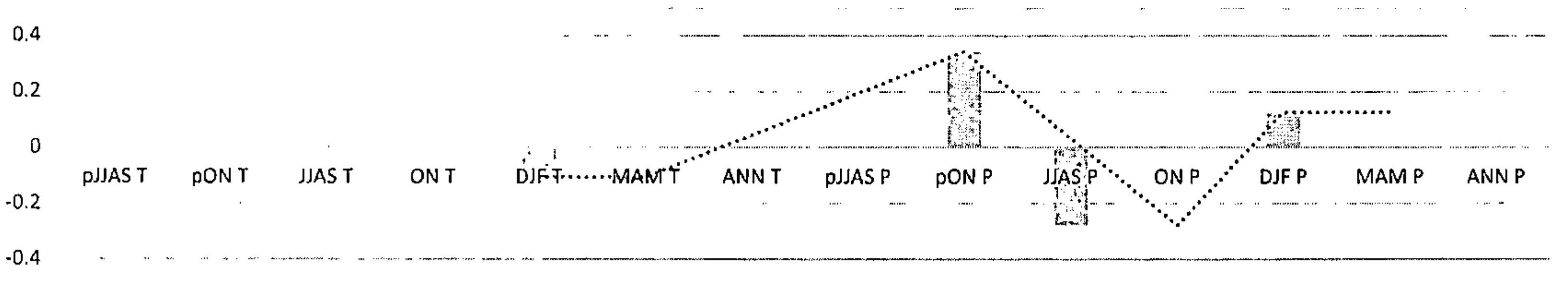

Figure 160 Bootstrapped response between seasonal climate and standard latewood ring chronologies at Conolly's plot

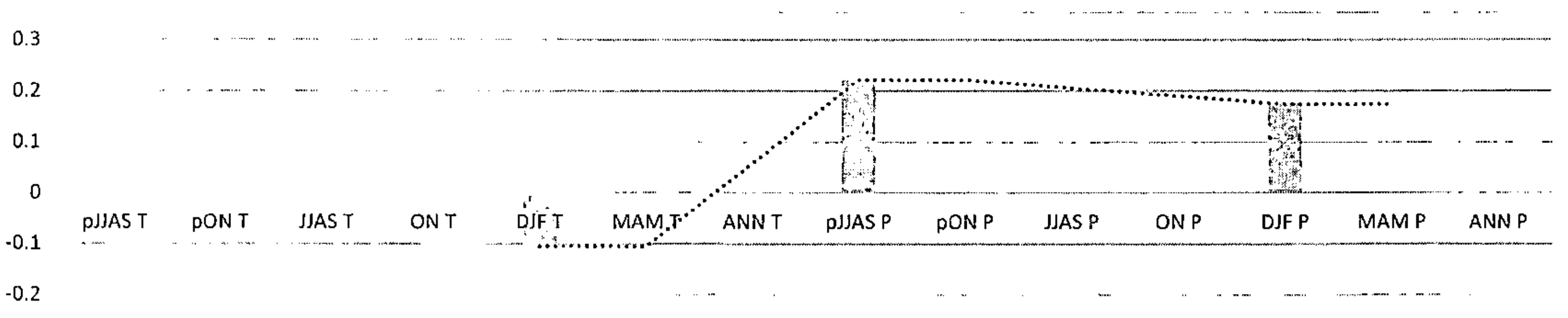

Figure 161 Bootstrapped response between seasonal climate and standard totalwood ring chronologies at Conolly's plot

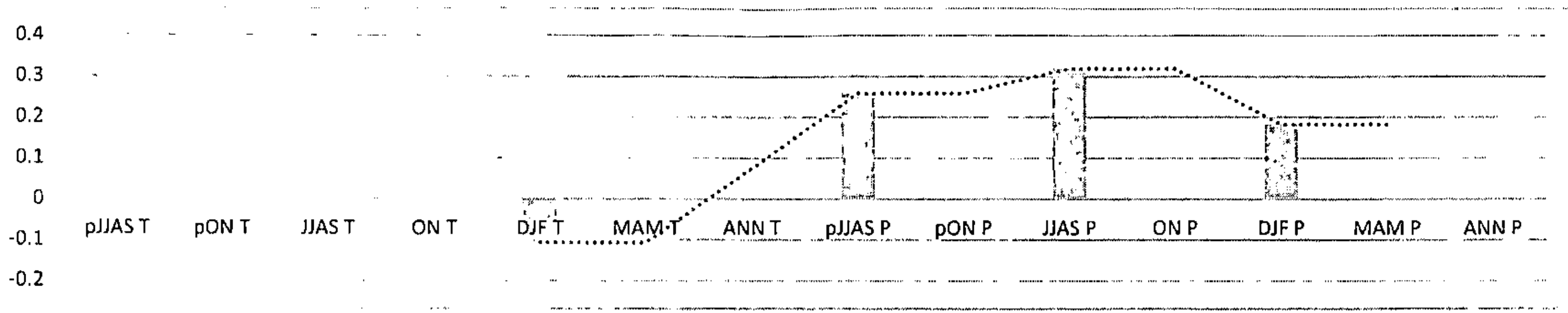

Figure 162 Bootstrapped response between seasonal climate and residual earlywood ring chronologies at Conolly's plot

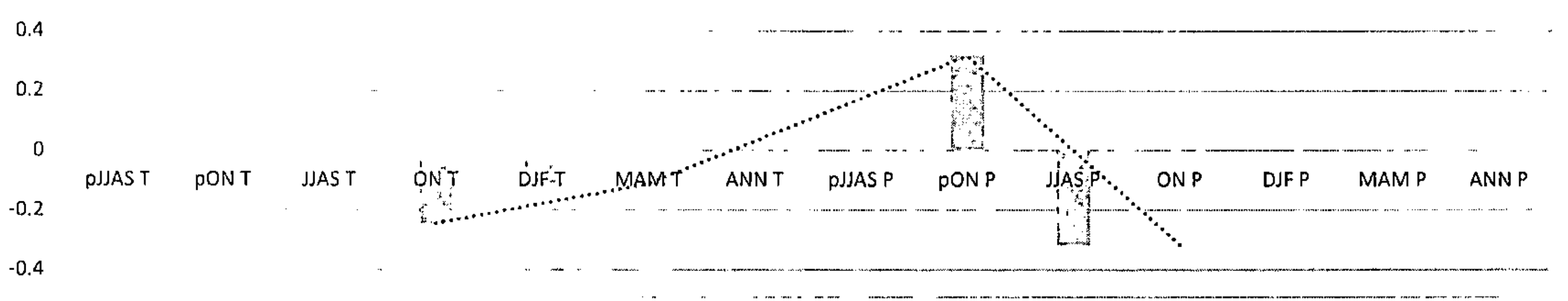

Figure 163 Bootstrapped response between seasonal climate and residual latewood ring chronologies at Conolly's plot

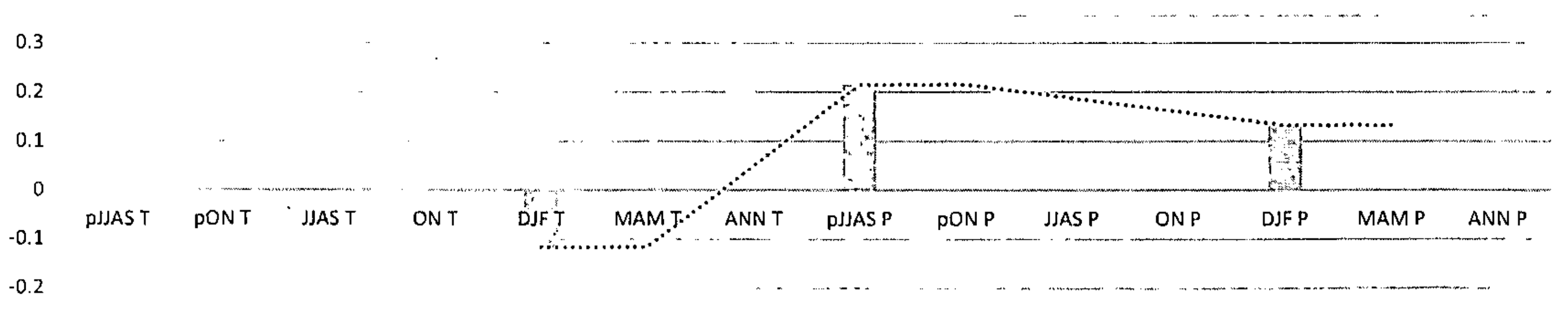

Figure 164 Bootstrapped response between seasonal climate and residual totalwood ring chronologies at Conolly's plot

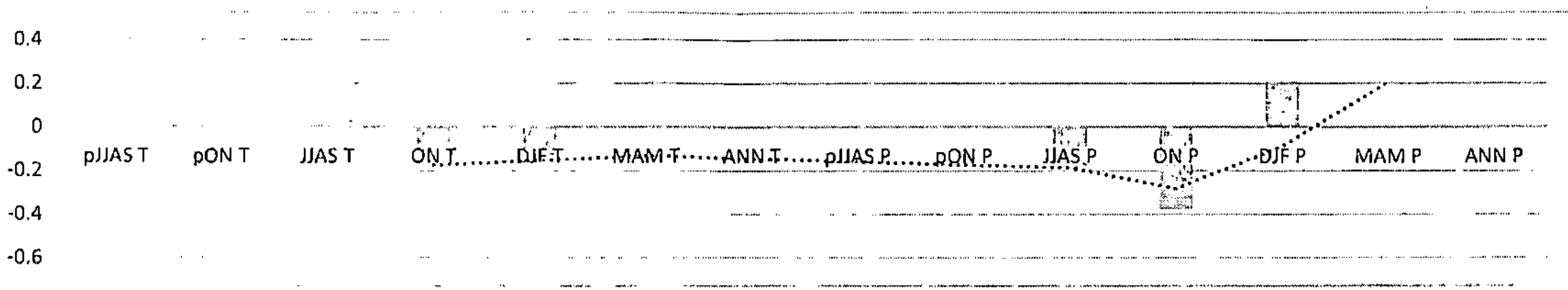

Figure 165 Bootstrapped response between seasonal climate and standard earlywood ring chronologies at Edakkode

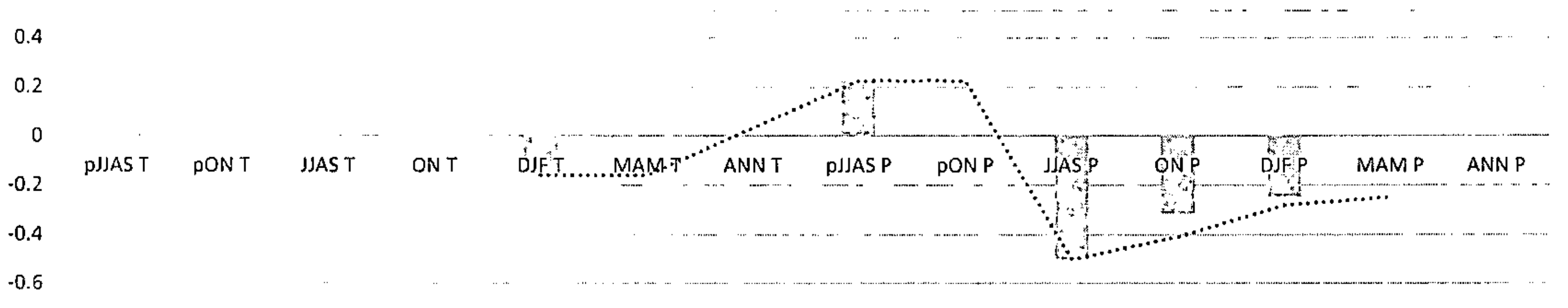

Figure 166 Bootstrapped response between seasonal climate and standard latewood ring chronologies at Edakkode

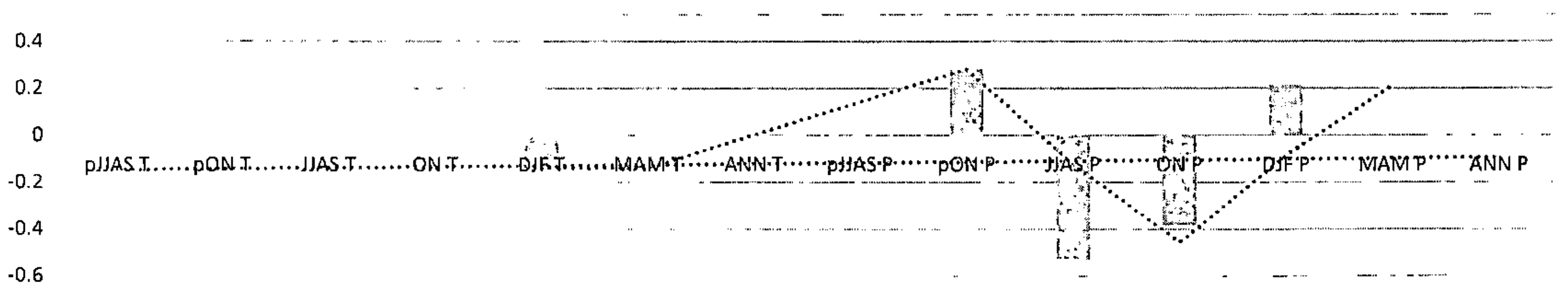

Figure 167 Bootstrapped response between seasonal climate and standard totalwood ring chronologies at Edakkode

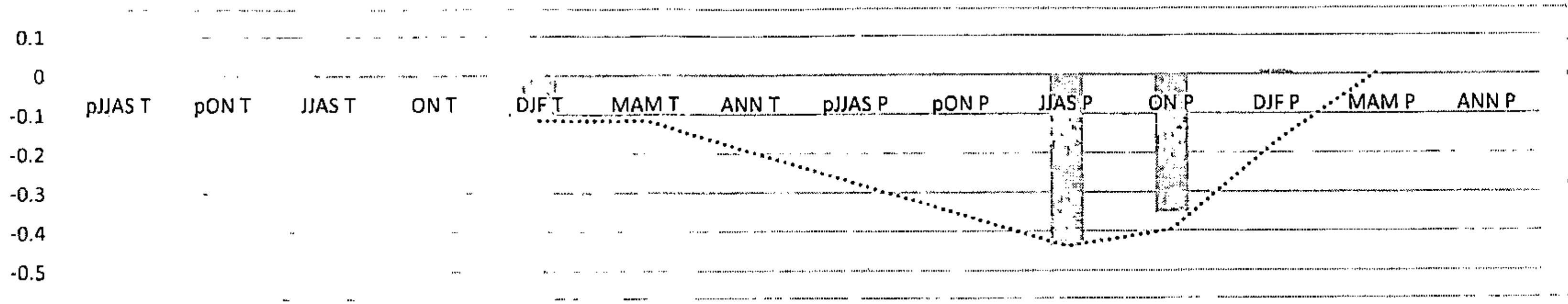

Figure 168 Bootstrapped response between seasonal climate and residual earlywood ring chronologies at Edakkode

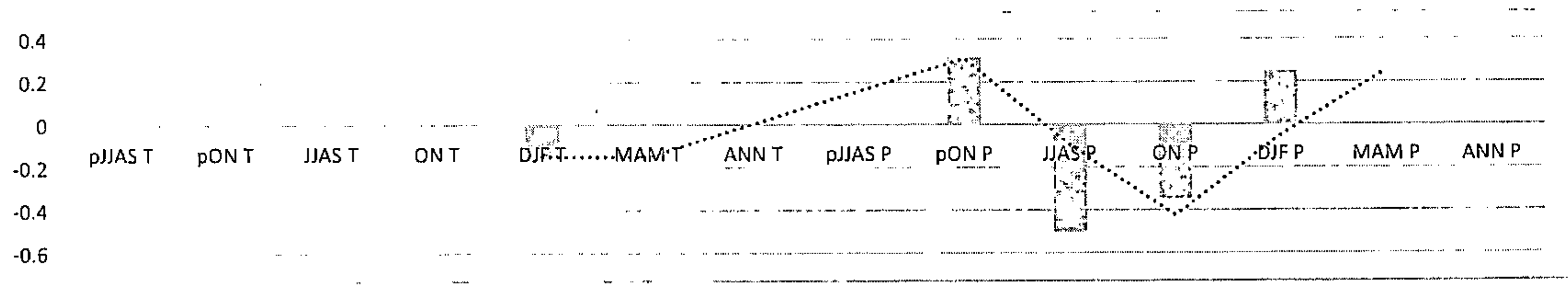

Figure 169 Bootstrapped response between seasonal climate and residual latewood ring chronologies at Edakkode

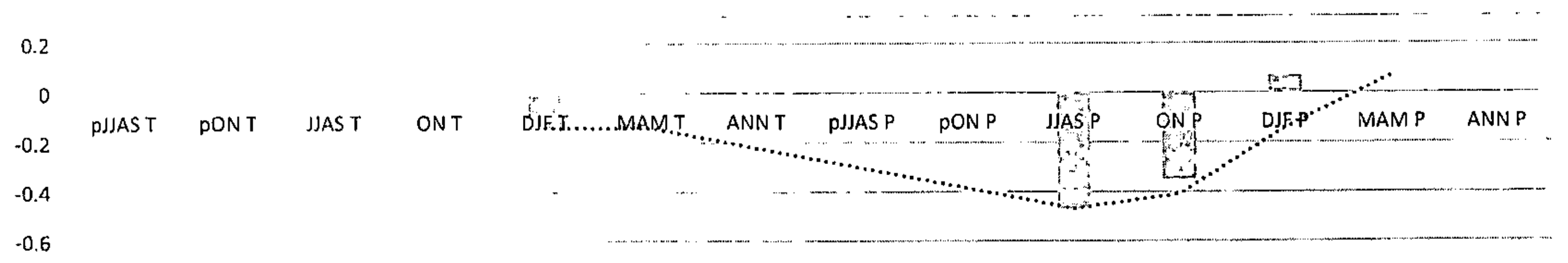

Figure 170 Bootstrapped response between seasonal climate and residual totalwood ring chronologies at Edakkode

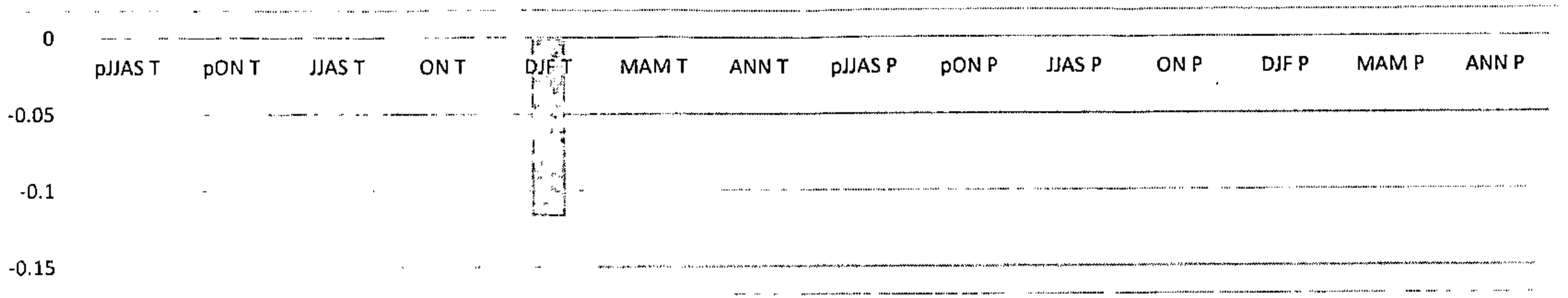

Figure 171 Bootstrapped response between seasonal climate and standard earlywood ring chronologies at Kanakuthu

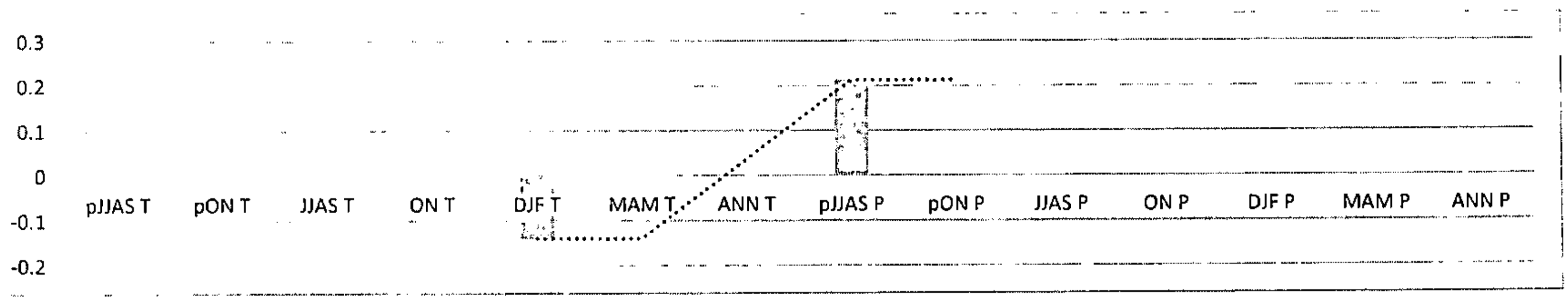

Figure 172 Bootstrapped response between seasonal climate and standard latewood ring chronologies at Kanakuthu

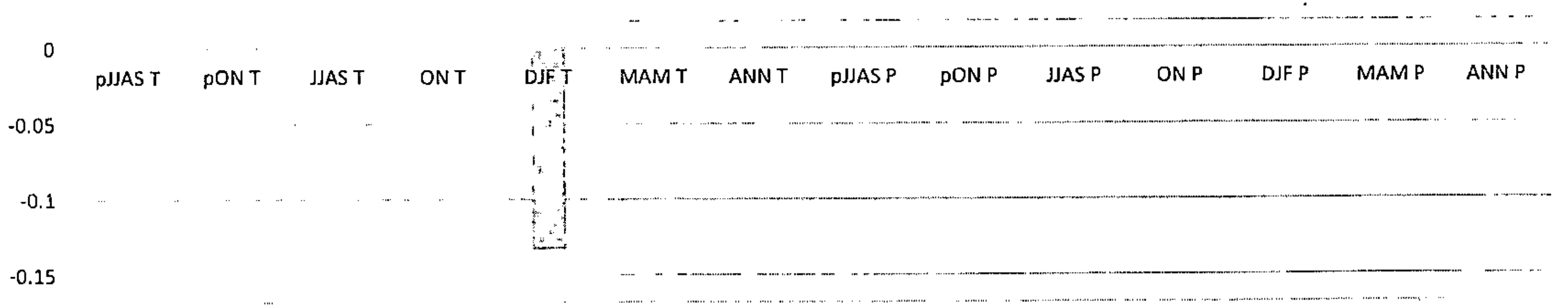

Figure 174 Bootstrapped response between seasonal climate and standard totalwood ring chronologies at Kanakuthu

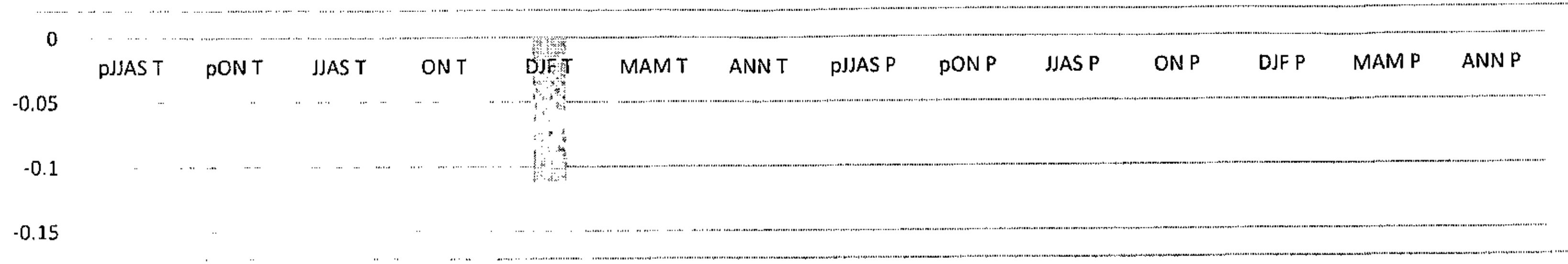

Figure 175 Bootstrapped response between seasonal climate and residual earlywood ring chronologies at Kanakuthu

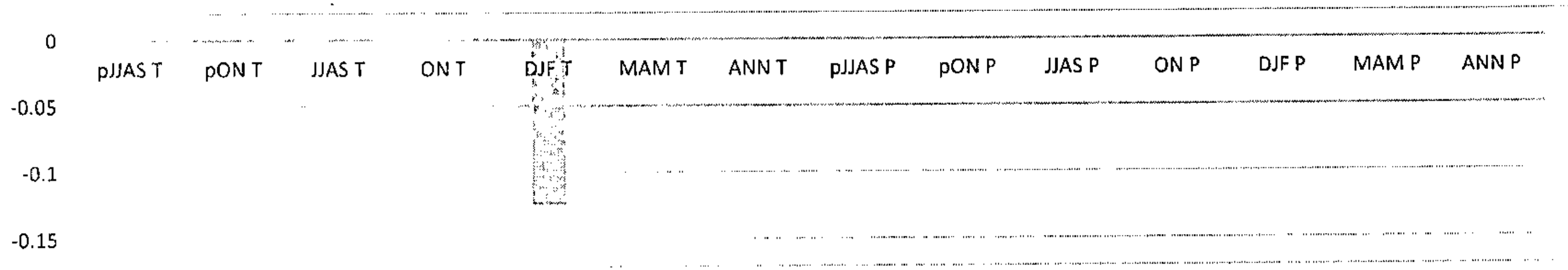

Figure 176 Bootstrapped response between seasonal climate and residual latewood ring chronologies at Kanakuthu

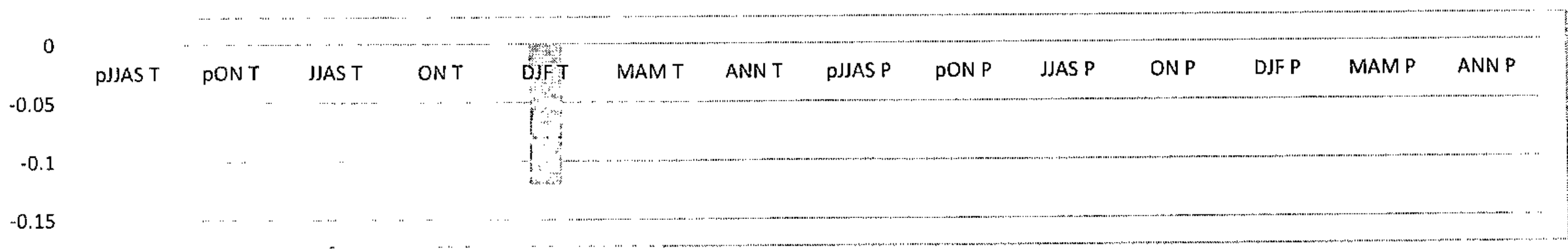

Figure 177 Bootstrapped response between seasonal climate and residual totalwood ring chronologies at Kanakuthu

4.9.3 Response between temperature and ring width

In Conolly's plot the standard and residual latewood chronologies showed negative response with January temperature (-0.408, -0.375). Standard and residual earlywood had positive response to previous June temperature (0.255, 0.255). At Edakkode the standard earlywood chronology negatively related with June temperature (-0.301) and residual earlywood chronology positively responded to June temperature (0.272). July temperature was negatively related to standard totalwood (-0.269) and residual latewood (-0.294) chronologies. At Kanakuthu July temperature showed negative response (-0.260) with standard latewood chronology and so did January temperature (-0.234) with latewood residual chronology. Previous June temperature showed positive response with both standard earlywood (0.259) and residual earlywood (0.271) chronologies. (Table 61-66; Figure 178-195).

4.9.4 Response between rainfall and mean vessel area

In the case of rainfall at Conolly's plot the early wood standard chronology showed negative response to January rainfall (-0.323) and positive response to previous June rainfall (0.339). In residual chronology negative relation was observed between previous September rainfall and latewood (-0.351), previous June rainfall had positive response (0.333) on earlywood. Standard and residual totalwood chronology at Edakkode responded negatively to May rainfall (-0.341, -0.352). While standard and residual totalwood chronologies was related positively to previous November rainfall (0.365, 0.349) at Edakkode. The standard and residual chronologies at Kanakuthu responded differently to rainfall. May rainfall was negative with standard earlywood (-0.352), while previous July rainfall was positive (0.272) with the same. For latewood residual chronology there was negative response to previous September rainfall (-0.270) but for earlywood residual there observed positive response (0.317) was observed with respect to to previous October rainfall. (Table 67-72, Figure 197-213)

Table 61 Bootstrapped response between temperature and standard ringwidth chronologies at Conolly's plot

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.255		-0.302					-0.340			-0.274								
Late								-0.408			-0.305	-0.245			-0.276				
Total	-0.261		-0.268								-0.297	-0.226							

Table 62 Bootstrapped response between temperature and residual ringwidth chronologies at Conolly's plot

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.255		-0.302					-0.340			-0.274								
Late								-0.375			-0.301	-0.241			-0.295				
Total			-0.258					-0.353			-0.318				-0.256				

Table 63 Bootstrapped response between temperature and standard ringwidth chronologies at Edakkode

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early													0.301						
Late														-0.29					
Total													0.272	-0.269					

Table 64 Bootstrapped response between temperature and residual ringwidth chronologies at Edakkode

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early													0.272						
Late														-0.294					
Total																			

Table 65 Bootstrapped response between temperature and standard ringwidth chronologies at Kanakuthu

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SE PT	OCT T	NOV T	DEC T
Early	0.259																-0.209		
Late					-0.250									-0.260					
Total	0.256																-0.211		

Table 66 Bootstrapped response between temperature and residual ringwidth chronologies at Kanakuthu

Ring width	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.271																		
Late								-0.234											
Total																			

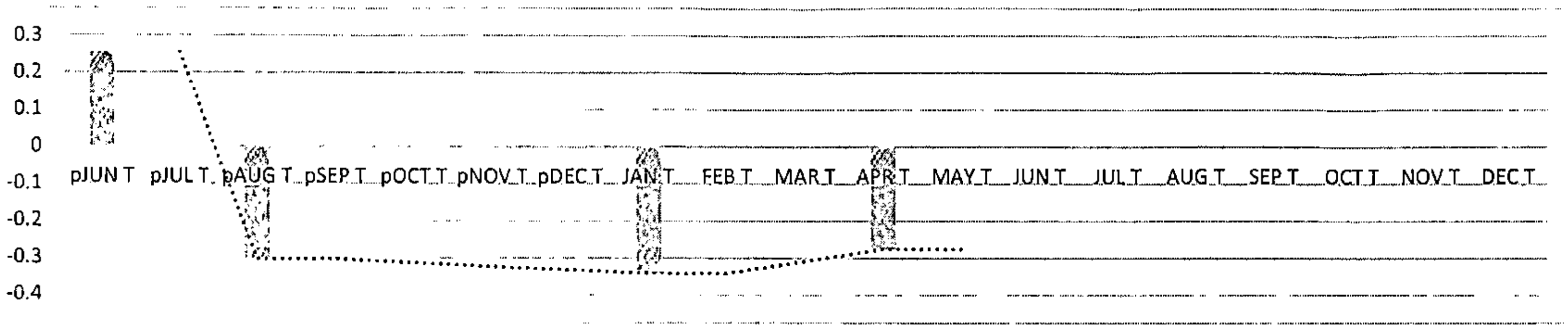

Fig 178 Bootstrapped response between temperature and standard earlywood ring width chronologies at Conolly's plot

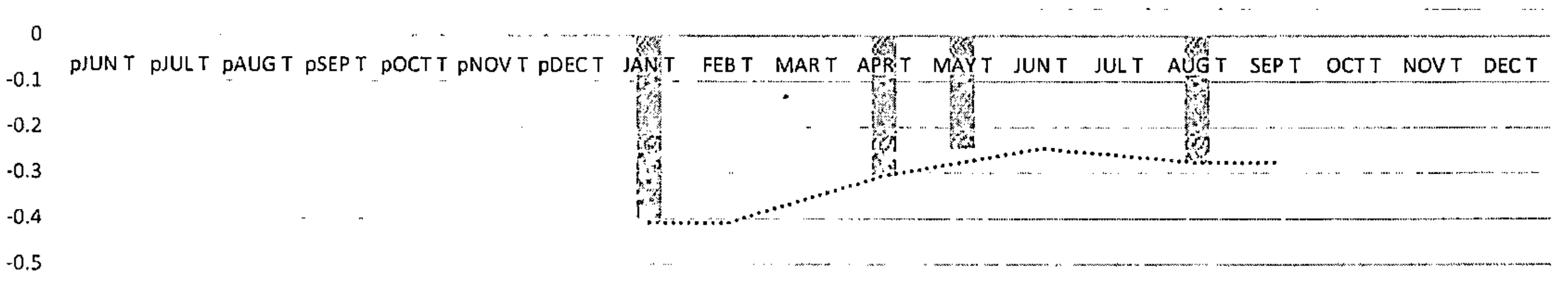

Fig 179 Bootstrapped response between temperature and standard latewood ring width chronologies at Conolly's plot

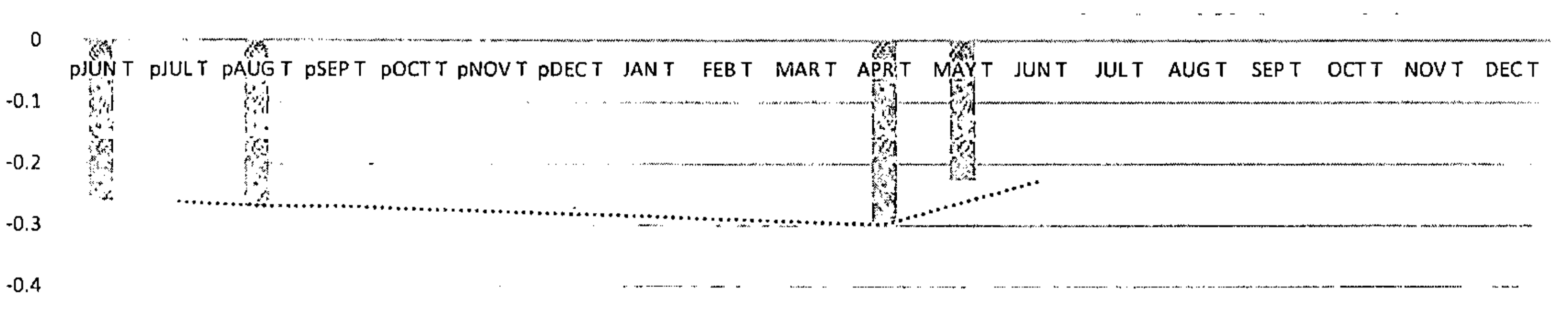

Fig 180 Bootstrapped response between temperature and standard totalwood ring width chronologies at Conolly's plot

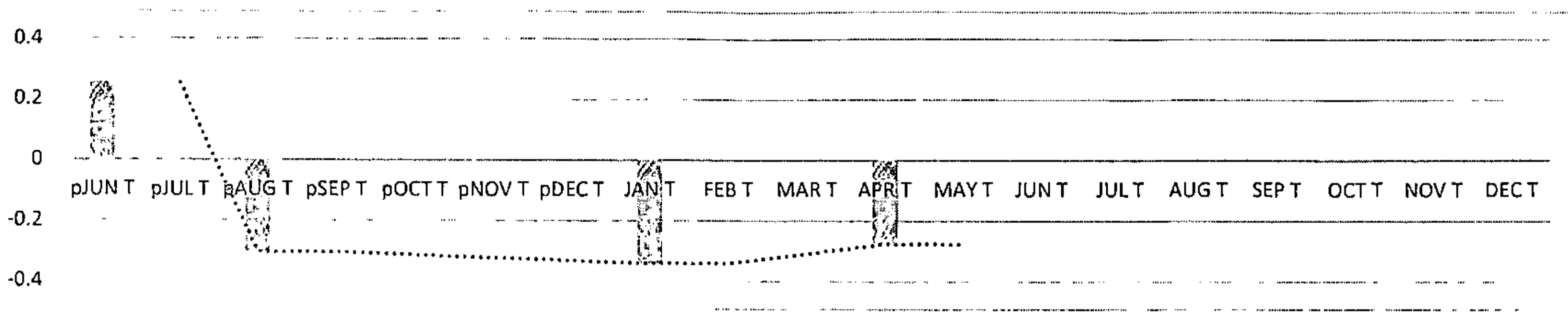

Fig 181 Bootstrapped response between temperature and residual earlywood ring width chronologies at Conolly's plot

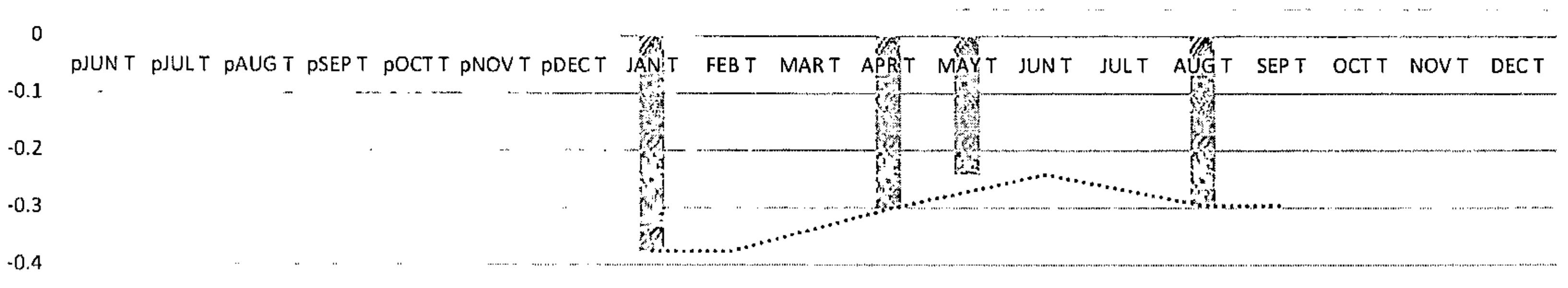

Fig 182 Bootstrapped response between temperature and residual latewood ring width chronologies at Conolly's plot

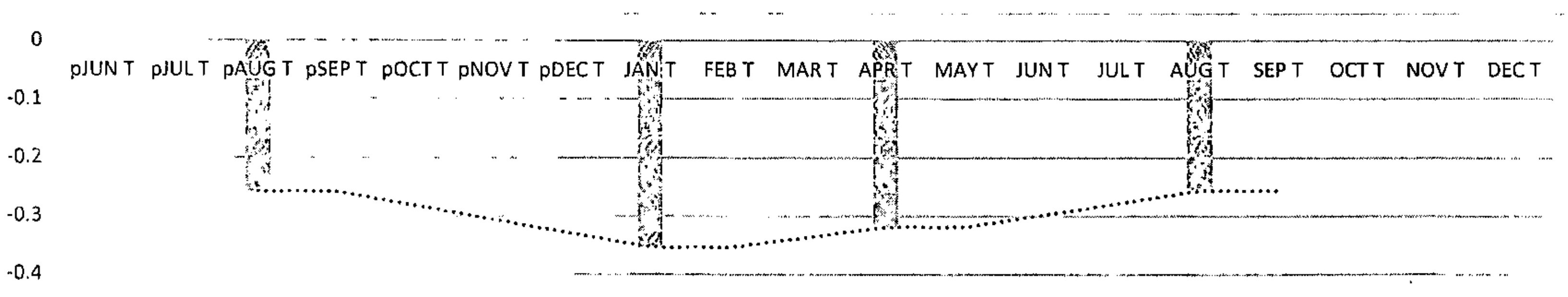

Fig 183 Bootstrapped response between temperature and residual totalwood ring width chronologies at Conolly's plot

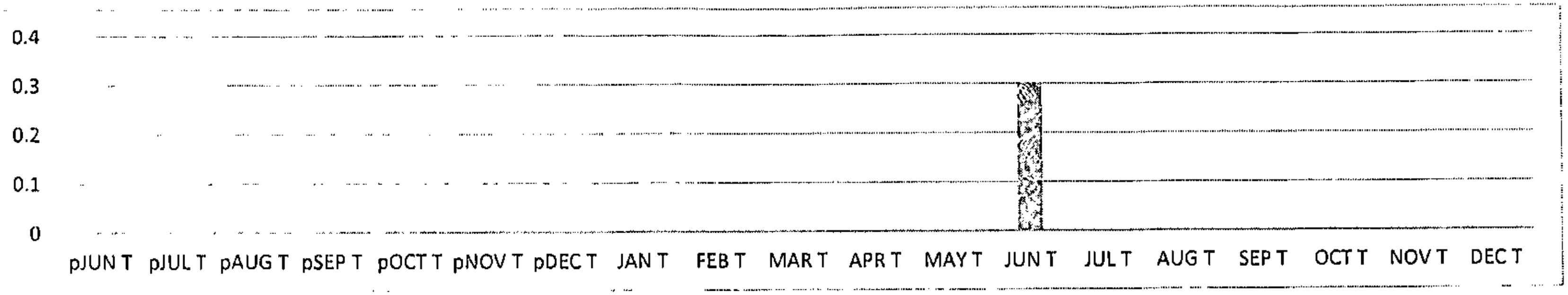

Fig 184 Bootstrapped response between temperature and standard earlywood ring width chronologies at Edakkode

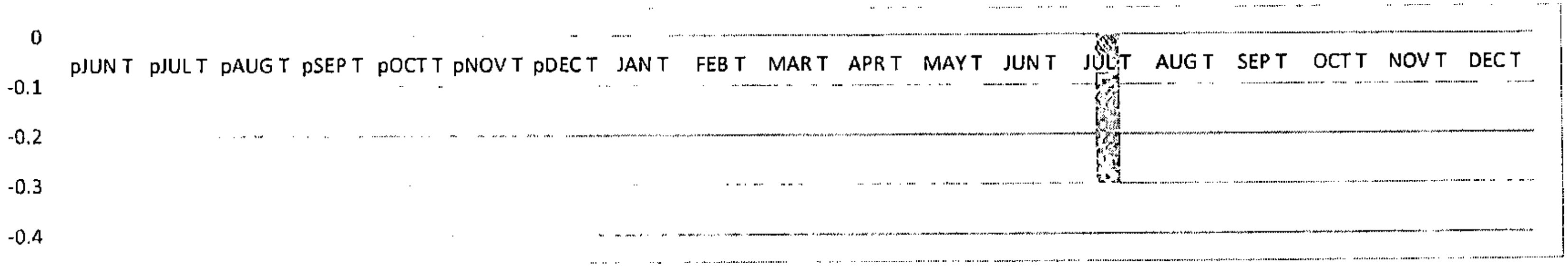

Fig 185 Bootstrapped response between temperature and standard latewood ring width chronologies at Edakkode

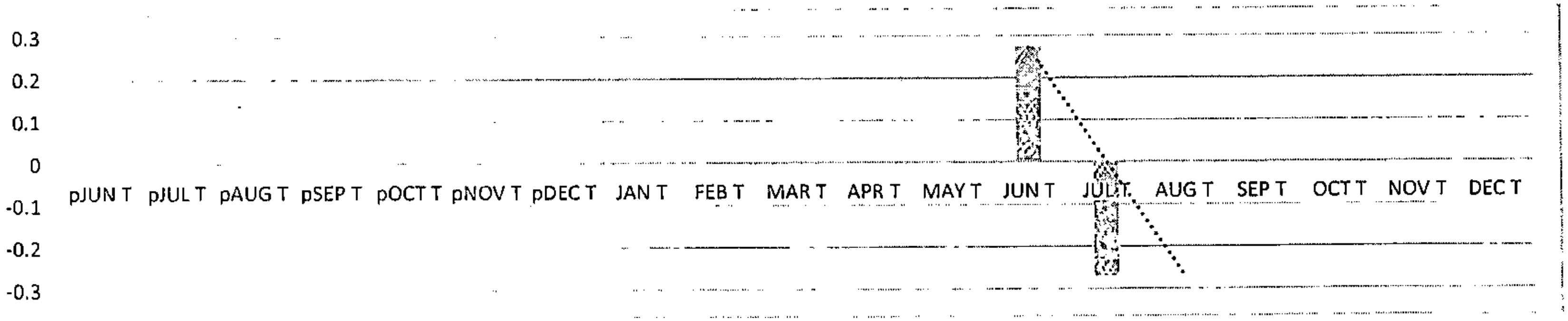

Fig 186 Bootstrapped response between temperature and standard totalwood ring width chronologies at Edakkode

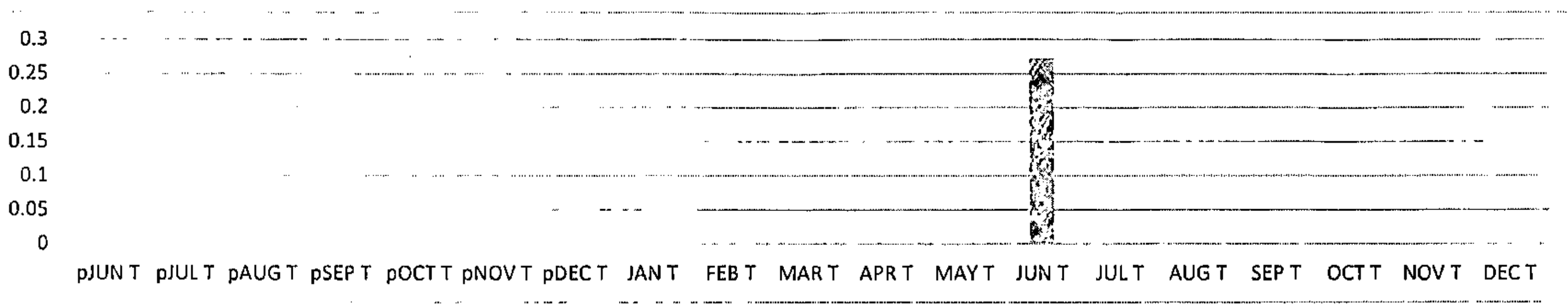

Fig 187 Bootstrapped response between temperature and residual earlywood ring width chronologies at Edakkode

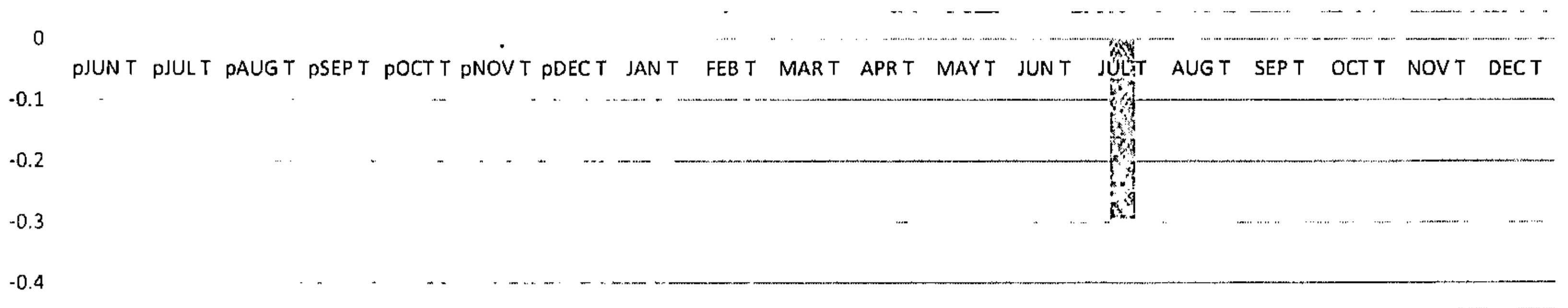

Fig 188 Bootstrapped response between temperature and residual latewood ring width chronologies at Edakkode

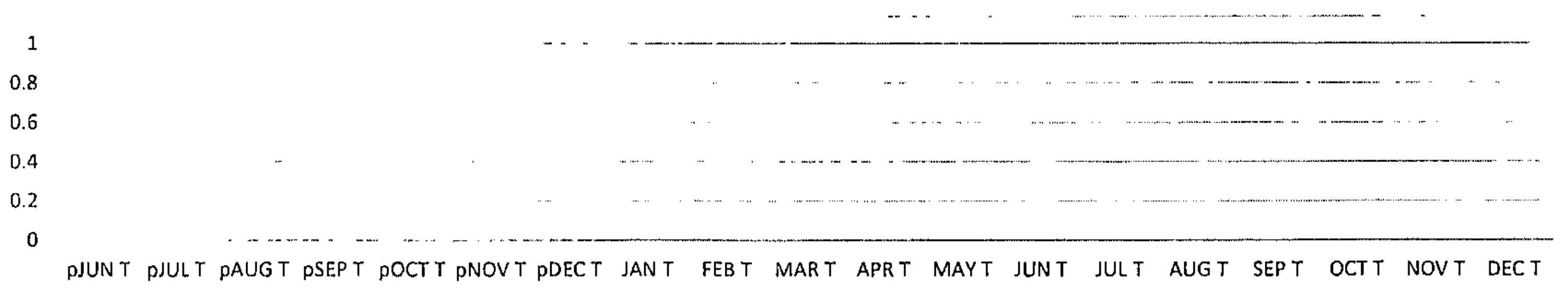

Fig 189 Bootstrapped response between temperature and residual totalwood ring width chronologies at Edakkode

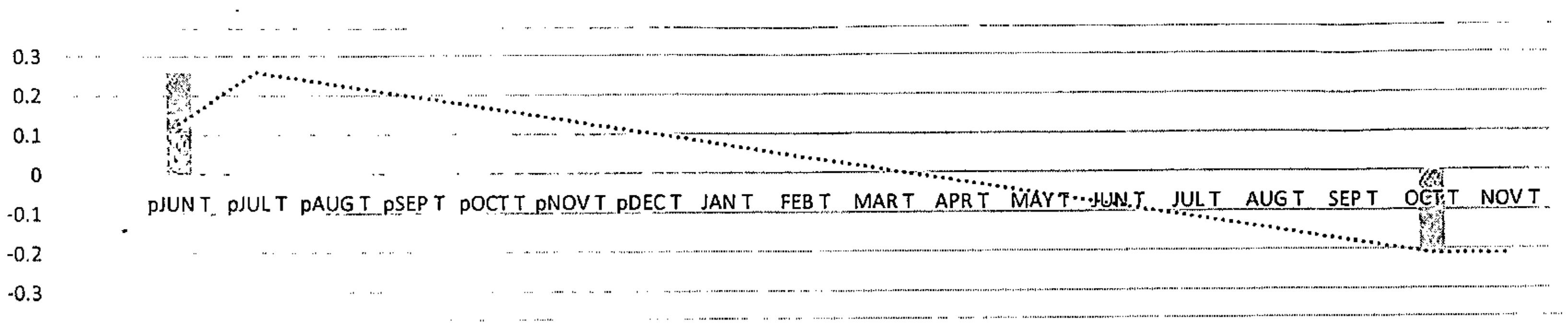

Fig 190 Bootstrapped response between temperature and standard earlywood ring width chronologies at Kanakuthu

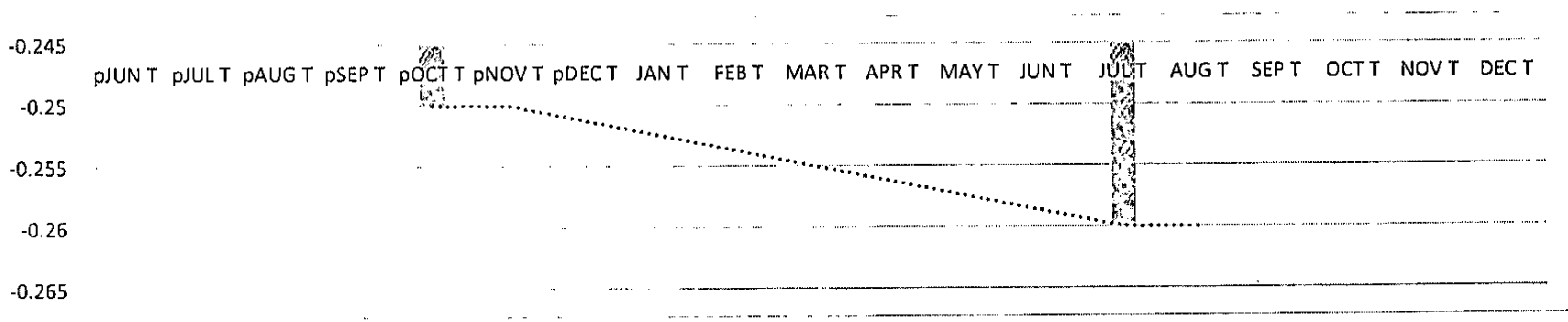

Fig 191 Bootstrapped response between temperature and standard latewood ring width chronologies at Kanakuthu

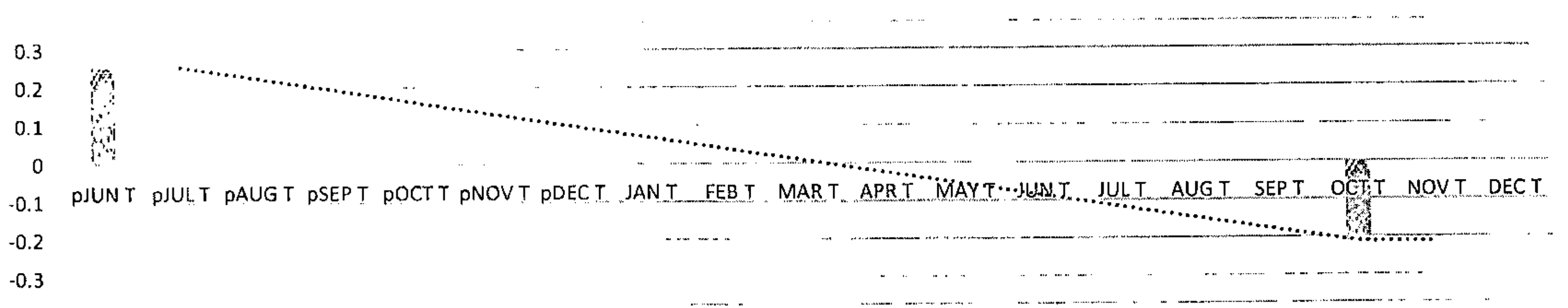

Fig 192 Bootstrapped response between temperature and standard totalwood ring width chronologies at Kanakuthu

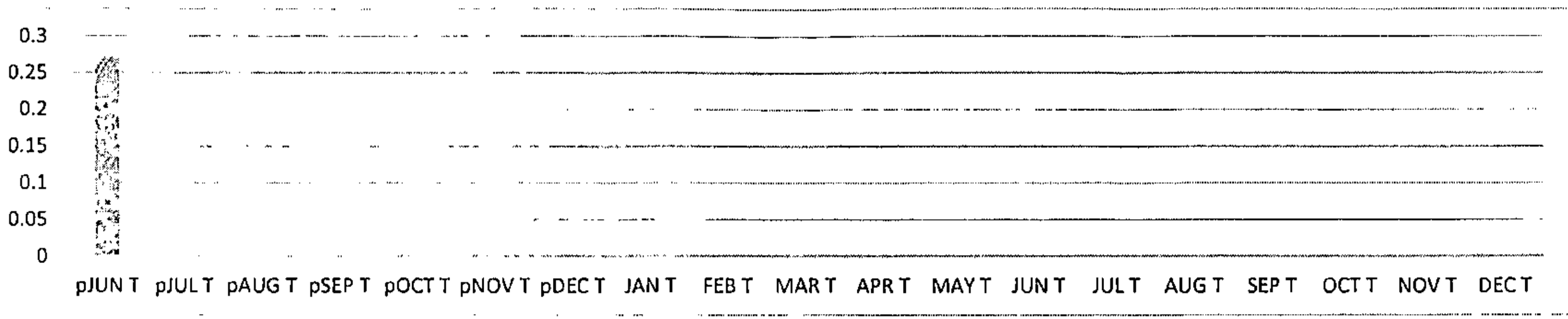

Fig 193 Bootstrapped response between temperature and residual earlywood ring width chronologies at Kanakuthu

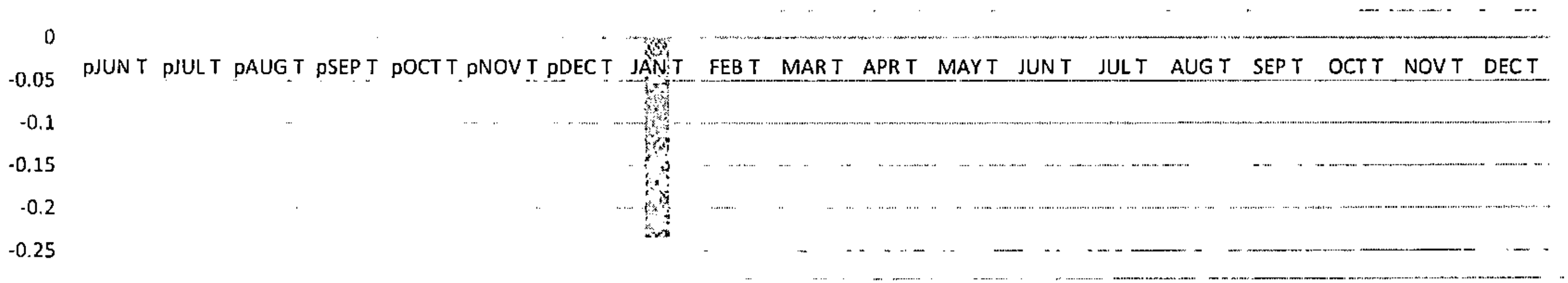

Fig 194 Bootstrapped response between temperature and residual latewood ring width chronologies at Kanakuthu

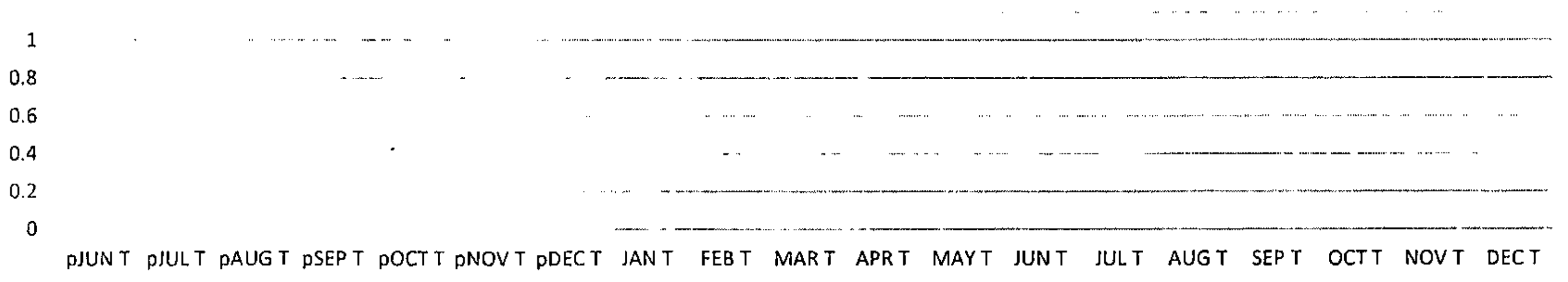

Fig 195 Bootstrapped response between temperature and residual totalwood ring width chronologies at Kanakuthu

Table 67 Bootstrapped response between precipitation and standard MVA chronologies at Conolly's plot

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early	0.339	0.290		0.257				-0.323			0.246		-0.260				0.229		0.334
late	-0.315		-0.254	-0.301	0.309				-0.293	0.310	-0.319						-0.269		
total	-0.305										-0.319	0.255							-0.308

Table 68 Bootstrapped response between precipitation and residual MVA chronologies at Conolly's plot

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early	0.333	0.292		0.257				-0.323			0.245		-0.263				0.230		0.313
late	-0.269			-0.351	0.308	-0.292				0.284	-0.310						-0.285		
total				-0.302							-0.335								-0.245

Table 69 Bootstrapped response between precipitation and standard MVA chronologies at Edakkode

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early		-0.253		0.313								0.276		-0.262		0.295			
late	0.264	0.285	-0.291			0.267						-0.277						0.245	
total						0.365			0.246			-0.339	0.205	-0.183				0.271	

Table 70 Bootstrapped response between precipitation and residual MVA chronologies at Edakkode

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early												0.252		-0.257		0.331			
late		0.302						0.213		-0.233		-0.268						0.3008	
total						0.349			0.240			-0.341	0.204	-0.183					

Table 71 Bootstrapped response between precipitation and standard MVA chronologies at Kanakuthu

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early		0.272						-0.253	0.245			-0.352		0.249					
late					-0.339														
total														0.223					

Table 72 Bootstrapped response between precipitation and residual MVA chronologies at Kanakuthu

MVA	pJUN P	pJUL P	pAUG P	pSEP P	pOCT P	pNOV P	pDEC P	JAN P	FEB P	MAR P	APR P	MAY P	JUN P	JUL P	AUG P	SEP P	OCT P	NOV P	DEC P
early					0.317		0.292	-0.264					0.244	0.261					
late				-0.270															
total									0.223					0.223					

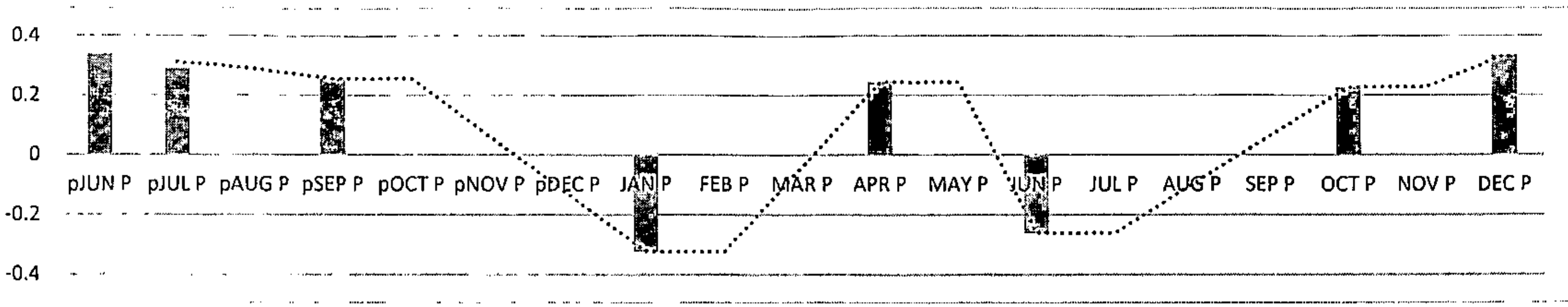

Fig 196 Bootstrapped response between rainfall and standard earlywood MVA chronologies at Conolly's plot

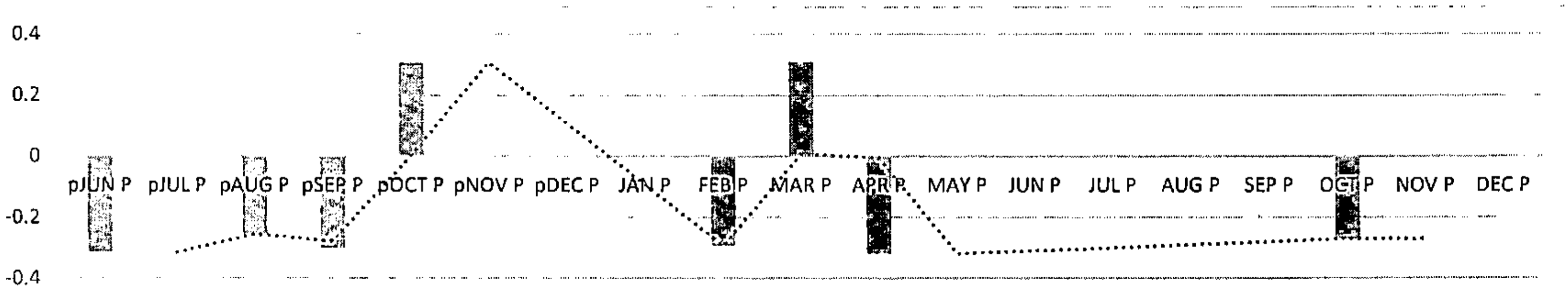

Fig 197 Bootstrapped response between rainfall and standard latewood MVA chronologies at Conolly's plot

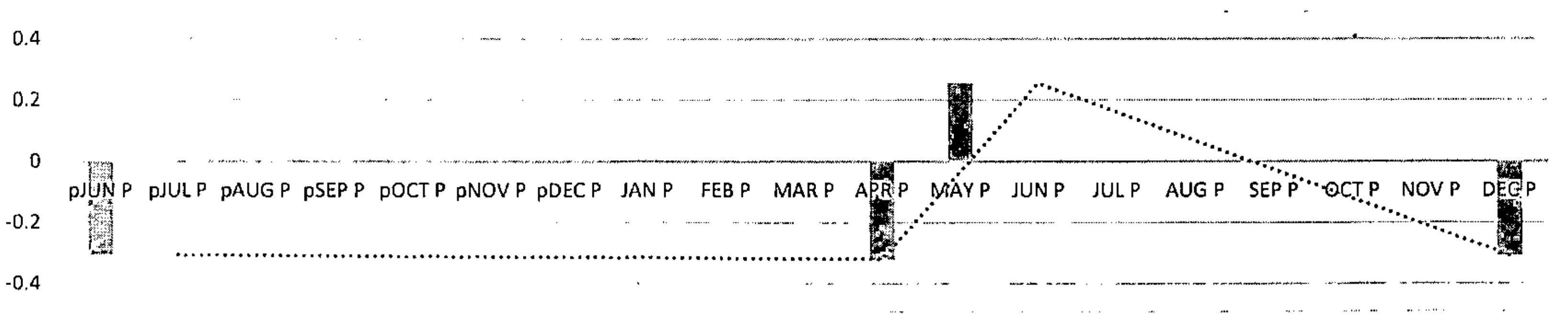

Fig 198 Bootstrapped response between rainfall and standard totalwood MVA chronologies at Conolly's plot

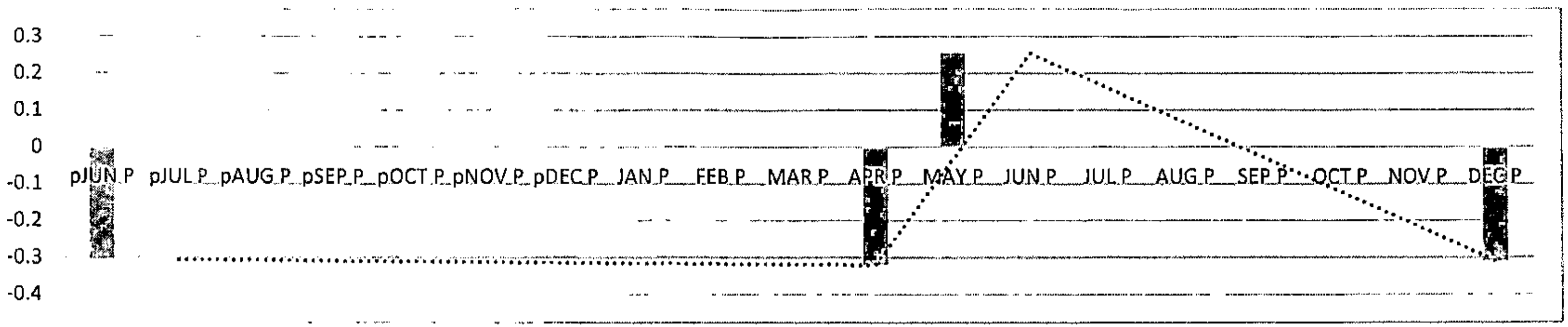

Fig 199 Bootstrapped response between rainfall and standard earlywood MVA chronologies at Conolly's plot

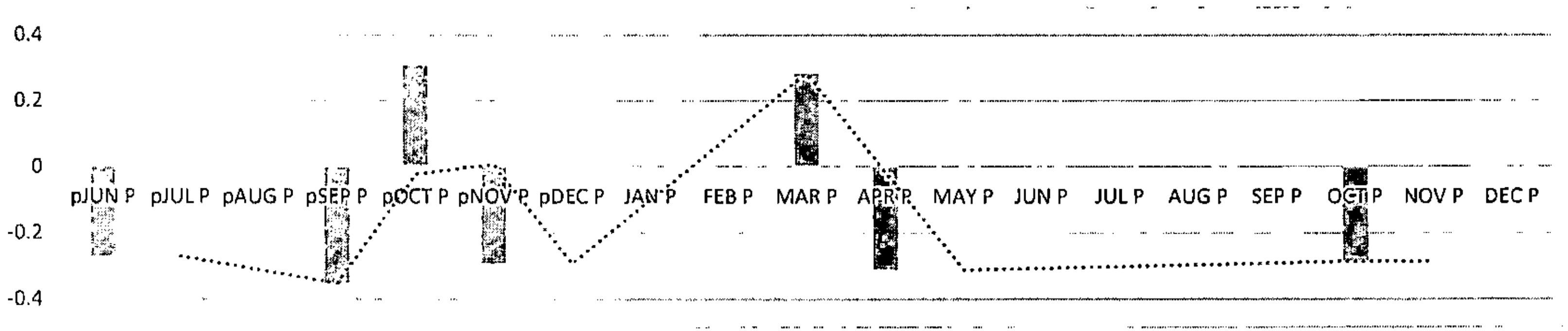

Fig 200 Bootstrapped response between rainfall and residual latewood MVA chronologies at Conolly's plot

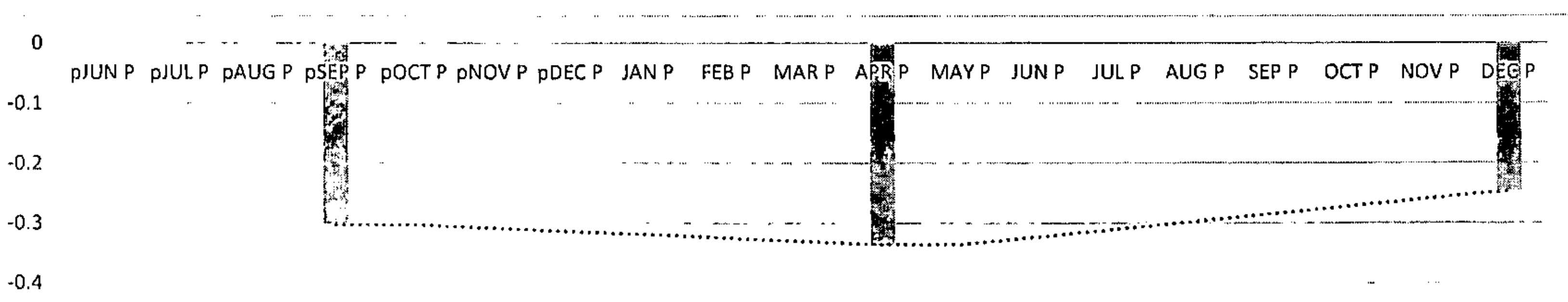

Fig 201 Bootstrapped response between rainfall and residual totalwood MVA chronologies at Conolly's plot

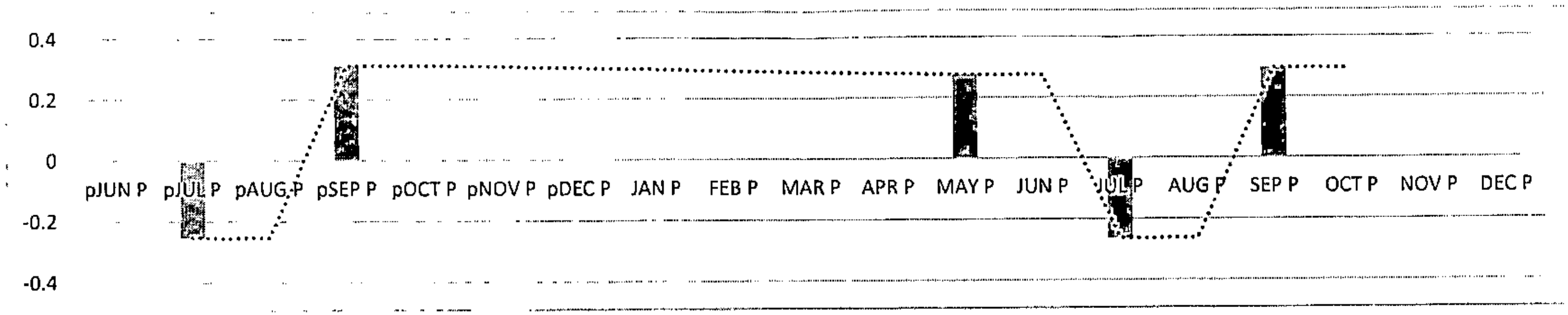

Fig 202 Bootstrapped response between rainfall and standard earlywood MVA chronologies at Edakkode

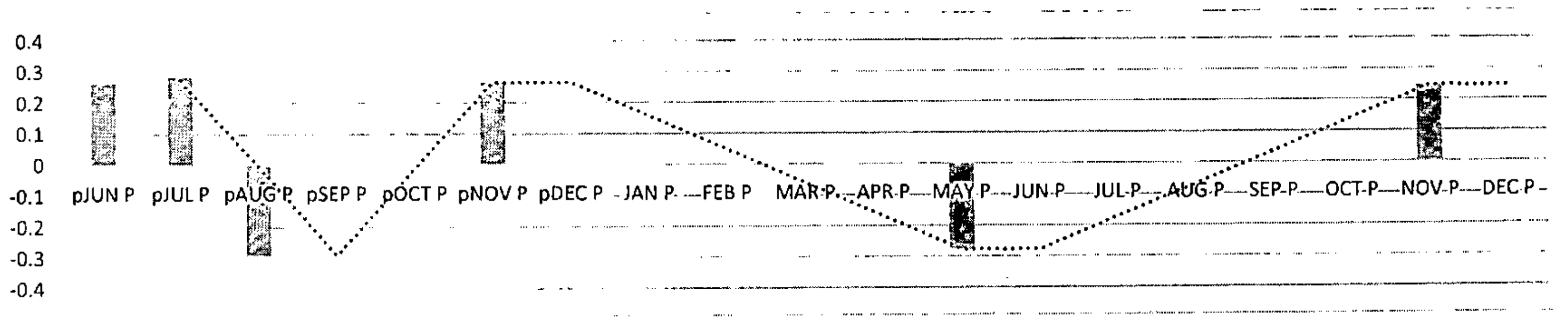

Fig 203 Bootstrapped response between rainfall and standard latewood MVA chronologies at Edakkode

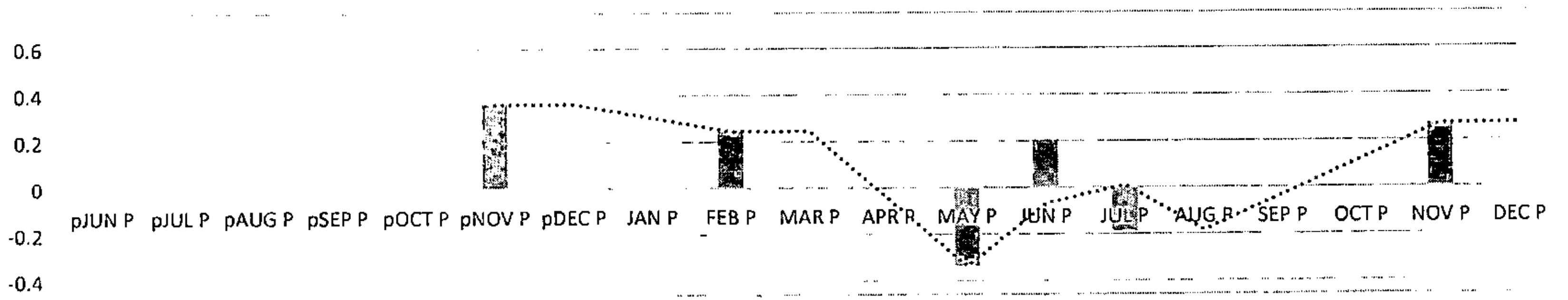

Fig 204 Bootstrapped response between rainfall and standard totalwood MVA chronologies at Edakkode

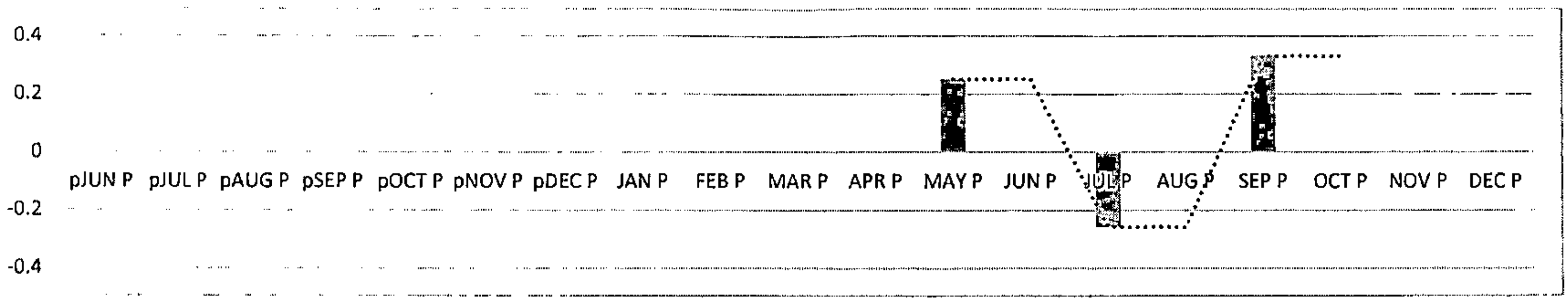

Fig 205 Bootstrapped response between rainfall and residual earlywood MVA chronologies at Edakkode

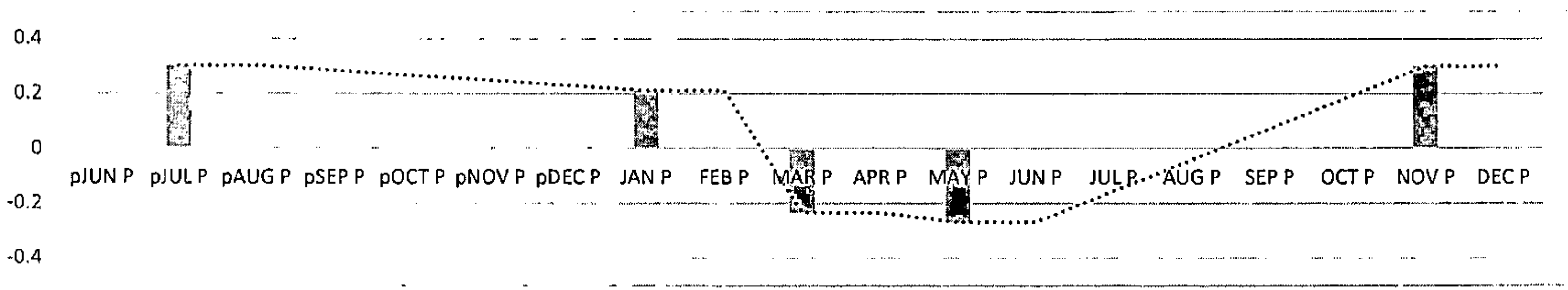

Fig 206 Bootstrapped response between rainfall and residual latewood MVA chronologies at Edakkode

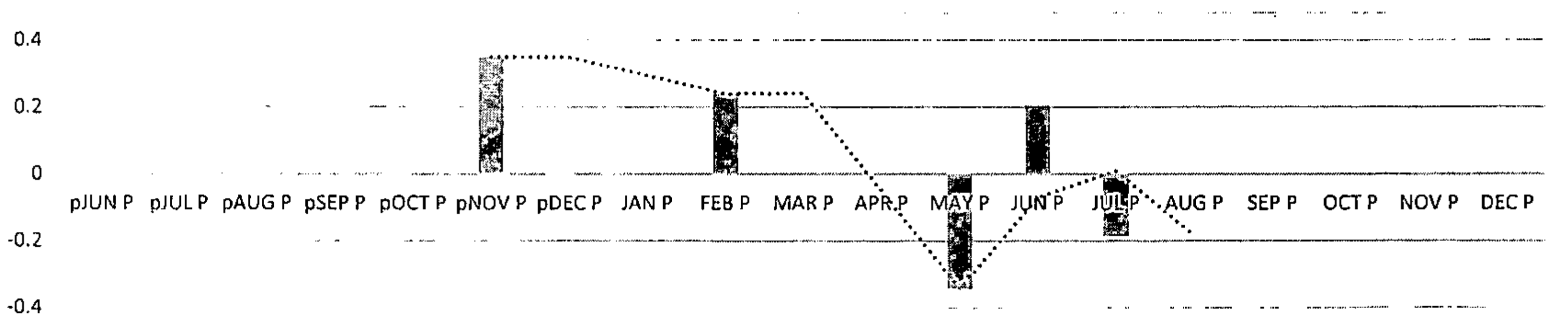

Fig 207 Bootstrapped response between rainfall and residual totalwood MVA chronologies at Edakkode

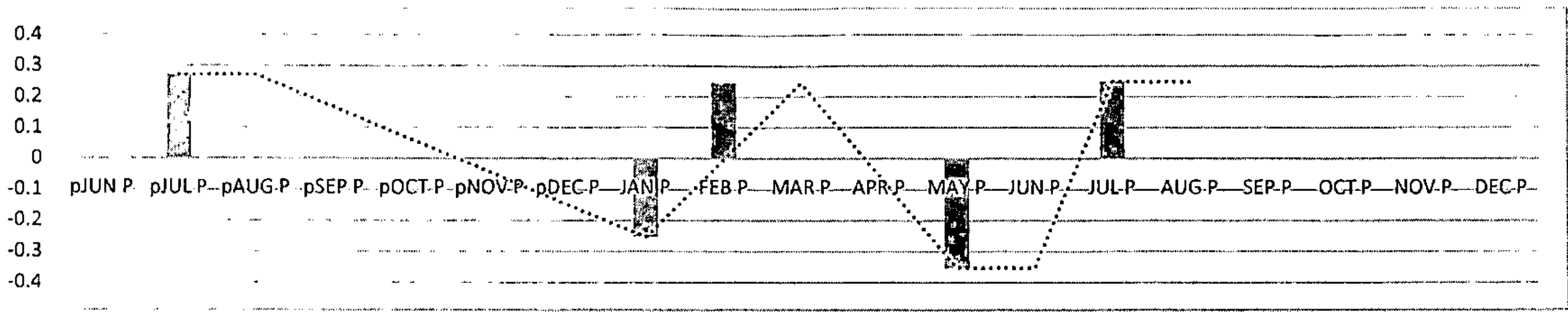

Fig 208 Bootstrapped response between rainfall and standard earlywood MVA chronologies at Kanakuthu

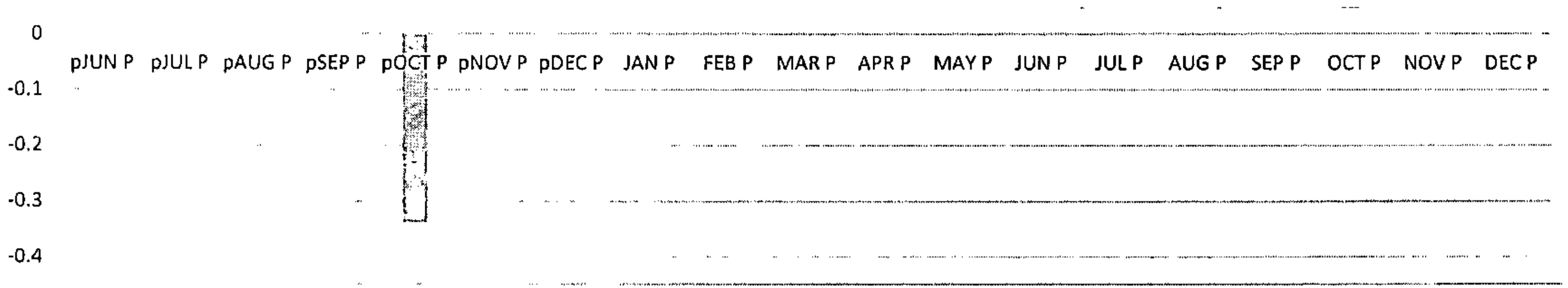

Fig 209 Bootstrapped response between rainfall and standard latewood MVA chronologies at Kanakuthu

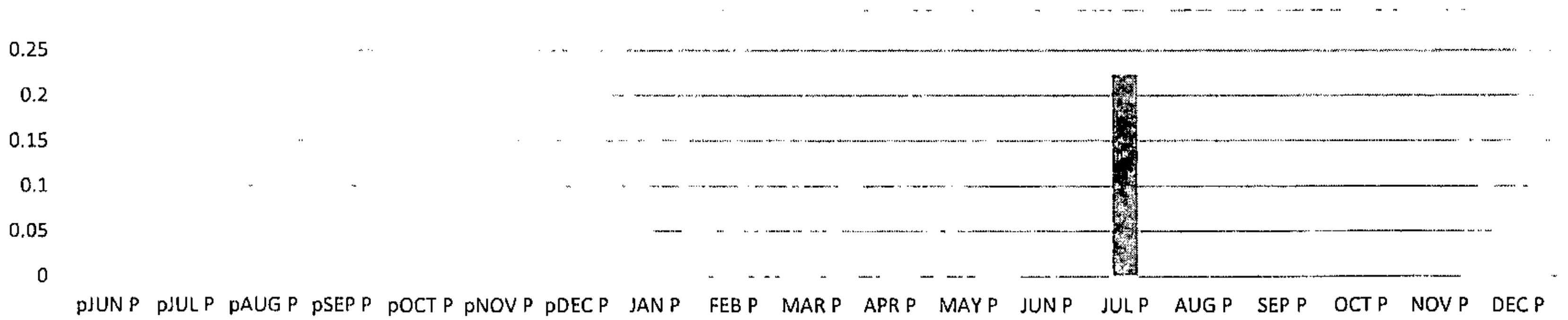

Fig 210 Bootstrapped response between rainfall and standard totalwood MVA chronologies at Kanakuthu

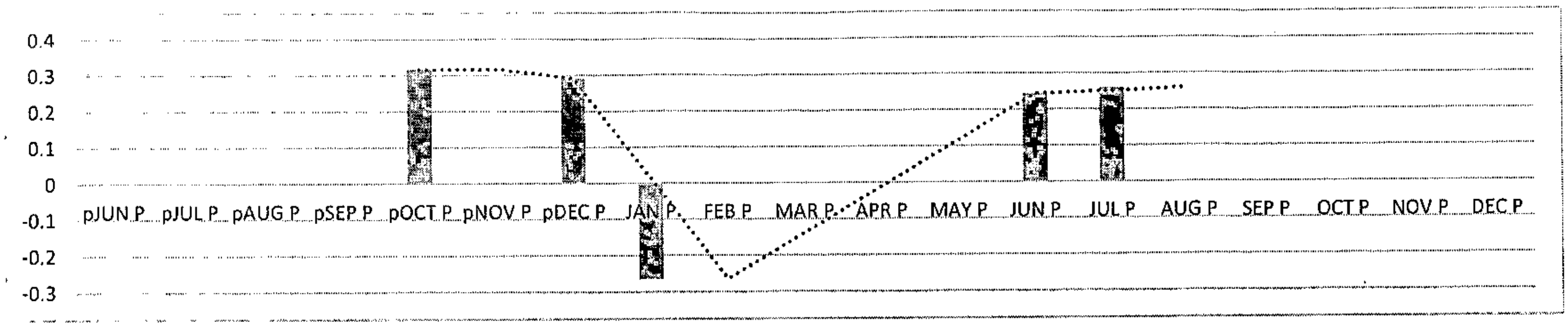

Fig 211 Bootstrapped response between rainfall and residual earlywood MVA chronologies at Kanakuthu

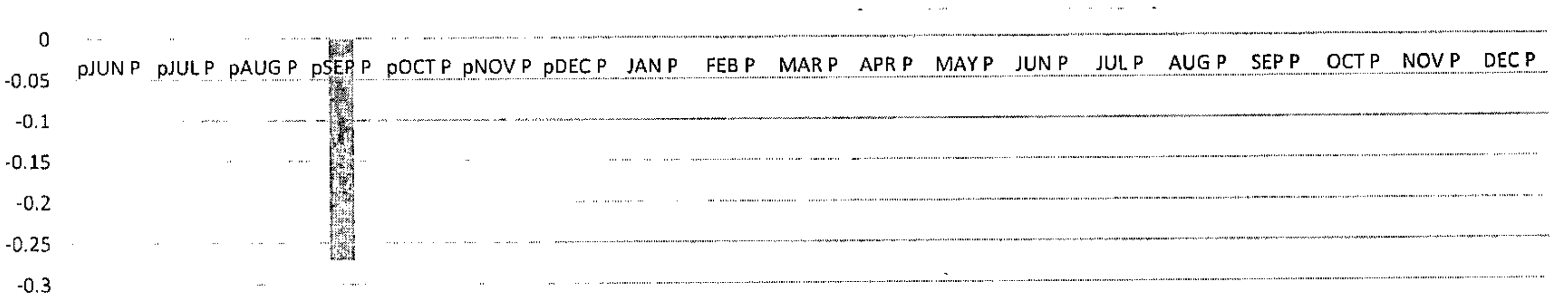

Fig 212 Bootstrapped response between rainfall and residual latewood MVA chronologies at Kanakuthu

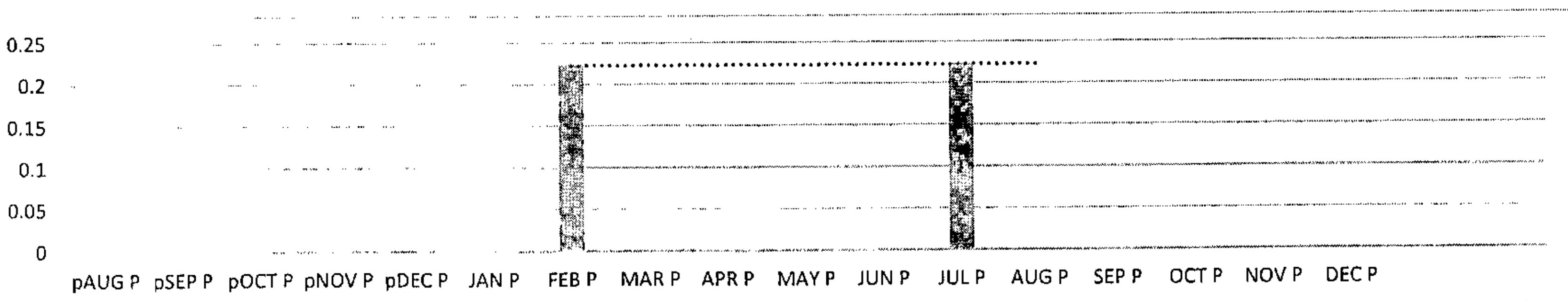

Fig 213 Bootstrapped response between rainfall and residual totalwood MVA chronologies at Kanakuthu

4.9.5 Response between seasonal climate and MVA

In Conolly's plot the negative response was the greatest between June-September temperature (-0.374) and standard earlywood chronology also was related with totalwood residual (-0.394). In standard and residual chronology there was positive response to June-September precipitation (0.352, 0.359) October-November temperature had positive connection with standard latewood (0.261) at Edakkode. Also previous October-November precipitation had positive relation (0.363) with standard totalwood. In residual latewood chronology at Edakkode there was positive response to December-February temperature (0.098) and totalwood residual chronology responded positive to October-November rainfall (0.405). At Kanakuthu, the standard and residual totalwood chronologies responded to October-Novemeber temperature (0.198, 0.196). Also, totalwood standard and residul totalwood chronologies had positive response with October-November rainfall with values of 0.341 and 0.342 respectively. (Table 72-78; Figure 214-232)

4.9.6 Response between monthly temperature and MVA

At Conolly's plot, there was positive response of standard and residual latewood chronologies to previous June temperature (0.310, 0.310). But there was negative relation between previous August temperature and standard latewood chronology (-0.310). Also, the earlywood July temperature responded negatively (-0.301) to residual earlywood chronology at Conolly's plot. In Edakkode there was positive response between standard and residual latewood chronologies to December temperature (0.311, 0.367). Previous July temperature was negatively related to standard latewood chronology (-0.324) and June temperature was also negatively related to latewood residual chronology (-0.315) at Edakkode. At Kanakuthu it was observed there was negative response of standard and residual latewood chronologies to previous August temperature (-0.351, -0.317). While the standard and residual totalwood chronologies at Edakkode responded positively to May temperature with values of 0.415 and 0.424 respectively. (Table 79-84; Figure 233-250)

Table 73 Bootstrapped response between seasonal variables and standard MVA chronologies at Conolly's plot

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early			-0.374					-0.222	0.297	0.352	-0.260			
Late			-0.286	-0.237	-0.116			0.201	-0.331					
Total	-0.218	-0.328	-0.382		-0.101			-0.192	0.259	-0.272				

Table 74 Bootstrapped response between seasonal variables and residual MVA chronologies at Conolly's plot

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early								-0.222	0.297	0.359	-0.259			
Late			-0.290	-0.249	-0.102				-0.307					
Total	-0.223	-0.331	-0.394		-0.100			-0.188	0.277	-0.369				

Table 75 Bootstrapped response between seasonal variables and standard MVA chronologies at Edakkode

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early											0.334			
Late				0.261	0.129				0.354		-0.342			
Total									0.363		-0.475			

Table 76 Bootstrapped response between seasonal variables and residual MVA chronologies at Edakkode

MVA	p JJAS T	p ON T	JJAS T	ON T	DJF T	MAM T	AM T	p JJAS P	p ON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early														
Late					0.098				0.392		0.402			
Total									0.370		0.405			

Table 77 Bootstrapped response between seasonal variables and standard MVA chronologies at Kanakuthu

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early					-0.088			0.264	-0.274	0.315	0.318			
Late					-0.105									
Total				0.198				0.249			0.341	0.208		

Table 78 Bootstrapped response between seasonal variables and residual MVA chronologies at Kanakuthu

MVA	pJJAS T	pON T	JJAS T	ON T	DJF T	MAM T	ANN T	pJJAS P	pON P	JJAS P	ON P	DJF P	MAM P	ANN P
Early								0.272		0.293	0.275			
Late												0.219		
Total				0.196				0.251	-0.286		0.342	0.211		

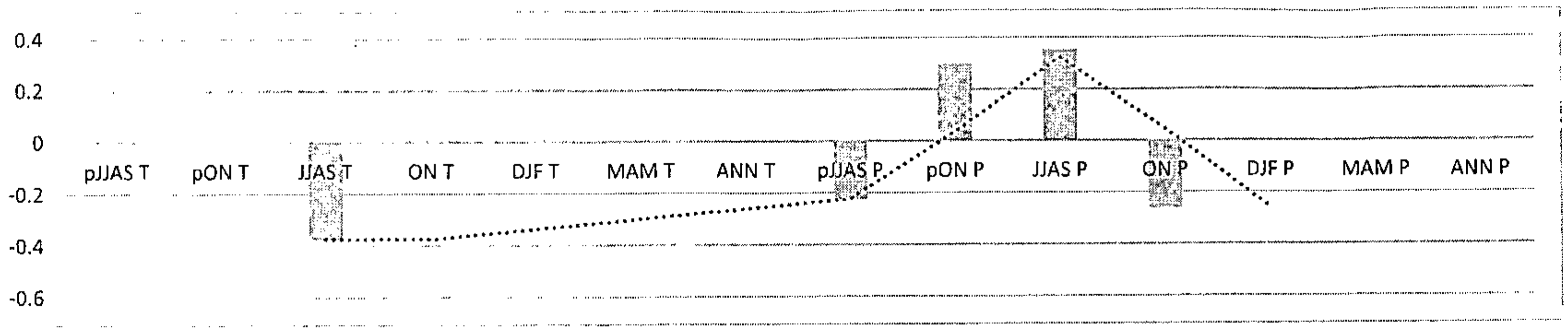

Fig 214 Bootstrapped response between seasonal climate and standard earlywood MVA chronologies at Conolly's plot

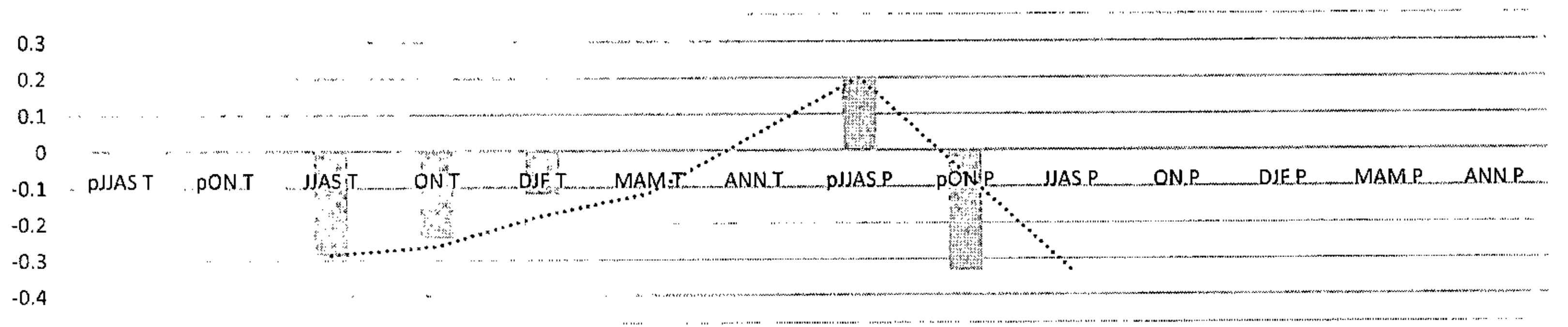

Fig 215 Bootstrapped response between seasonal climate and standard latewood MVA chronologies at Conolly's plot

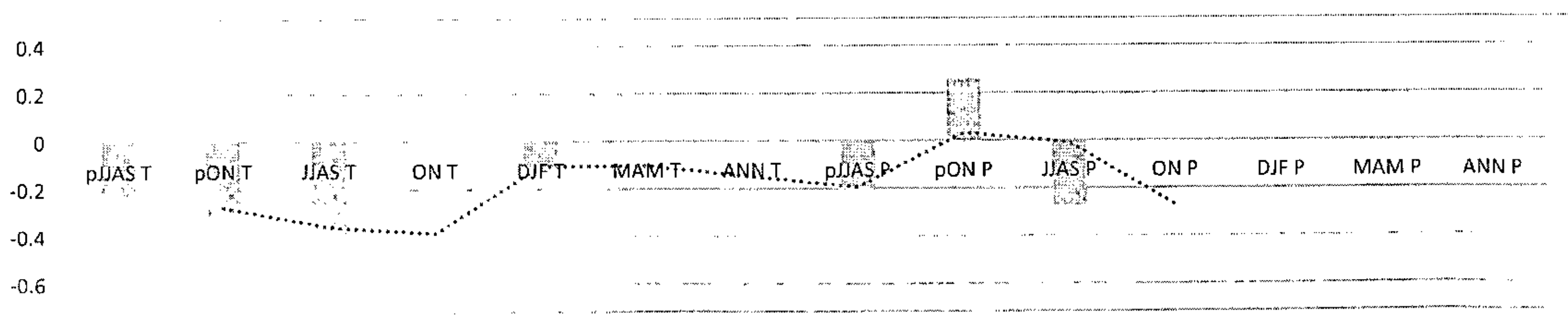

Fig 216 Bootstrapped response between seasonal climate and standard totalwood MVA chronologies at Conolly's plot

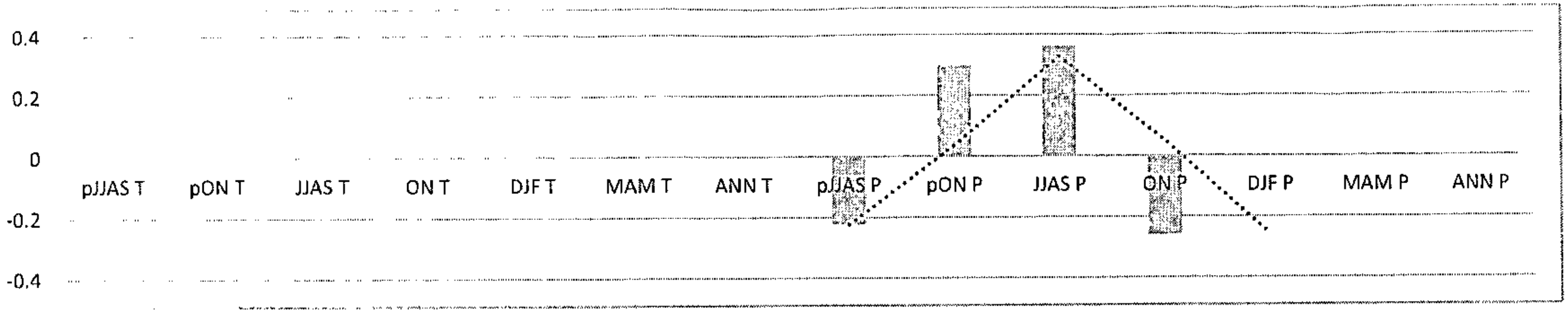

Fig 217 Bootstrapped response between seasonal climate and residual earlywood MVA chronologies at Conolly's plot

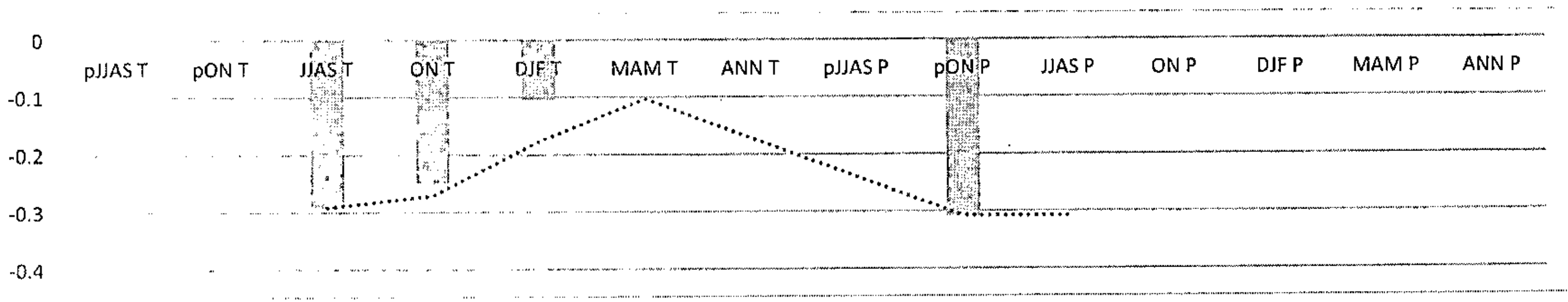

Fig 218 Bootstrapped response between seasonal climate and residual latewood MVA chronologies at Conolly's plot

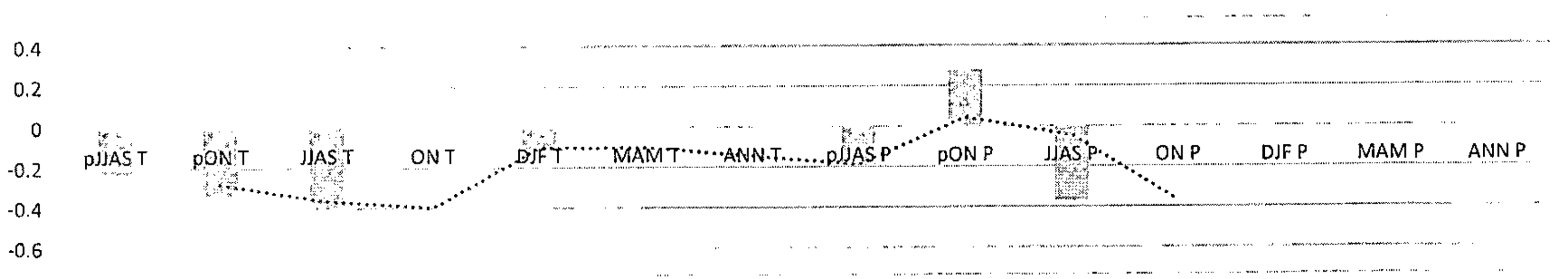

Fig 219 Bootstrapped response between seasonal climate and residual totalwood MVA chronologies at Conolly's plot

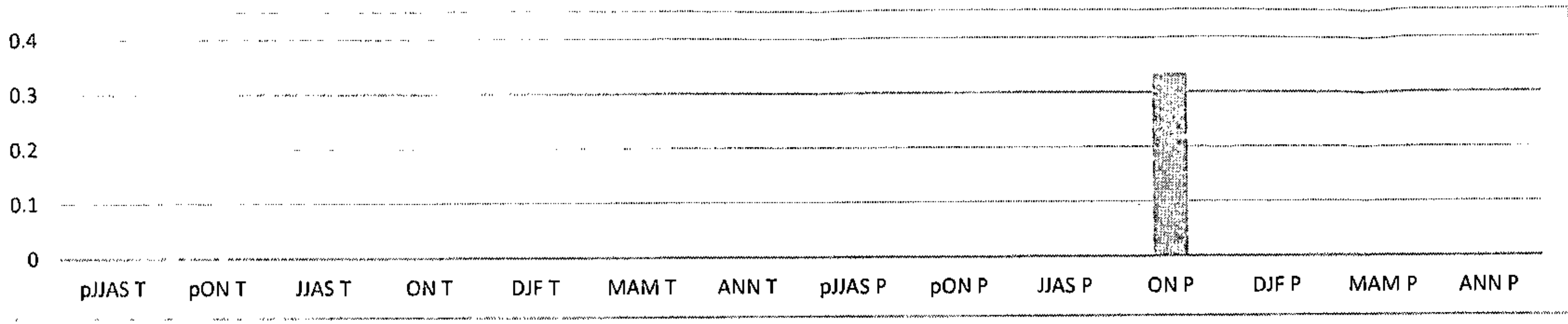

Fig 220 Bootstrapped response between seasonal climate and residual earlywood MVA chronologies at Edakkode

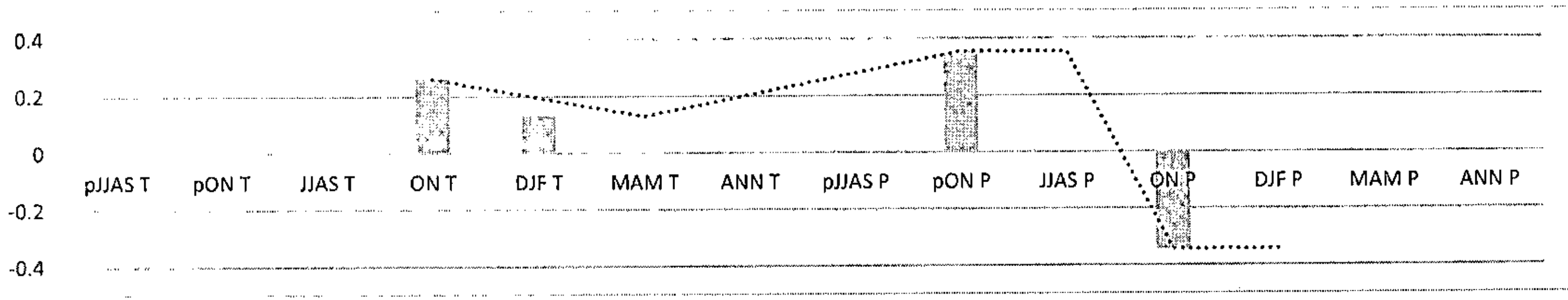

Fig 221 Bootstrapped response between seasonal climate and standard latewood MVA chronologies at Edakkode

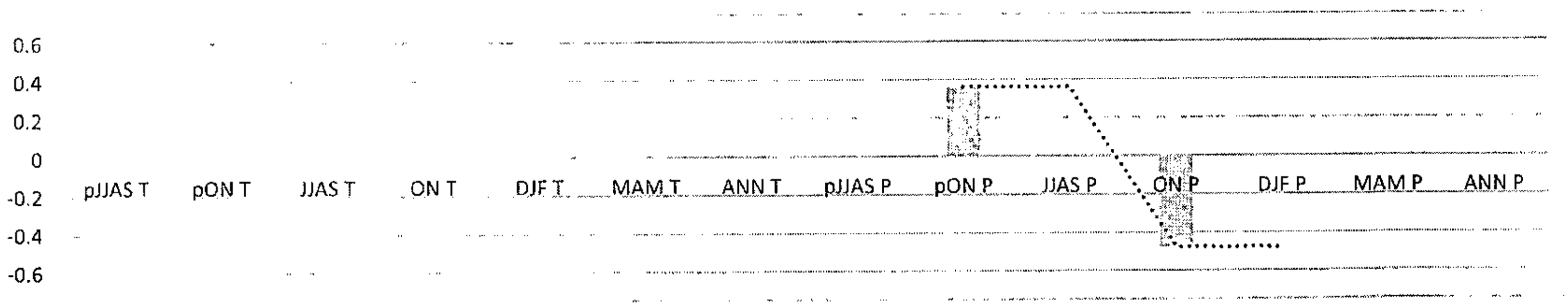

Fig 222 Bootstrapped response between seasonal climate and standard totalwood MVA chronologies at Edakkode

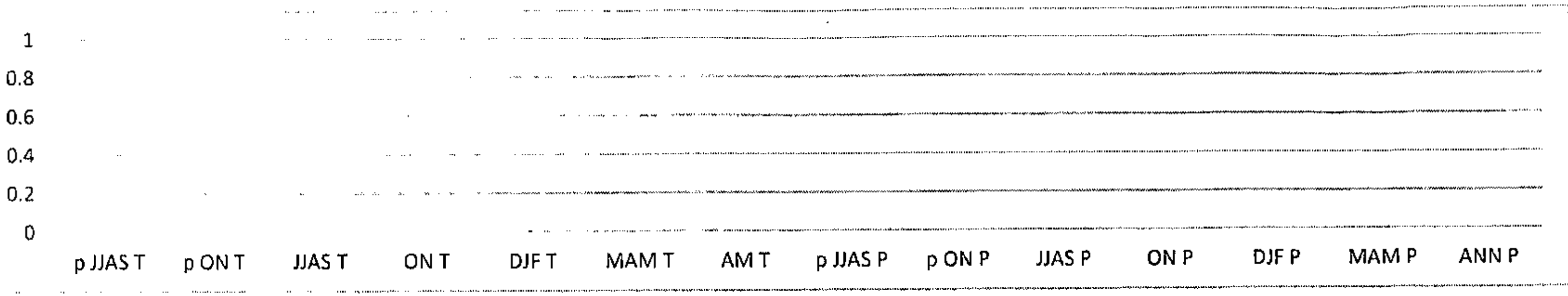

Fig 223 Bootstrapped response between seasonal climate and standard earlywood MVA chronologies at Edakkode

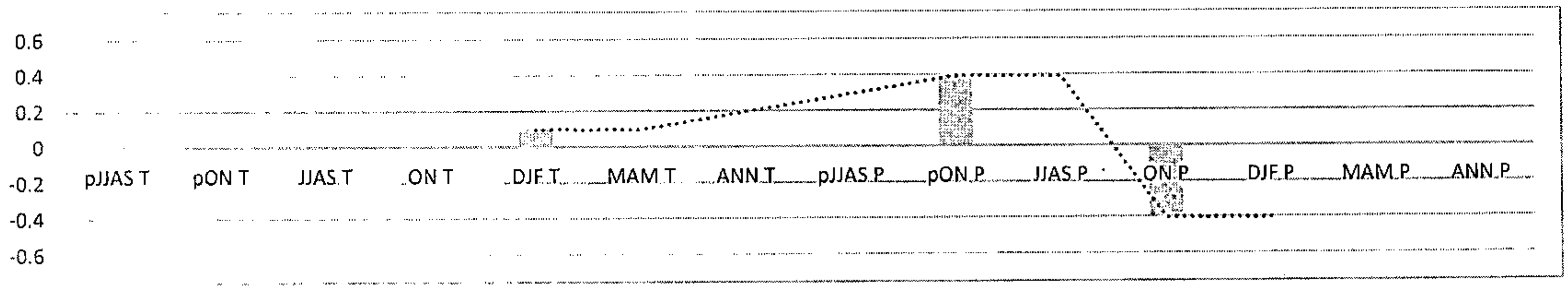

Fig 224 Bootstrapped response between seasonal climate and residual latewood MVA chronologies at Edakkode

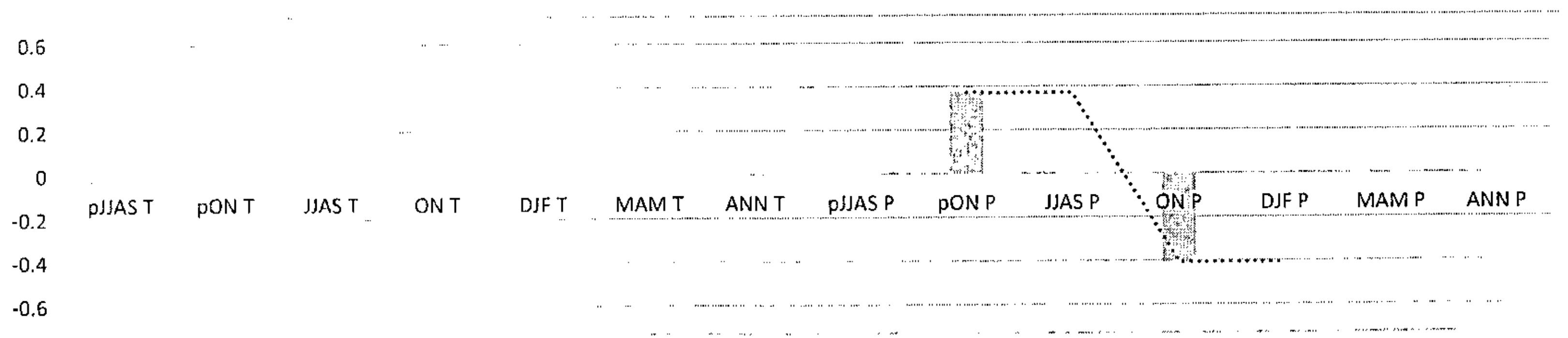

Fig 225 Bootstrapped response between seasonal climate and residual totalwood MVA chronologies at Edakkode

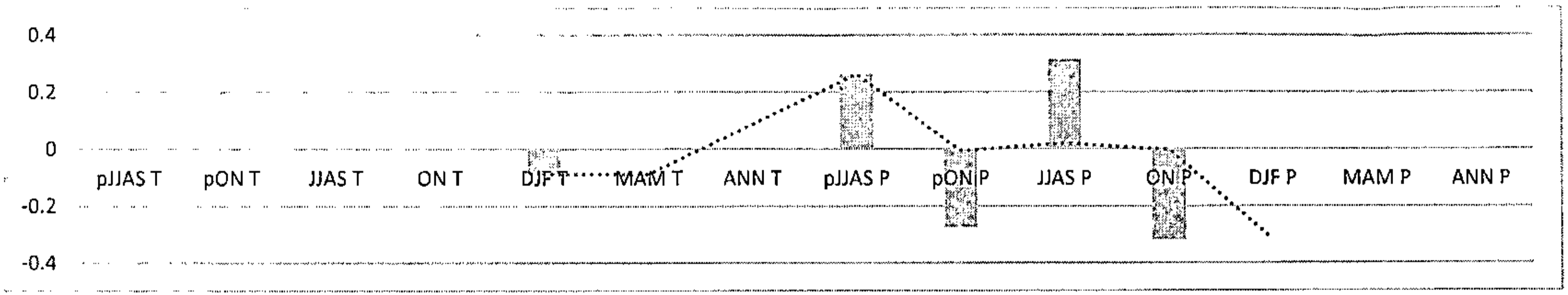

Fig 226 Bootstrapped response between seasonal climate and standard earlywood MVA chronologies at Kanakuthu

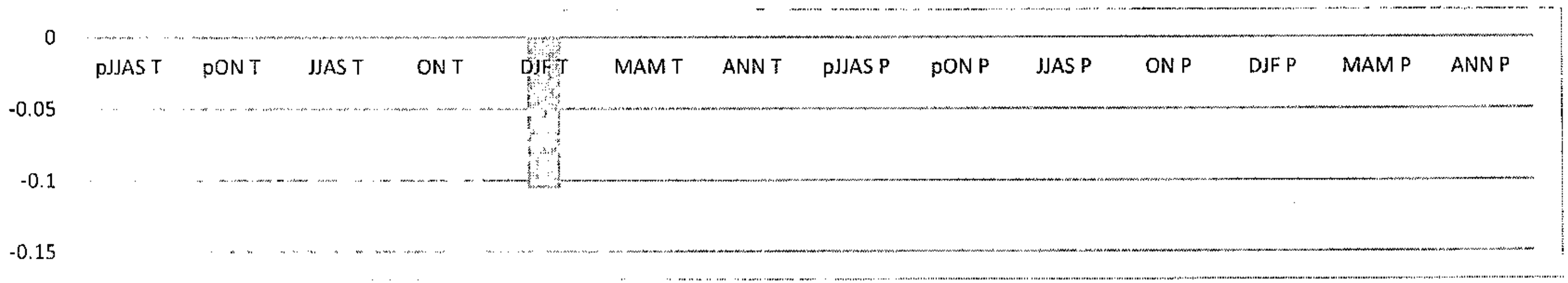

Fig 227 Bootstrapped response between seasonal climate and standard latewood MVA chronologies at Kanakuthu

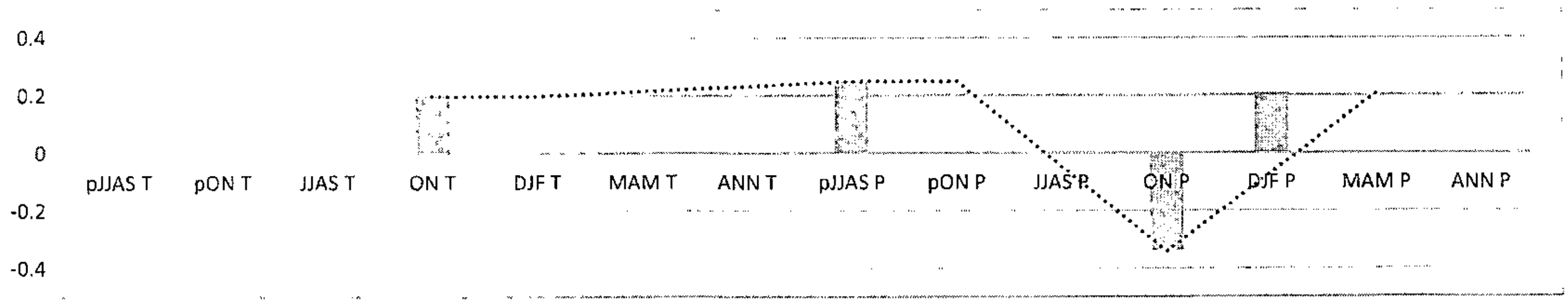

Fig 229 Bootstrapped response between seasonal climate and standard totalwood MVA chronologies at Kanakuthu

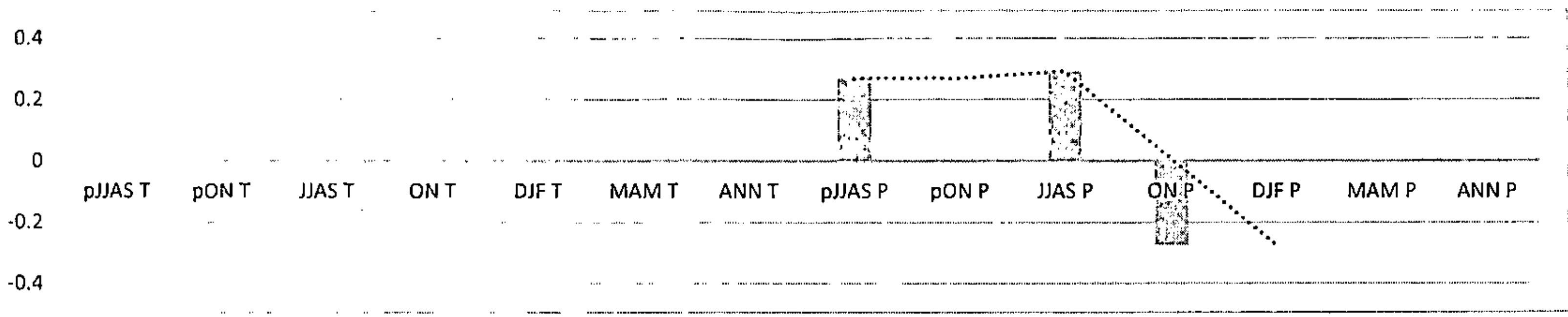

Fig 230 Bootstrapped response between seasonal climate and residual earlywood MVA chronologies at Kanakuthu

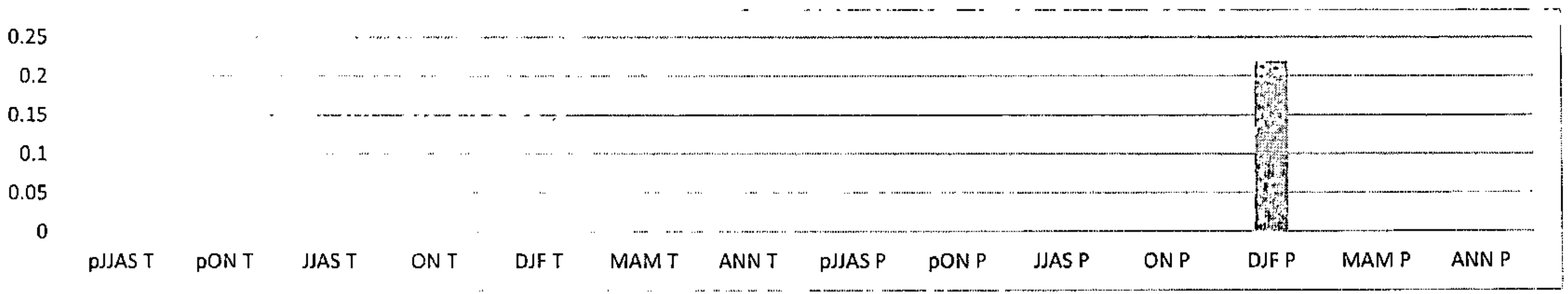

Fig 231 Bootstrapped response between seasonal climate and residual latewood MVA chronologies at Kanakuthu

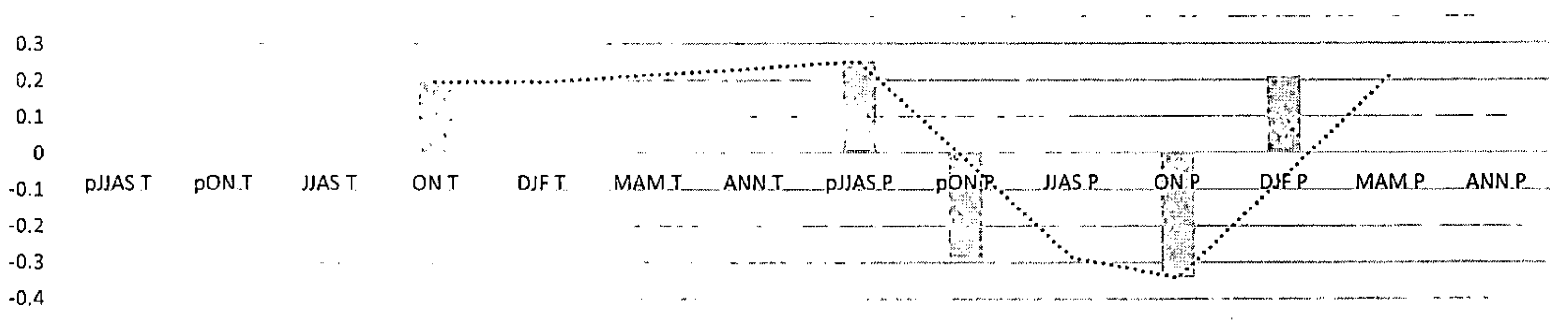

Fig 232 Bootstrapped response between seasonal climate and residual totalwood MVA chronologies at Kanakuthu

Table 79 Bootstrapped response between temperature and standard MVA chronologies at Conolly's plot

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early														-0.301		-0.288			-0.267
Late	0.310		-0.310									-0.294			-0.265				
Total	0.230							0.252	-0.268										

Table 80 Bootstrapped response between temperature and residual MVA chronologies at Conolly's plot

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early														-0.301		-0.287			-0.267
Late	0.310											-0.276			-0.260				
Total	0.229							0.258	-0.270										

Table 81 Bootstrapped response between temperature and standard MVA chronologies at Edakkode

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	-0.239										0.203		-0.306						
Late	-0.225	-0.324												-0.274				0.252	0.311
Total		-0.218																	0.257

Table 82 Bootstrapped response between temperature and residual MVA chronologies at Edakkode

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early													-0.317						
Late	-0.245	-0.261												-0.249					0.307
Total																			0.239

Table 83 Bootstrapped response between temperature and standard MVA chronologies at Kanakuthu

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early	0.253			-0.294								0.402	0.265	-0.262	0.232	-0.285			
Late	-0.256		-0.315																
Total												0.415				-0.303			

Table 84 Bootstrapped response between temperature and residual MVA chronologies at Kanakuthu

MVA	pJUN T	pJUL T	pAUG T	pSEP T	pOCT T	pNOV T	pDEC T	JAN T	FEB T	MAR T	APR T	MAY T	JUN T	JUL T	AUG T	SEP T	OCT T	NOV T	DEC T
Early												0.354	0.254	-0.277					
Late	-0.227		-0.317						0.236										
Total												0.424				-0.302			

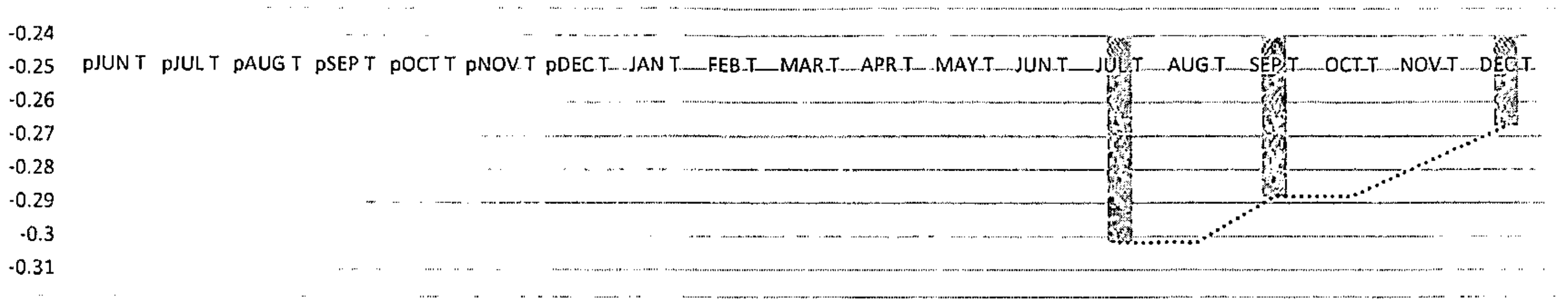

Fig 233 Bootstrapped response between temperature and standard earlywood MVA chronologies at Conolly's plot

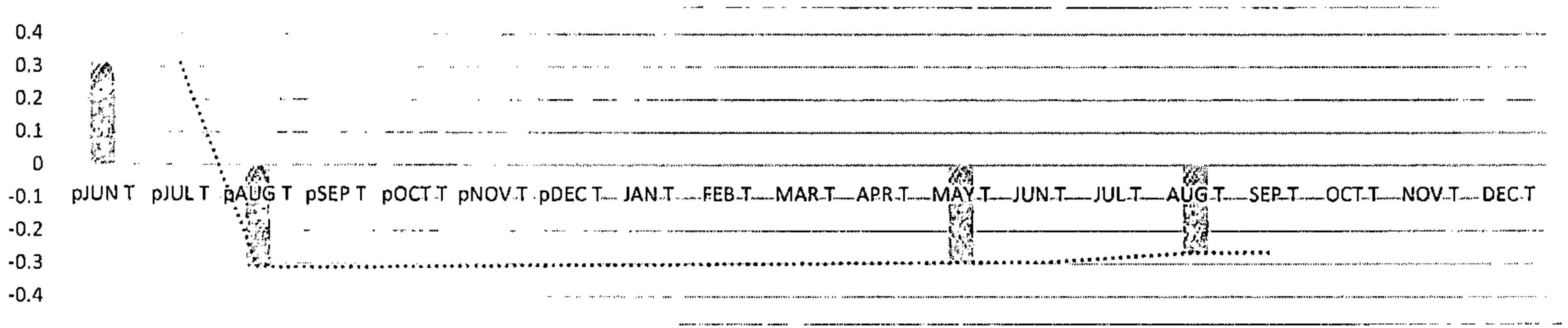

Fig 234 Bootstrapped response between temperature and standard latewood MVA chronologies at Conolly's plot

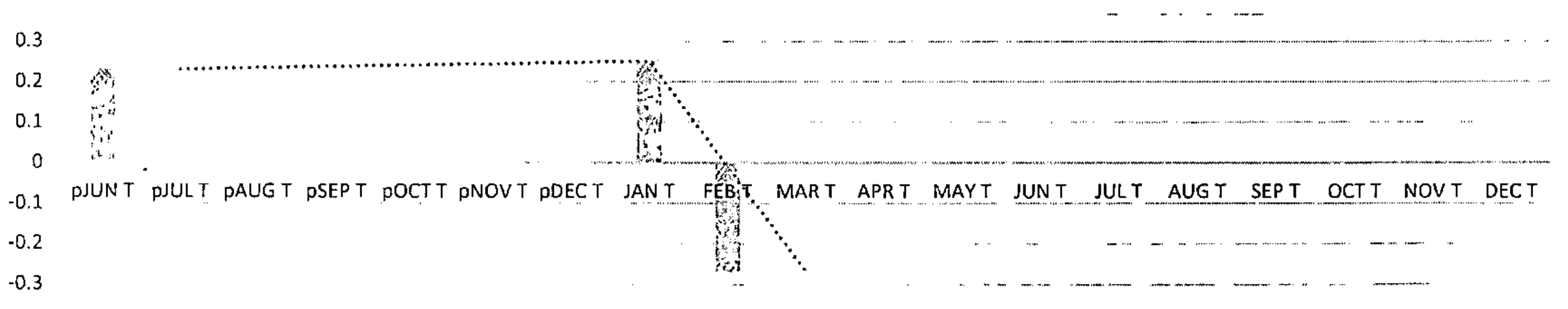

Fig 235 Bootstrapped response between temperature and standard latewood MVA chronologies at Conolly's plot

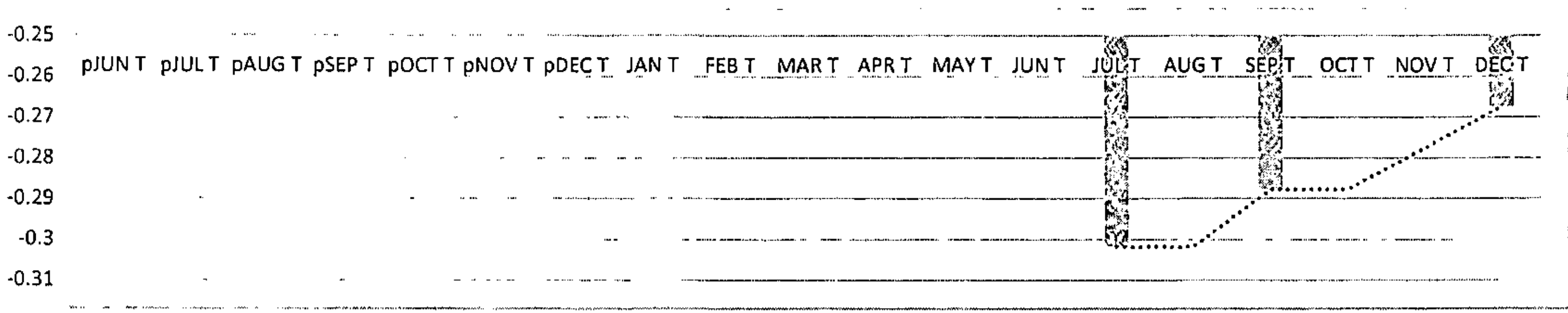

Fig 236 Bootstrapped response between temperature and residual earlywood MVA chronologies at Conolly's plot

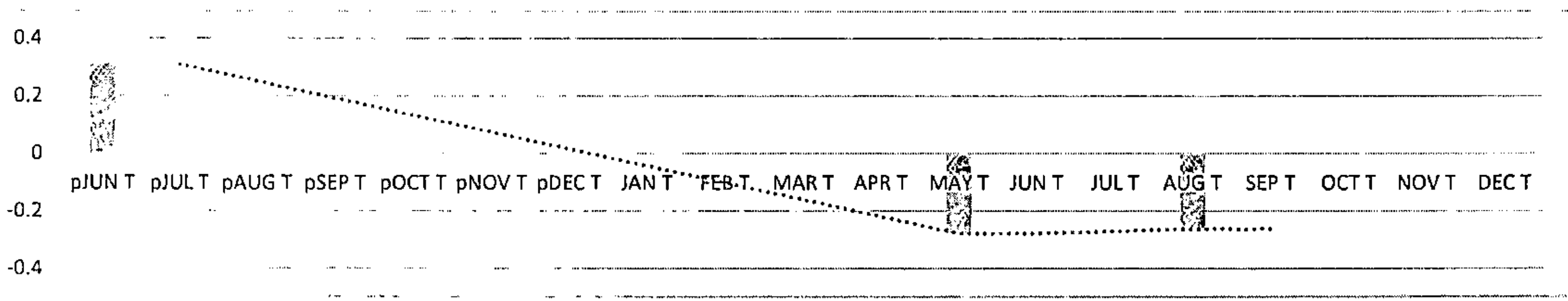

Fig 237 Bootstrapped response between temperature and residual latewood MVA chronologies at Conolly's plot

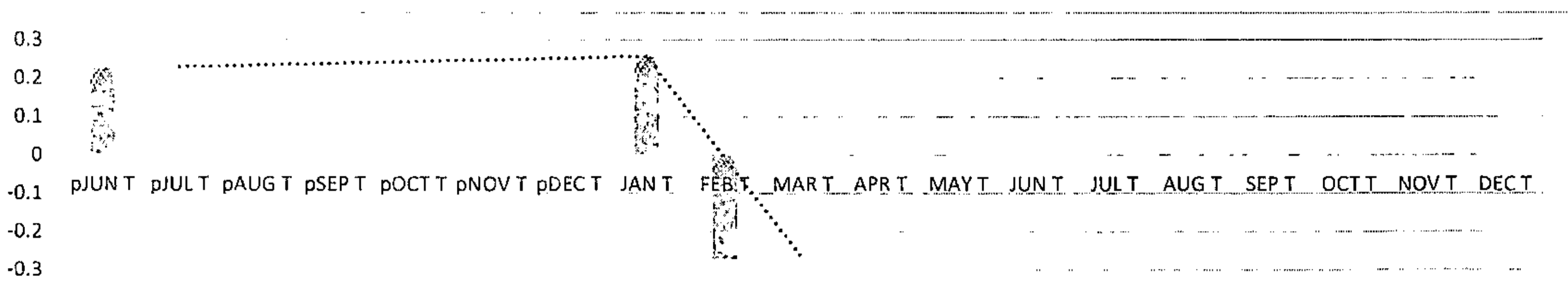

Fig 238 Bootstrapped response between temperature and residual totalwood MVA chronologies at Conolly's plot

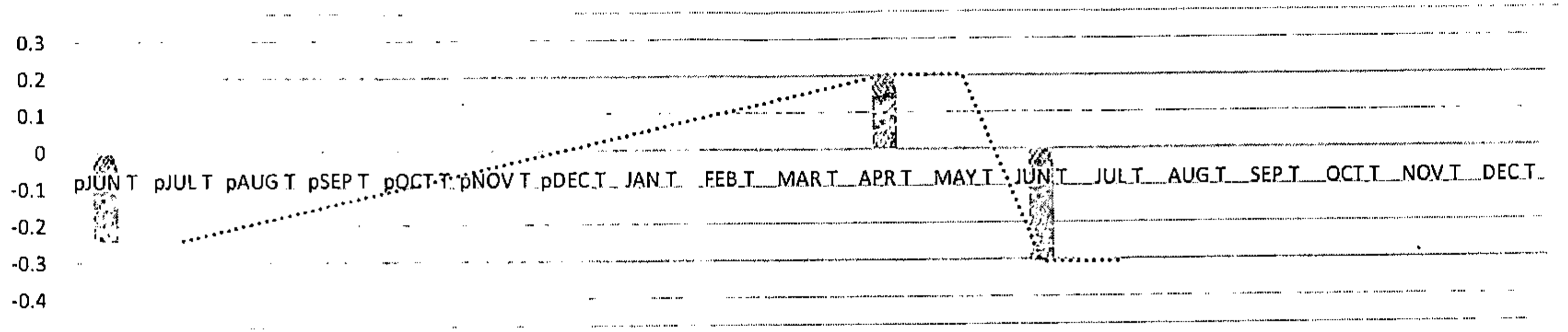

Fig 239 Bootstrapped response between temperature and standard earlywood MVA chronologies at Edakkode

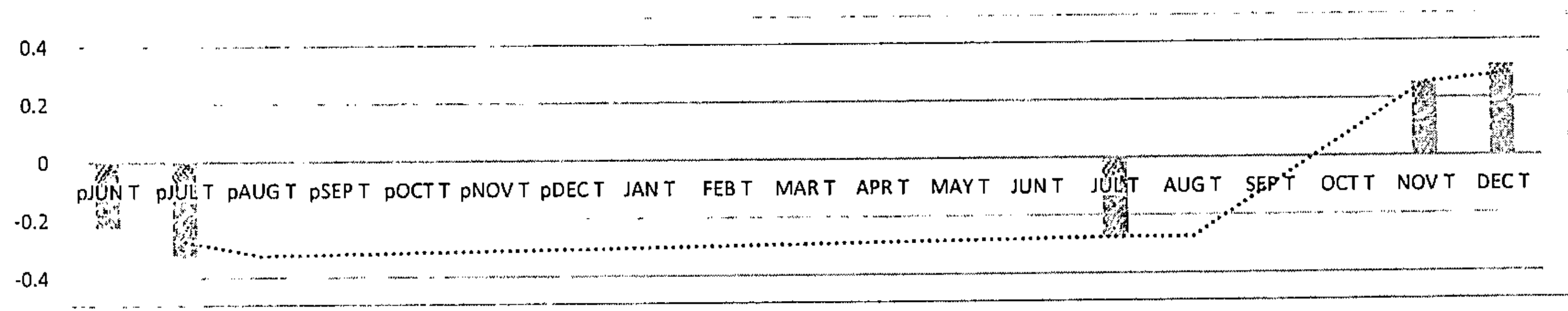

Fig 240 Bootstrapped response between temperature and standard latewood MVA chronologies at Edakkode

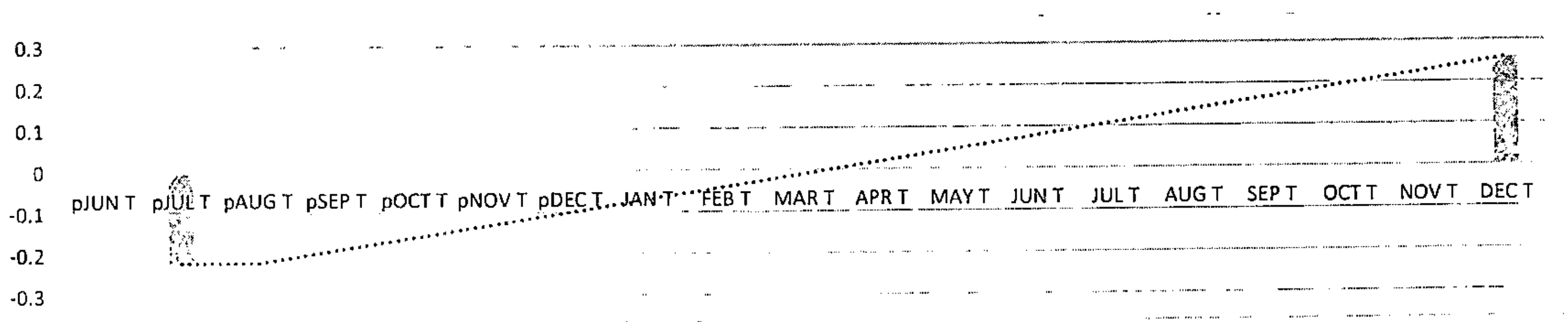

Fig 241 Bootstrapped response between temperature and standard totalwood MVA chronologies at Edakkode

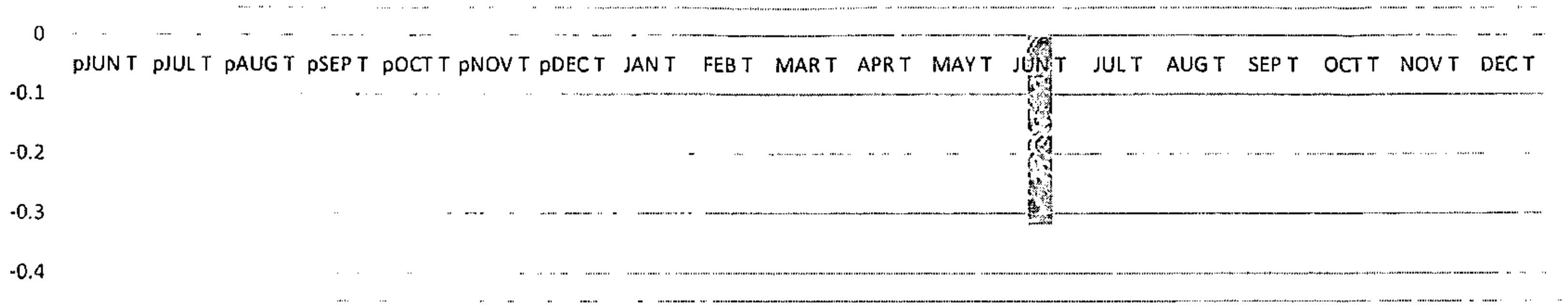

Fig 242 Bootstrapped response between temperature and residual earlywood MVA chronologies at Edakkode

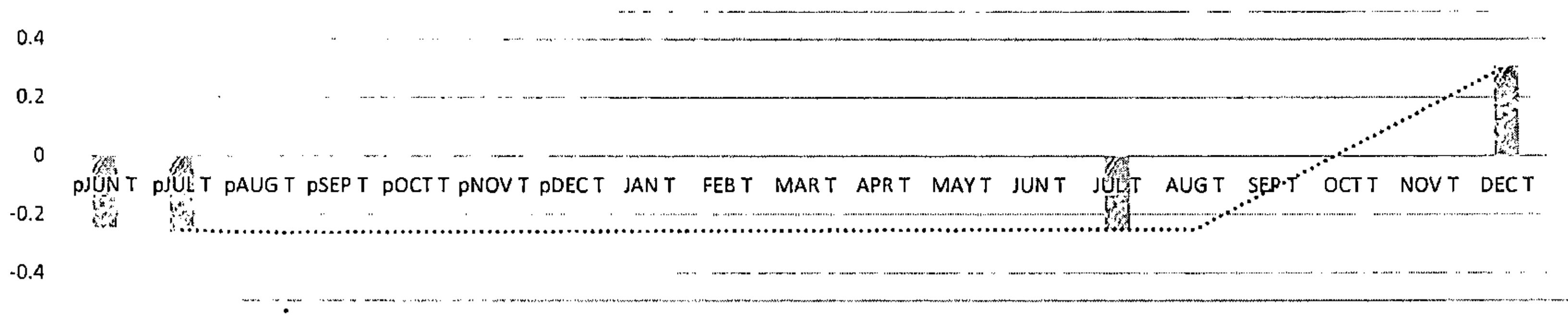

Fig 243 Bootstrapped response between temperature and residual latewood MVA chronologies at Edakkode

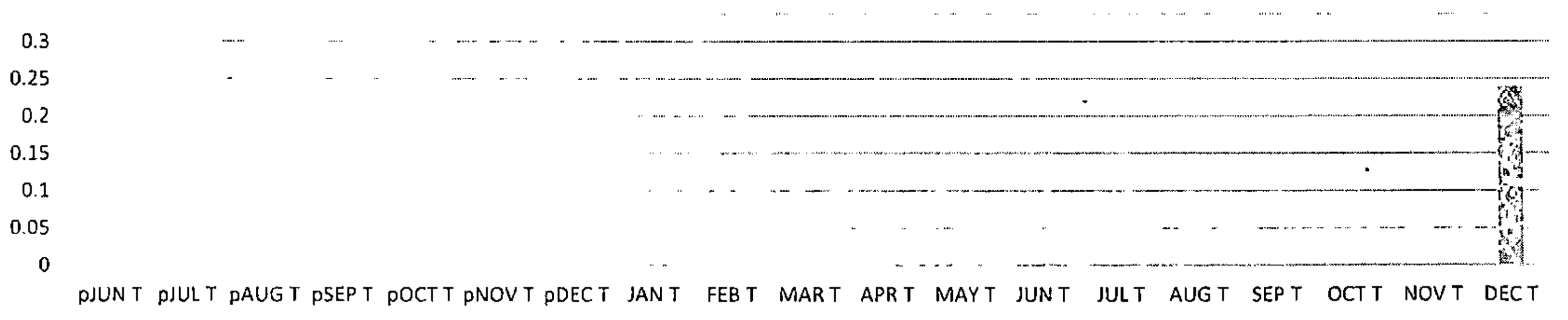

Fig 244 Bootstrapped response between temperature and residual totalwood MVA chronologies at Edakkode

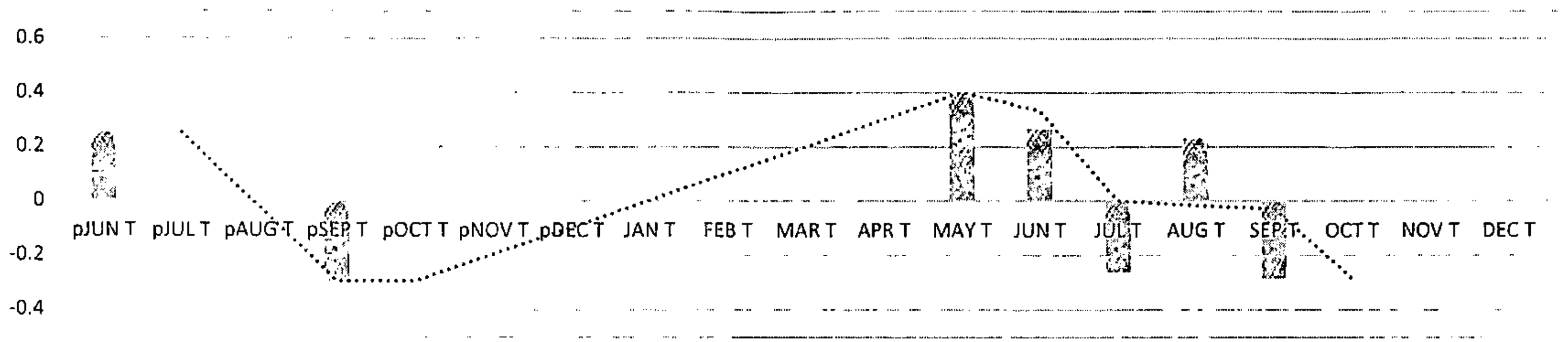

Fig 245 Bootstrapped response between temperature and standard earlywood MVA chronologies at Kanakuthu

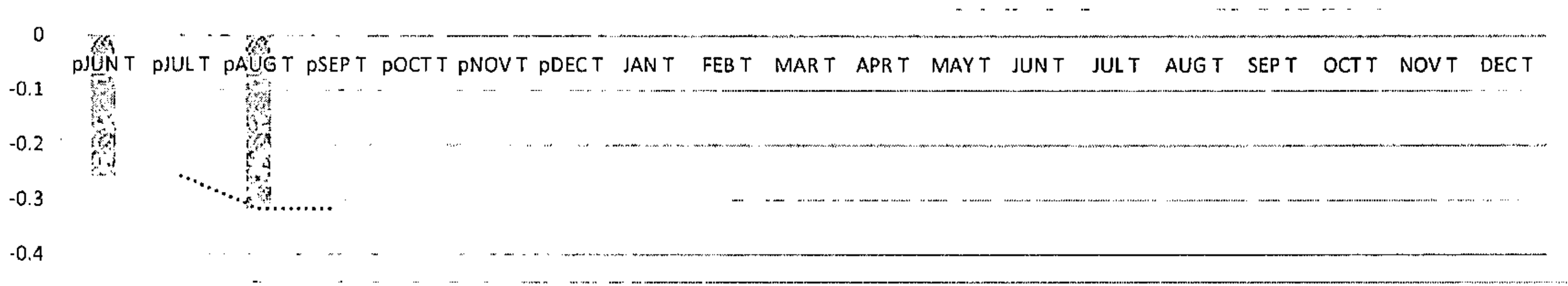

Fig 246 Bootstrapped response between temperature and standard latewood MVA chronologies at Kanakuthu

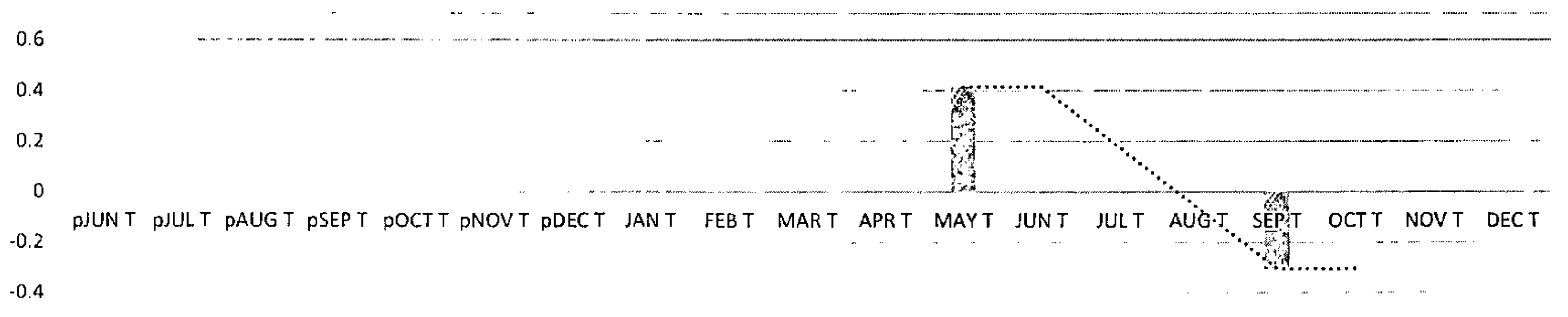

Fig 247 Bootstrapped response between temperature and standard totalwood MVA chronologies at Kanakuthu

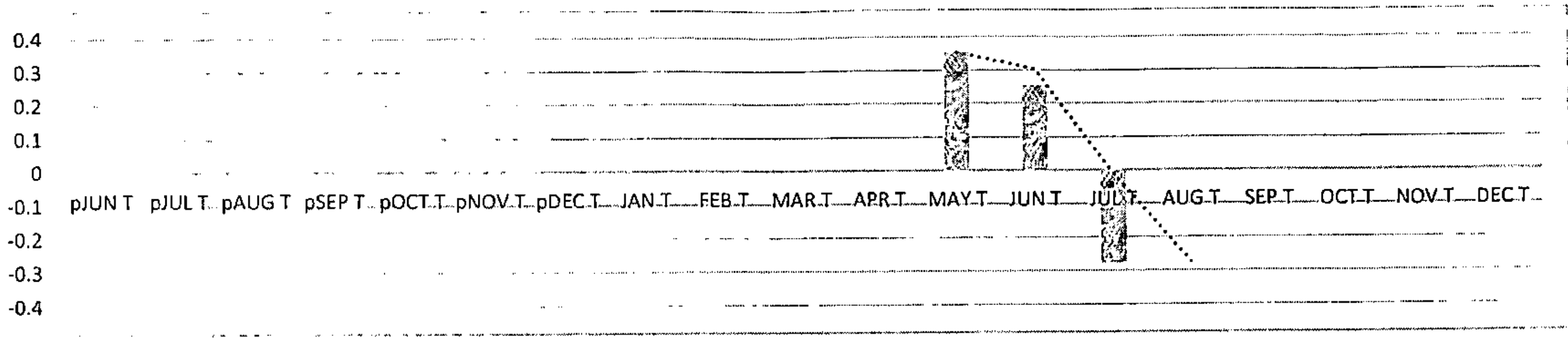

Fig 248 Bootstrapped response between temperature and residual earlywood MVA chronologies at Kanakuthu

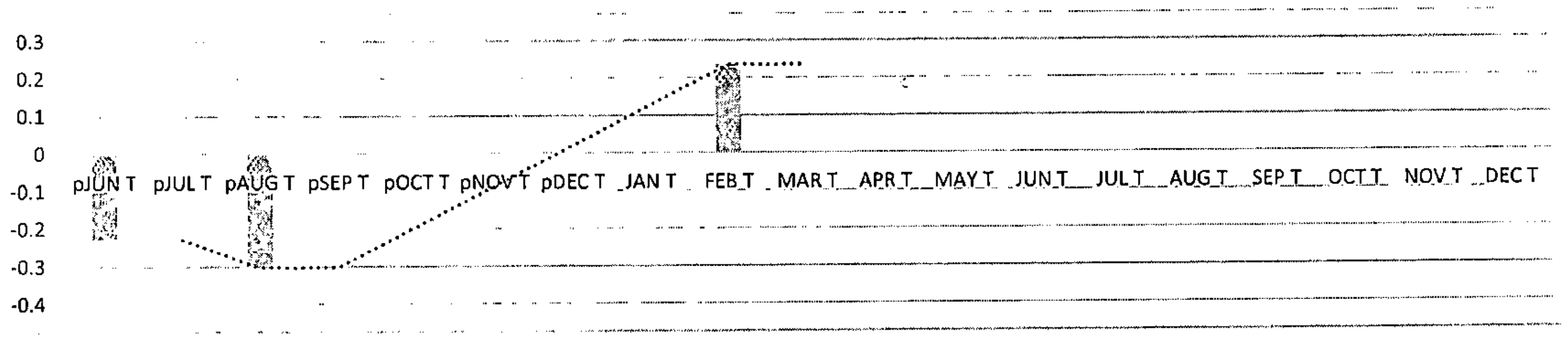

Fig 249 Bootstrapped response between temperature and residual latewood MVA chronologies at Kanakuthu

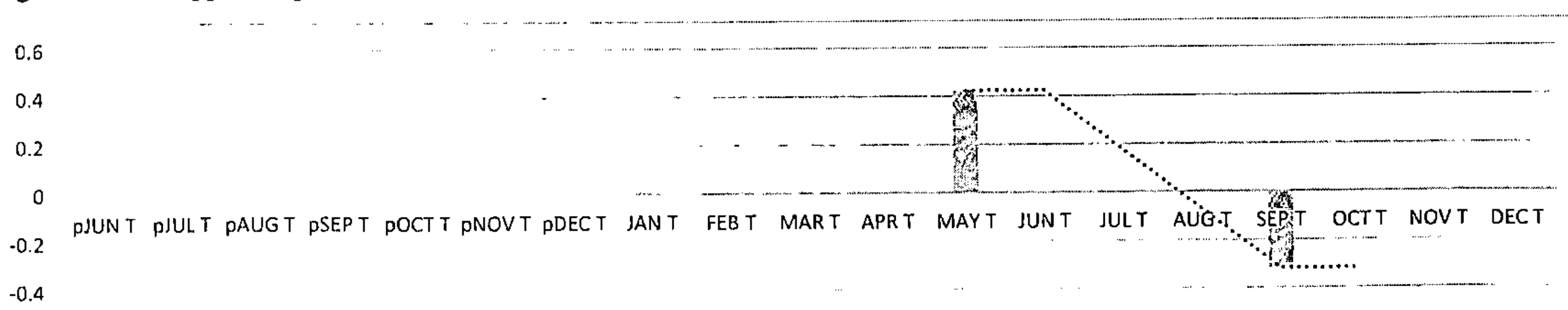

Fig 250 Bootstrapped response between temperature and residual totalwood MVA chronologies at Kanakuthu

4.10 Reconstruction of past climate from tree ring data

The months and seasons with most responses were selected and transfer functions were built to reconstruct past rainfall and temperature. Climate for the period 1870-1900 for which instrumental data were not available was reconstructed using tree ring data. The reliability of reconstructions were checked by calibration (1956-2010) and verification (1-1955) and results were satisfactory.

4.10.1 Climatic reconstruction from ring width

Rainfall was reconstructed for the months, previous July, previous December and October. Winter temperature (December-January) and southwest monsoon (June-September) were reconstructed from ring width. The monthly temperatures for January and previous June were also built (Fig 251, 254).

4.10.2 Climatic reconstruction from mean vessel area

Monthly rainfall for months previous June, previous September, previous November and current May were reconstructed from mean vessel area. Seasonal climates reconstructed were southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Monthly temperatures reconstructed were of previous August, current May and December (Fig 252, 253, 255, 256).

Table 85 Calibration statistics of ring width and climatic variables (1956-2010)

	pJuly P	pDec P	Oct P	DJF T	JJAS T	Jan T	pJuly T
r	0.456	-0.471	0.319	-0.327	-0.327	-0.428	-0.372
r^2	30.8%	27.6%	27.6%	25.8%	24.4%	31.5%	22.6%

Table 86 Calibration statistics of MVA and climatic variables (1956-2010)

	pJune P	pSep P	pNov P	May P	JJAS P	ON P	JJAS T	Aug T	May T	Dec T
r	0.398	0.328	-0.397	-0.429	0.379	0.402	0.487	-0.350	0.392	-0.392
r^2	30.5%	25.7%	29.2%	33.2%	22.2%	35.9%	37.4%	23.2%	29.4%	23.9%

r- Correlation coefficient

r^2 – Percentage of variance explained

Table 87 Verification statistics of ring width and climatic variables (1901-1955)

	pJuly P	pDec P	Oct P	DJF T	JJAS T	Jan T	pJuly T
r	0.317	0.380	0.349	-0.465	-0.325	0.408	0.331
r^2	30.9%	23.4%	27.6%	25.8%	24.9%	35.3%	24.9%

Table 88 Verification statistics of ring width and climatic variables (1901-1955)

	pJune P	pSep P	pNov P	May P	JJAS P	ON P	JJAS T	Aug T	May T	Dec T
r	0.315	0.306	0.487	-0.331	0.365	0.436	0.341	0.361	0.374	0.411
r^2	26.4%	23.7%	36.5%	26.8%	29.3%	40.5%	29.0%	26.5%	27.4%	31.1%

r- Correlation coefficient

r^2 – Percentage of variance explained

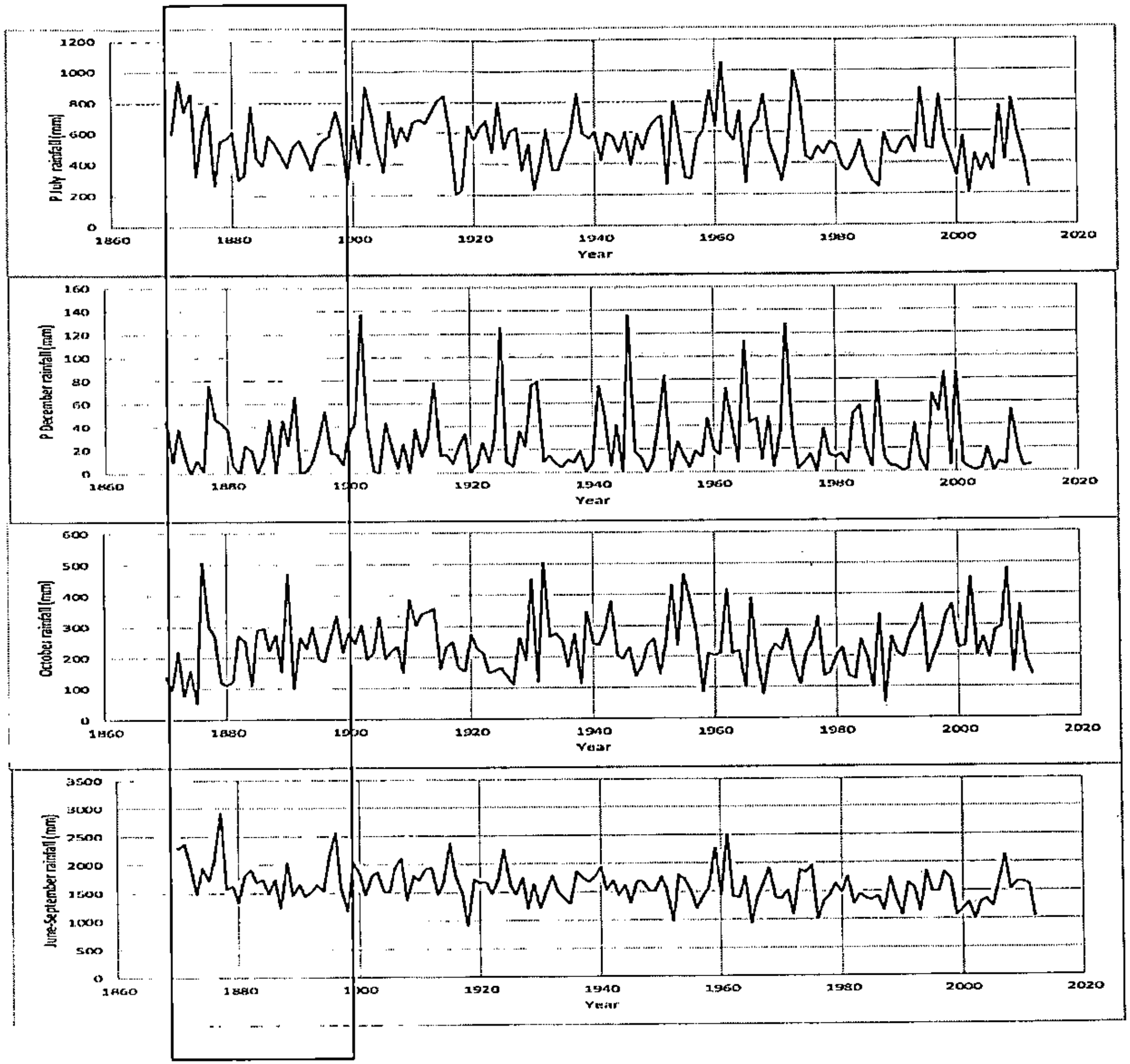

Fig 251. Selected monthly and seasonal rainfall of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using tree ring width data

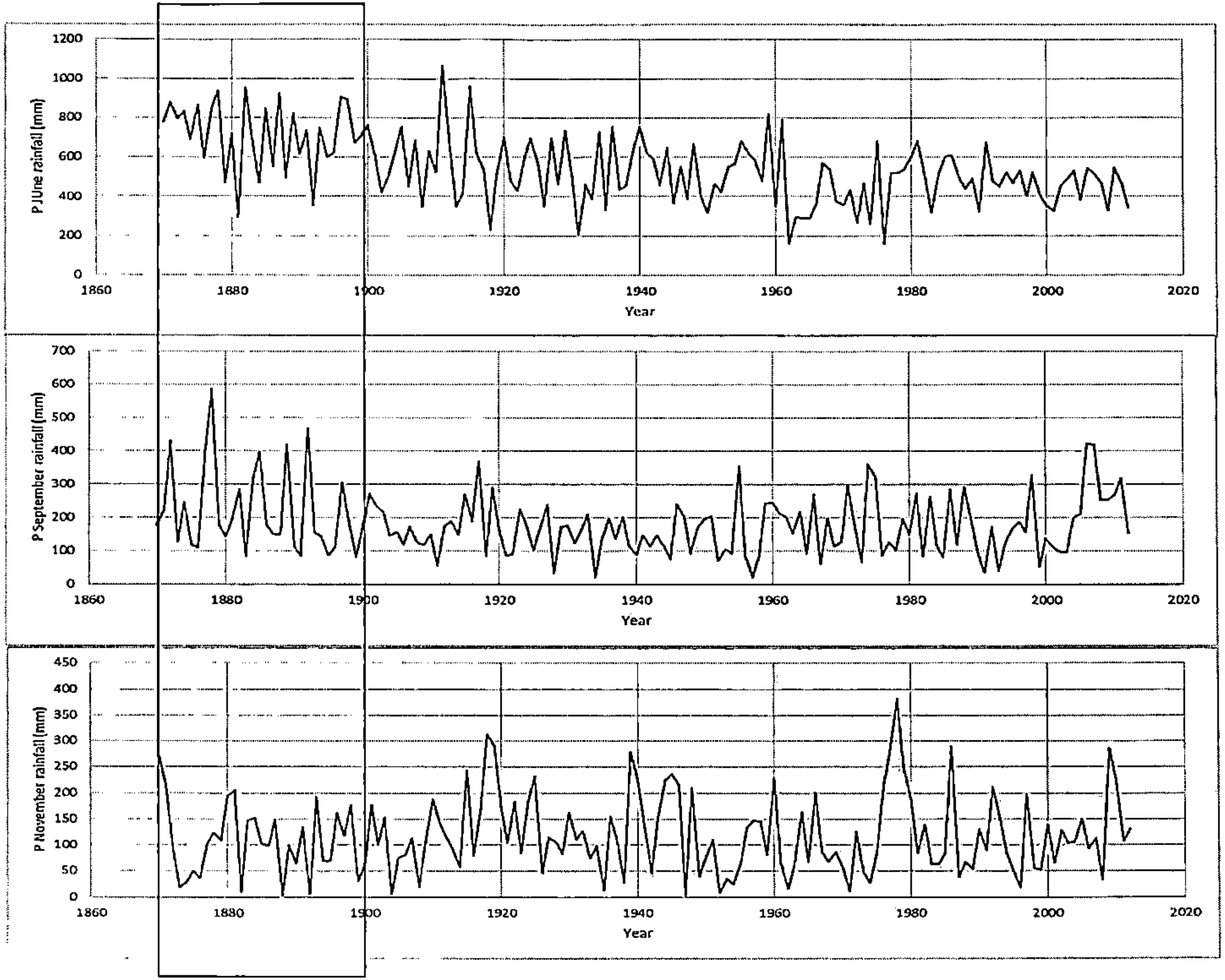

Fig 252. Selected monthly rainfall of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using tree MVA data

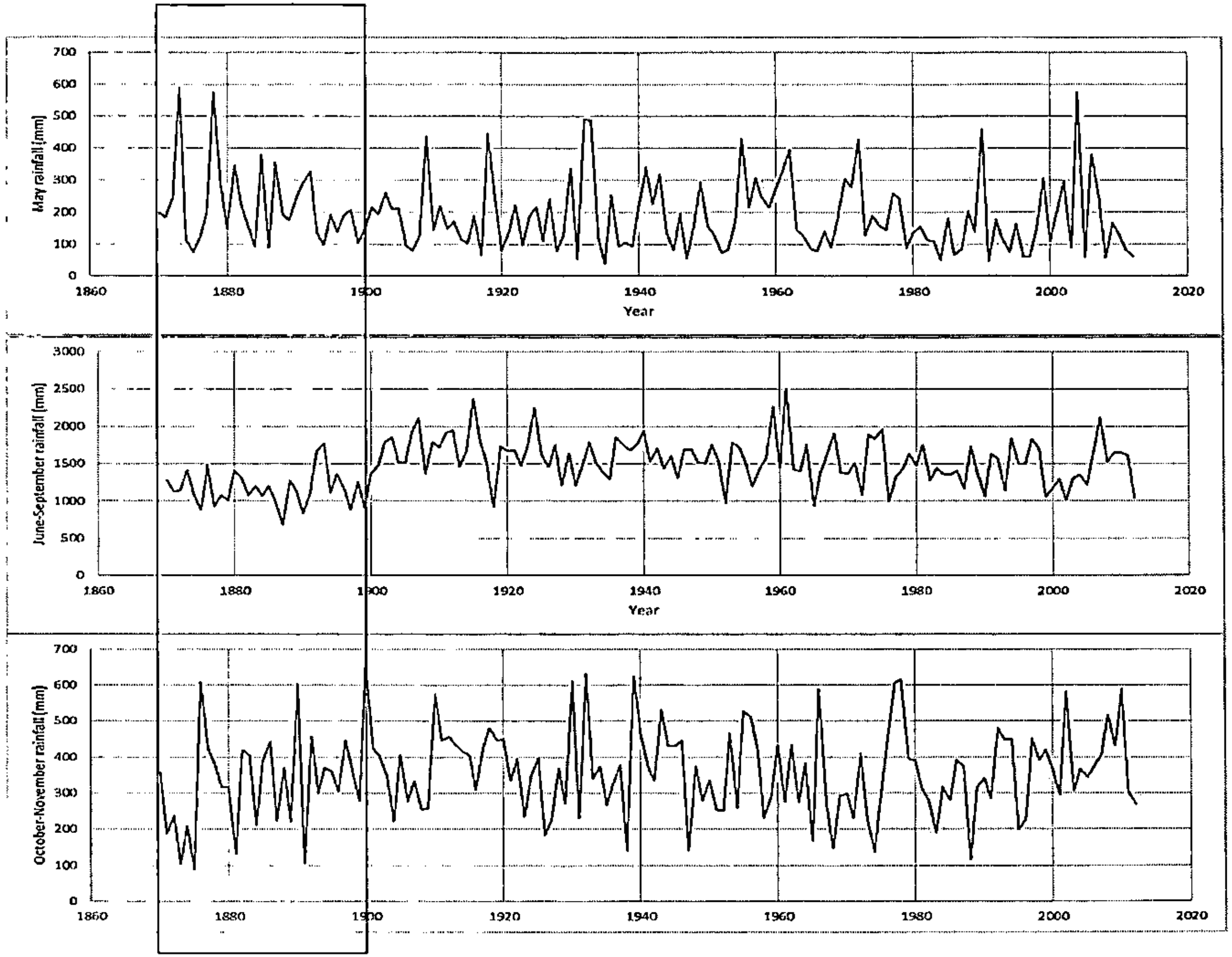

Fig 253. Selected monthly and seasonal rainfall of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using MVA data

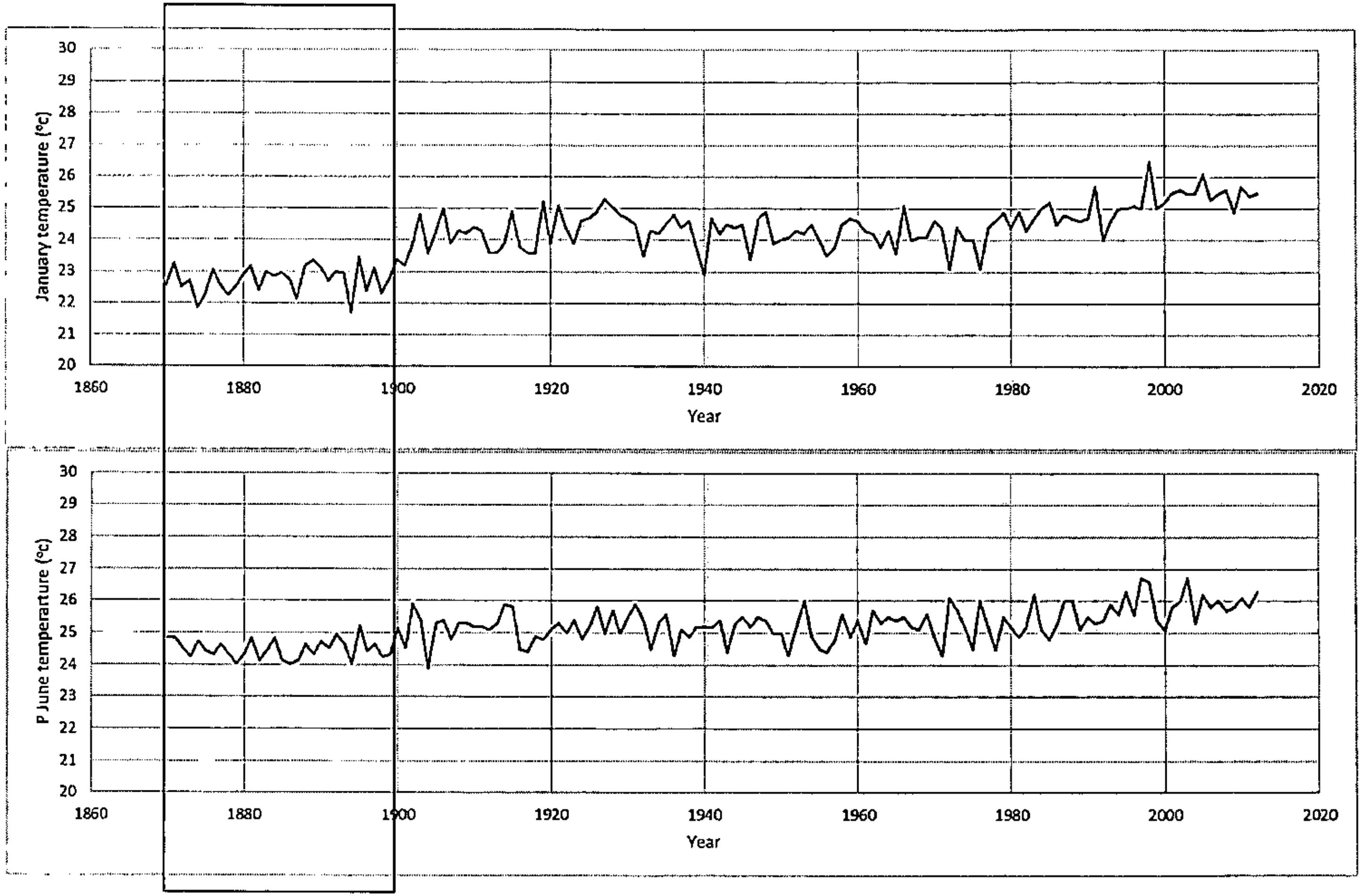

Fig 254. Selected monthly temperature of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using tree ring width data

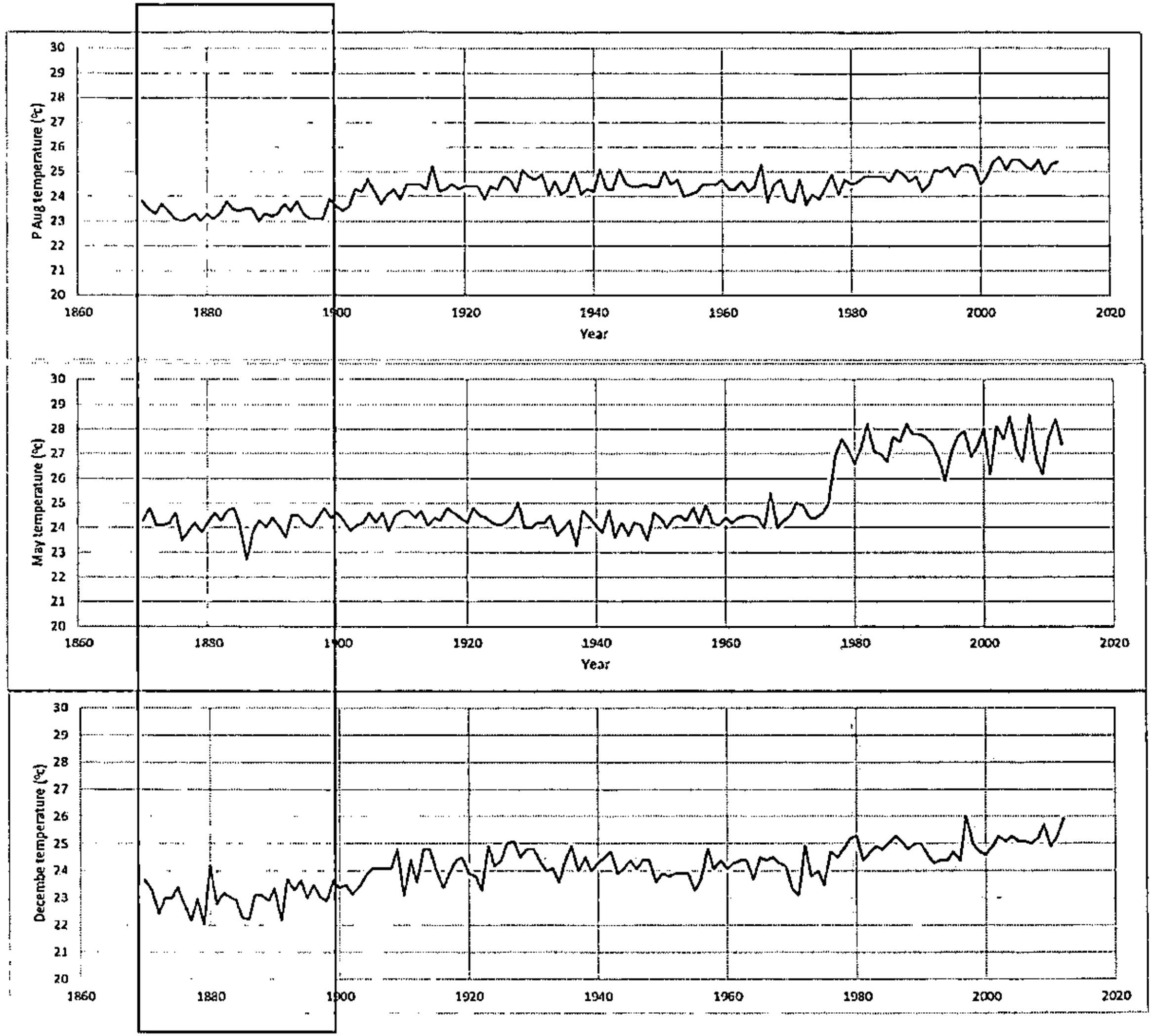

Fig 255. Selected monthly temperature of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using MVA data

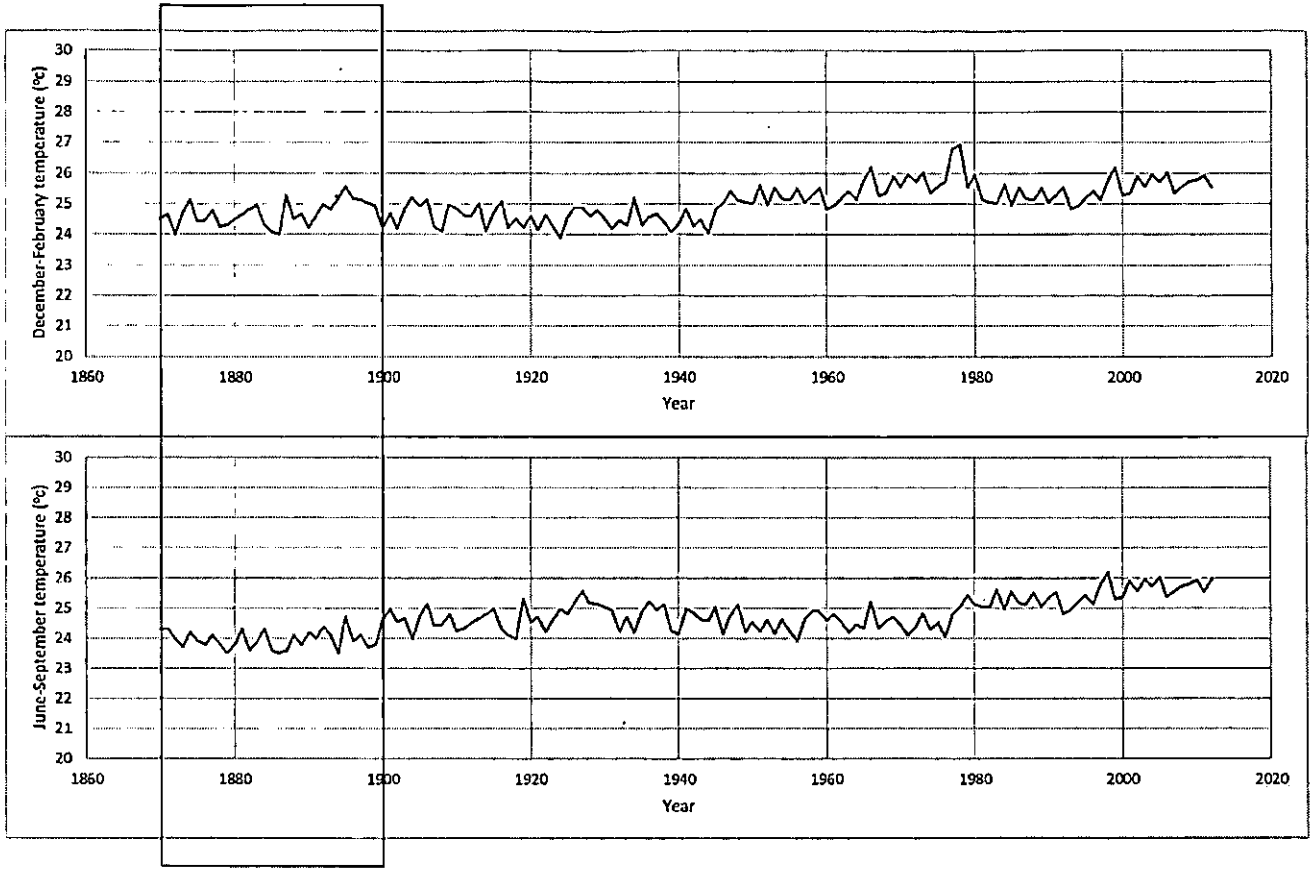

Fig 256. Selected monthly temperature of Nilambur from 1870-2012. The climatic data of the period in the boxes (1870-1900) was reconstructed using MVA data

5. DISCUSSION

DISCUSSION

A detailed dendroclimatological investigation on teak (*Tectona grandis*) in selected locations in Nilambur (North) forest division of Kerala was taken up in the present study. The salient findings of the study are discussed hereunder.

5.1 Wood density

The air dry wood density of the three sites were 0.73, 0.75 and 0.84 for Edakkode, Kanakuthu and Conolly's plot respectively. From the present study it is clear that the old growth teak had higher relationship between wood density and age. However in Togolese teak, Kokutse *et al.* (2004) reported that wood density or wood specific gravity do not differ significantly with age after reaching the age of 40–45 years. Bhat (1995) found that 51 year old teak tree had only 5 % higher wood density than that of 8 year old tree, growing in the same region. In *Swietenia macrophylla* also, Ashaduzzaman *et al.* (2011) reported a poor correlation between tree age and wood density under air dry condition.

Moya (2001) found that basic density for teak grown in Costa Rica presented a positive correlation with age of vascular cambium (r = 0.66), suggesting that wood density increases with increasing age and with decreasing tree growth rate. In general, the average values of wood dry density found in this study are at similar levels to those reported elsewhere (Baillères and Durand 2000, Betancur *et al.* 2000) for plantation grown teak. On the other hand, Bhat *et al.* (2001) report no significant differences in wood density between young and mature teak, hence rotation period of fast-growing tree species can be reduced without affecting timber strength The air dry specific gravity values obtained in the study by Anish *et al.* (2015) ranged from 0.60 to 0.82 respectively. These values are closer to those observed by Richter *et al.* (2003) in plantation grown Ghana teak, Jayawardana and Amarasekera (2009) for plantation grown teak in Sri Lanka. The values are slightly higher than those reported by Bhat

(1998) in fast and slow grown samples from Nilambur, Konni, Peechi, Walayar and Aryankavu. Bhat (1998) also suggested that fast grown teak was not necessarily less dense and lighter. Furthermore, Jayawardana and Amarasekera (2009) reported that, there is little relationship between specific gravity and growth rate and also the fast growth rate in shorter rotations is unlikely to reduce specific gravity in teak. The present study also implies that faster growth do not affect density of teak as the younger samples were of satisfactory density.

4.2 Heartwood-Sapwood ratio

The heartwood to sapwood ratio was highest in Conolly's plot (6.99) followed by Kanakuthu (5.71) and Edakkode (4.81). The heartwood percentage also followed the same pattern with Conollly's plot having 87.49 % followed by Kanakuthu (85.11 %) and Edakkode (82.81 %). The proportion of heartwood ranged between 28 and 76 % in young and mature teak plantations in Costa Rica. The study by Cordero and Kanninen (2003) indicates that, in Costa Rica, this species presents a heartwood proportion of 55 % of the total volume at 30 years, increasing logarithmically with increasing age and consequently with DBH. Arce (2001) found heartwood proportions of 33–37 % in 10-year-old teak grown in a dry region of Costa Rica.

In Karnataka the highest heartwood proportion of total tree volume was 56.33% while the lowest was 37.05% (average 46.35%). The proportion of sapwood ranged from 12.95% to 23.04% (average 18.37%) The heartwood proportion was marginally higher in the 32 year old plantation (47%) than in the 30 year old plantation (45.8%) while sapwood content was similar (18.1% and 18.7%). (Tewari and Mariswamy, 2013). The percentage of heartwood differed significantly in trees depending on the ecological zone in which they grew in Togo (Kokutse *et al.*, 2004). Thirteen year-old trees possessed 26 % heartwood at breast height compared to 12-year-old trees with 37 % heartwood. Suggesting correlation of heartwood formation with tree age in trees from ecological zones. Compared to other plantation species, heartwood formation begins relatively early in teak trees, at about 7 years of age (Okuyama *et al.*, 2000). At the age of 11–13 years, 30 % of the wood surface is heartwood in Togolese teak, which is lower than that in teak growing in Kerala, India, where the same volume of heartwood is already formed in 8-year-old trees (Bhat, 1995). When comparing the results of heartwood volume in Togolese teak to that in plantation teak from Kerala, India, it was found that 77 % of the stem surface at BH, was transformed into heartwood in 51-year-old trees from Kerala, compared to 71% in 70-year-old Togo- lese teaks (Bhat *et al.*, 1985). These results support the findings by Kjaer *et al.* (1999), that the volume of heartwood in teak originating from Asia, is greater than that in African teak. Heartwood volume in teak therefore appears to be influenced by tree age, silvicultural practices and genetic provenance.

5.3 Growth rate

Fast growth is usually indicated by rings wider than 5–25 mm (FRI, 1986), those samples with an average ring width more than 5 mm are categorized as fast grown and those with a ring width less than 5 mm are considered as the slow grown category. Edakkode had highest average ring widths (3.82 mm) followed by Kanakuthu (3.20 mm) and Conolly's plot (1.46 mm). Anish *et al.* (2015) reported average ring width of 5mm from Nilambur, but all the samples from this study were below 5mm. Hence, all samples collected in the present study can be considered to be originating from slow grown teak. But the results are similar with that of East Timor grown teak with 3.6mm (Sousa *et al.*, 2012). This is in agreement with Worbes (1989), who identified the lack of radial uniformity as the variation factor in growth rings of tropical trees. Besides the age factor, stem eccentricity and deviations from circularity were also a significant factor for ring width variation. In addition to differences in soil characteristics, tree competition would influence stem development and ring width, resulting in between site differences.

5.4 Ring width

Ring width (early wood, late wood and total) at all sites showed an age related growth trend. During the initial years of growth, the ring width was large and with increase in age the ring width decreased. Average raw ring width obtained were 3205.44 μm (1823.91 μm for earlywood, 1381.52 μm for latewood) in Kanakuthu, 3820.27 μm (2230.15 μm for earlywood and 1590.11μm for late wood) in Edakkode, and 1455.87 μm (834.58 μm for earlywood, 621.29 μm for latewood) in Conolly's plot.

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-characteristics and age differences produce significant variation in tree-ring width series (Brookhouse and Brack, 2008). It was reported that the location factor contributes to 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.

5.4 Mean Vessel Area

Mean vessel area showed a different trend from ring width in all the three sites. During early years of growth, with increase in age, mean vessel area was showing decreasing-increasing trend radially from pith to periphery. The mean vessel area obtained were 28205.27 μm^2 (17640.57 μm^2 for earlywood, 10564.70 μm^2 for latewood) in Kanakuthu, 25486.05 μm^2 (13153.23 μm^2 for earlywood and 12332.82 μm^2 for late wood) in Edakkode, and 36962.33 μm^2 (19615.56µm for earlywood, 17346.77 μm^2 for latewood) in Conolly's plot. Seasonal differences between earlywood and latewood in total vessel surface area of the mangrove *Rhizophora mucronata* showed mean measurements of 90000 μm^2 and 12000 μm^2 (Verheyden *et al.*, 2005) respectively.

5.5 Vessel frequency

The early wood vessel frequency was highest at Edakkode (53/mm^2)· followed by Kanakuthu (31/mm^2) and Conolly's plot (30/mm^2). The latewood vessel frequency was highest at Edakkode (33/mm^2) followed by Conolly's plot (32/mm^2) and Kanakuthu (30/mm^2). The totalwood frequency was also highest in Edakkode (86/mm^2) followed by Conolly's plot (62/mm^2) and Kanakuthu (61/mm^2). In *Rhizophora mucronata* the earlywood frequency was 22/mm^{-2} and latewood frequency was 34mm^{-2} (Verheyden *et al.*, 2005). On a tangential ring width of 10 mm, García-González and Fonti (2008) counted an average of 49 earlywood vessels for chestnut and 41 for oak, with about half of them in the latewood (24 for chestnut, 20 for oak). There are 20-250 vessels per annual ring in chestnut in 8mm wide strip (García-González and Fonti, 2004).

5.6 Vessel diameter

The vessel diameter of samples from Conolly's plot was highest among the three sites for earlywood (183.49 µm), latewood (141.80 µm) as well as totalwood (162.64 µm). Edakkode has second highest values for earlywood (181.308 µm) and totalwood (149.37 µm) and least value for latewood (117.44 µm) followed by Kanakuthu (164.77

μm for earlywood and 121.73 μm for latewood). In *Rhizophora mucronata* the earlywood vessel diameter was 87 μm and latewood diameter was 79 μm. (Verheyden *et al.*, 2005). On a tangential ring width of 10 mm, they counted an average of 49.1 earlywood vessels for chestnut and 41.0 for oak, with about half of them in the first row (24.2 for chestnut, 20.1 for oak). Oak vessels are larger than those of chestnut if all earlywood vessels are considered (49,772 vs. 45,963 μm^2) but are nearly equal in size for the first row (around 62,000 μm^2) (García-González and Fonti, 2008). The earlywood mean vessel diameter ranged from 106 to 130 μm during the period with a mean (±SE) diameter of 111.60±1.25 μm. Mean earlywood vessel diameters decreased after severe summer droughts during the previous years. During the same period, the mean latewood vessel diameter was 36.71±1.25 μm with a range of 35–39 μm. (Corcuera · *et al.*, 2006).

5.7 Tree ring chronologies

5.7.1 Ring width index chronology

The statistical properties of ring-width-index chronologies from the three sites were assessed for their dendroclimatic potential. The Edakkode ring width index chronology showed highest mean correlation among all radii (0.522) followed by Kanakuthu (0.45) and Conolly's plot (0.36) chronologies. The mean correlation between trees was high in Conolly's plot ring width index chronology (0.55), followed by Edakkode (0.49) and Kanakuthu (0.44) 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 for Kanakuthu (2.95) followed by Edakkode (2.22) and Conolly's plot (1.09). 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). In the lower running-EPS plot, a value of 0.85 is plotted as a rough cutoff 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 in the present study. All chronologies have the acceptable range of EPS values such as 1.02 for Kanakuthu, 1.02 for Edakkode and 1.10 for Conolly's plot ring width index chronology.

5.7.2 Mean vessel area index chronology

In the case of mean vessel area index chronology, Kanakuthu (0.325) ring width index chronology showed highest mean correlation among all radii, followed by Edakkode (0.221) and Conolly's plot (0.175) chronologies. The mean correlation between trees was highest at Edakkode (0.577) followed by Kanakuthu (0.488) and Conolly's plot mean vessel area index chronologies (0.447).

The value of SNR for ring width index chronologies of the three study sites is high. SNRs were in the order Edakkode (7.88) > Kanakuthu (5.19) > Conolly's plot (3.58). Also, the value of EPS is higher for all the mean vessel area index chronologies. All chronologies have the acceptable range of EPS values as 1.051 for Kanakuthu, 1.088 for Edakkode and 1.294 for Conolly's plot. 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 Nilambur (North) forest division in Kerala.

5.8 Correlation between climate and ring width

5.8.1 Monthly rainfall and ring width

Earlywood and totalwood of study sites showed a positive correlations with June, July precipitation of the current year and previous November rainfall. The latewood and totalwood showed negative correlation with previous December rainfall and current May rainfall. Analysis of tree-growth and climate relationship at Mundagod, Karnataka by Sinha *et al.* (2011) suggested April rainfall of the current year and October rainfall of the preceding year had negative influence on ring width. Analysis of tree growth and climate relationship at Chandrapur, Karnataka (Sinha *et al.*, 2011) suggests that the rainfall during March of the current year and October of the preceding year has positive influence, whereas April rainfall has negative influence on the growth of teak. Temperature does not show any significant effect on the growth of teak in this region. Besides, rainfall during October of the previous year also plays an important role.

5.8.2 Seasonal climate and ringwidth

The current southwest monsoon (JJAS) had positive correlation latewood chronologies. While previous June-September temperature and previous October-November temperature had negative correlation with earlywood, latewood and totalwood chronology. Dendroclimatological studies from peninsular region of India using teak had showed that rainfall received in previous southwest and north east monsoons and that during current year monsoons has significant relation to teak growth. (Deepak *et al.*, 2010; Sinha *et al.*, 2011; Babu *et al.*, 2015). Teak from Central India also shows a signal of monsoon (JJAS) rainfall useful for reconstruction (Shah *et al.*, 2007). Buckley *et al.* (2007) have demonstrated a decadal scale drought history for Thailand based on a multi-century teak chronology. They suggest that the variability in annual growth of teak is dependent on soil moisture availability and rainfall during the monsoon season. Monsoon and annual rainfall of Kerala have a significant positive relationship with teak tree ring chronologies from Kerala (Borgaonkar *et al.*, 2010).

They found that although temperature is an important parameter in the relationship between tree growth and climate, a direct influence of temperature is not evident. General observations on the relationship between variations in teak ring width and climate revealed that low growth years (narrow rings) are significantly associated with deficient Indian rainfall. However, normal or above normal rainfall is not consistently reflected as higher tree growth, possibly due to a moisture threshold being reached, above which trees can no longer respond. Less moisture at the root zone may certainly limit tree growth, and this is the likely mechanism affecting the tree growth–climate relationship seen at this site (Yoshifuji *et al.*, 2006). The negative correlation with previous monsoon may be due to the carry-over effect of moisture at the root zone. Higher rainfall during any particular year helps in maintaining the normal growth of the tree for the next two-three years even though the rainfall during these years could be less (Ram *et al.*, 2008). The reverse process is also true when very less rainfall during any particular year creates moisture stress condition at root zone which may continue in the next one-two years resulting in below normal tree growth in successive years.

Teak grown in Bori, central India (Ram *et al.*, 2008) showed negative correlation with current year's October-November temperature and annual temperature. Ram *et al.* (2011) reports in the case of temperature, the seasons (-JJAS, -ON, DJF, MAM, JJAS, ON and annual) showed highly significant negative correlation with ring-width data for teak. Higher temperature accelerates evaporation and evapotranspiration resulting in anomalous moisture stress condition for the growth of the trees. Therefore, the negative response of temperature as observed in the analysis.

5.8.3 Monthly temperature and ring width

January and July temperature temperature had negative correlation with earlywood, latewood as well as totalwood. August and October temperature was negatively correlated with earlywood. While latewood and totalwood showed negative correlation with previous December temperature. Current July and November temperature and previous November temperature were the best predictors of growth of teak at Rio Abajo, Puerto Rico. (Margaret and Bernard, 2003) The principle of limiting factors is important to dendrochronology (Fritts 1976). The range of rainfall reported for teak in its native habitat in Southeast Asia is 1200-3400 mm (Salazar and Albertin, 1974). The 3000 mm per year of rainfall at Nilambur appears to be sufficient for teak during most of the year, so mean temperature can become the limiting factor in some micro sites. Current July and October temperature were negatively correlated with the growth of teak, indicating that radial growth of the species is greater when the temperature is lower than average in July and October. Increased evaporation and transpiration caused by temperature rise may decrease topsoil moisture and restrict tress from obtaining it in subsequent growing season. In addition, higher temperature can be preventing effective photosynthesis and respiration to take place (Fritts, 1976). There is an optimum range of temperature for net photosynthesis and it depends upon season, site, moisture, both light availability and intensity (Fritts, 1976) in which tree gives good growth and variation from that optimum range might have resulted in the negative correlation of temperature with ring width index experienced in the study sites. The results of the present study are different from early reports which might be due to soil moisture already present in the sites.

5.8.4 Monthly rainfall and mean vessel area (MVA)

Early wood had maximum climatic signals. In earlywood chronology was negatively correlated with January rainfall while it has positive correlation with previous June rainfall, previous September and May rainfall. May rainfall was negatively correlated with totalwood chronologies. Also the previous November and July rainfall was positively correlated with totalwood chronologies. Moisture availability is the most important climatic variable in developing the early wood vessel of an annual ring. The findings 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 Ecstein, 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, 1999).

There is, however, a significant negative correlation between MVA and vessel density, indicating that the formation of numerous vessels is associated with a small size, probably as a result of rapid differentiation, and vice versa; this result should be interpreted in terms of density. The inverse relationship between vessel size and density was observed not only when comparing wood anatomy of different species (Carlquist, 1975), but also under different climatic conditions (Villar-Salvador *et al.*, 1997) or even in time series of vessel features (Woodcock, 1989; Pumijumnong and Park, 1999). Favorable growth conditions increase wood production, therefore producing more earlywood vessels and wider rings, but also results in faster differentiation that leads to smaller vessels.

5.8.5 Seasonal climate and mean vessel area

The March-May temperature had negative correlation with totalwood. Also totalwood chronology was positively correlated with and June-September rainfall and previous June-September rainfall while the earlywood chronology was positively correlated with previous June-September rainfall. Previous October-November precipitation, June-September temperature and October-November temperature had positive correlation with latewood MVA. The findings agree with the views of Shah *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 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. Cambial activity studies by Priya and Bhat (1999) have shown that the pre-monsoon showers break the cambial dormancy and higher amount of rainfall contributes to the greater amount of wood formation. The authors also pointed out concurrence of the period of the highest cambial activity and the period of the highest rainfall.

Moreover, the influence of other internal factors seems to also have a vital role in the formation of wider vessels. These factors seem to be more effective at the beginning than the end of the growing period. The incidence of wider vessel in the beginning of the growing season probably for efficient water transportation in the initiation of growth process and once such a vital process started, necessity of water does not seem to be critical. This might be the reason for the subsequent formation of comparatively low size vessel in the peak growing period of the tree, when intensity of monsoon rainfall is high. Stored energy of the previous growth year and water availability at the beginning of the growing period are important for the vessel development

5.8.6 Monthly temperature and mean vessel area

Earlywood chronologies were negatively correlated with June temperature. The May temperature and November temperature was positively correlated with earlywood chronologies. March temperature, November temperature and previous June temperature was positively correlated with latewood. There were negative correlations between previous June temperature, previous November temperature and latewood chronologies. There was a negative correlation between November temperature and totalwood. In chestnut, mean vessel lumen area is mainly negatively related to temperature in the current March and to some extent, in February (i.e. just before the beginning of the growing season). Ring-porous trees like chestnut begin developing the first earlywood vessels just before or at the time of bud break (Schmitt *et al.*, 2000), earlier than the resumption of photosynthetic activity. Thus, the beginning of earlywood formation is supported by the mobilization of reserves stored during the previous growing season (Barbaroux and Breda, 2002).

5.9 Response function analysis between climate and tree rings

5.9.1 Response between monthly rainfall and ringwidth

Rainfall in previous July, previous December and current October showed more response at study sites. Previous October showed response in the study conducted by Shah *et al.* (2007). June, July and September rainfall also had significant response in the same study.

5.9.2 Response between seasonal climate and ringwidth

Winter temperature (December-January) and southwest monsoon (June-September) were the seasonal climatic variables which controlled ringwidth the most in the study sites. Ringwidth was found to be related with southwest monsoons by different studies in teak from peninsular India (Sinha *et al.*, 201; Deepak *et al.*, 2011, Babu *et al.*, 2015, Ram *et al.*, 2008, Ram *et al.*, 2011). The amount of water received during monsoon months (JJAS) is highest which moderates the temperature during these months and accelerates the photosynthesis. As this is the peak growing season of teak (Chowdhury 1964), monsoon rainfall shows significant positive relationship with tree-ring variations.

5.9.3 Response between monthly temperature and ring width

The monthly temperatures for January and previous June were monthly temperature variables that created more response in ringwidth. Borgaonkar *et al.* (2010) observed that although temperature is an important parameter in the relationship between tree growth and climate, a direct influence of temperature is not evident in their study of teak from Kerala. To study the exact role of moisture (as a function of temperature and precipitation) in the tree growth process, Borgaonkar *et al.* (2010) used seasonal Palmer Drought Severity Index (PDSI) for was used. PDSI is a meteorological drought index. It represents regional change in the water-holding capacity of the soil and responds to weather conditions that have been abnormally dry or wet. The significant positive relationship of ringwidth with PDSI of lag-1 and the current monsoon season (JJAS) indicates moisture dependence of tree growth in Kerala.

5.9.4 Response between monthly rainfall and MVA

Mean vessel area responded to monthly rainfall for months previous June, previous September, previous November and current May. Vessel chronologies from Thailand also responded to April and May rainfall (Pumijumnong and Park, 1999). Analysis of MVA/climate relationship at Parambikulam, Kerala shows that the MVA is positively correlated with the precipitation of April of the current year (Shah *et al.*, 2007). The amount of variance explained by climate was 57.15%. Several studies clearly demonstrate that previous year's growth has a major role in the growth of earlywood of subsequent years (Fritts, 1976). Positive correlation with the precipitation of April of the current year suggests that precipitation plays an important role in the development of vessels. Earlier, increased temperature during pre-monsoon month was recorded to have an important role in the initiation of cambial activity (Chowdhury, 1940). However, the present study suggests that water plays a significant role in the growth or expansion of vessel size.

5.9.5 Response between seasonal climate and MVA

Seasonal climate which showed responses were of southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Analysis of MVA/climate relationship at Parambikulam, Kerala shows that the MVA is positively correlated with the precipitation of October and November of the previous year (Shah *et al.*, 2007). The mean lumen area of earlywood vessels in oak was smaller in drought years. Vessel lumen area is an indicator of the water availability at the time of cell differentiation (Eilmann *et al.*, 2006)

5.9.6 Response between monthly temperature and MVA

Mean vessel area responded to monthly temperatures of previous August, current May and December. In Thailand, June temperature produced negative response in mean vessel area of teak (Pumijumnong and Park, 1999). Also, a weak positive effect of temperature in both March and May was observed in chestnut García-gonzález and Fonti, 2004). In *Castanea sativa*, mean monthly temperature and mean vessel lumen area were most closely related to March and June temperature (Sass and Eckstein, 1995). Increased temperature during pre-monsoon month was found to have an important role in the initiation of cambial activity (Priya and Bhat, 1999).

5.10 Dendroclimatic reconstruction

5.10.1 Climatic reconstruction from ring width

Rainfall pattern was reconstructed for previous July, previous December and October from ring width. Winter temperature (December-January) and southwest monsoon (June-September) were also reconstructed from ring width. The monthly temperatures for January and previous June were also built. Shah *et al* (2007) reconstructed June–September precipitation of Hoshangabadh, Madhya Pradesh for 1835 to 1997 using teak tree rings. Therrell *et al.* (1999) reconstructed rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* from Zimbabwe. Borgaonkar *et al.* (2010) reconstructed El Niño and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L.f.) trees from south India.

5.10.2 Climatic reconstruction from mean vessel area

Monthly rainfall for months previous June, previous September, previous November and current May were reconstructed from mean vessel area. Seasonal climates reconstructed were southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Monthly temperatures reconstructed were of previous August, current May and December. Based on mean vessel area Bhattacharyya *et al* (2007) reconstructed the northeast monsoon of Parambikulam, Kerala, which extends from AD 1743 to 1986. However, except a few from the tropical region, application of vessel parameters in these aspects has been assessed mostly from temperate and Mediterranean hard wood (Sass and Eckstein, 1995).

5.11 Conclusion

The present study revealed that statistical parameters like Signal to Noise Ratio (SNR) and Expressed Population Signals (EPS) of all chronologies have desired levels and the sites have good dendroclimatic potential. Both temperature and rainfall influenced growth parameters viz., Ring Width and Mean Vessel Area (MVA). There are significant responses of ring width and MVA to climate in teak. Ring width is more related with rainfall during previous southwest monsoon, current south west monsoon and winter rainfall but temperature has negative influence on ring width formation except in north east monsoon and winter seasons. Vessel formation has significant correlations with both monsoons, but it is more influenced by temperature during previous south west monsoon and current southwest monsoon. Rainfall in previous southwest monsoon and current northeast monsoon influence MVA. More chronologies from different sites will help in understanding past monsoon variability in a bigger picture and thereby making climate-growth predictions.

6. SUMMARY

SUMMARY

Dendroclimatological investigations on 23 plantation grown teak (*Tectona grandis*) trees of 64 to 140 years age from Edakkode, Kanakuthu and Conolly's plot of Nilambur (North) division forest of Kerala were conducted in the Department of Wood Science, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur. Results of the investigations are summarised below.

1. The highest air dry wood density among the three sites was at Conolly's plot (0.84 g/cm^3) and was least at Edakkode (0.73 g/cm^3)

2. The heartwood to sapwood ratio was highest in Conolly's plot (6.99) followed by Kanakuthu (5.71) and Edakkode (4.81). The heartwood percentage also followed the same trend.

3. Average raw ring width obtained were highest in Edakkode and lowest in Conolly's plot. Earlywood was the highest at Edakkode followed by Kanakuthu and Conolly's plot. Latewood ringwidth also followed the same pattern.

4. The mean vessel area (total, early and late) was high at Conolly's plot. Latewood vessel area was high at Edakkode, while earlywood showed second highest values at Kanakuthu.

5. Earlywood vessel frequency was highest at Edakkode followed by Kanakuthu and Conolly's plot. The latewood vessel frequency was highest at Edakkode followed by Conolly's plot and Kanakuthu. The totalwood frequency was also highest in Edakkode followed by Conolly's plot and Kanakuthu.

6. The vessel diameter of Conolly's plot was highest among the three sites for earlywood, latewood as well as totalwood. Edakkode had the second highest values for earlywood and totalwood and least value for latewood.

7. The Edakkode ring width index chronology showed highest mean correlation among all radii followed by Kanakuthu and Conolly's plot chronologies. The mean correlation between trees was high in Conolly's plot ring width index chronology, followed by Edakkode (0.493) and Kanakuthu chronologies.

8. The value of Signal to Noise ratio (SNR) is moderately high for all the four ring width index chronologies with the highest SNR for Kanakuthu (2.95) followed by Edakkode (2.22) and Conolly's plot (1.09) implying the dendroclimatic potential of the sites.

9. The value of Expressed Population Signal (EPS) is also moderately higher for all the ring width index chronologies. All chronologies have the acceptable range of EPS values such as 1.02 for Kanakuthu, 1.02 for Edakkode and 1.10 for Conolly's plot ring width index chronology implying the reliability of population for further dendroclimatic analysis.

10. In the case of mean vessel area index chronology, Kanakuthu showed the highest mean correlation among all radii, followed by Edakkode and Conolly's plot chronologies. The mean correlation between trees was highest at Edakkode followed by Kanakuthu and Conolly's plot mean vessel area index chronologies

11. Rainfall in the months previous July, previous December and current October showed more response at the study sites. Winter temperature (December-January) and southwest monsoon (June-September) were the seasonal climatic variables which controlled ring width at most of study sites.The monthly temperatures for

January and previous June were monthly temperature variables that created more response in ring width.

12. Mean vessel area responded to monthly rainfall for months previous June, previous September, previous November and current May. Seasonal climate which showed responses were southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Mean vessel area responded to monthly temperatures of previous August, current May and December.

13. Rainfall was reconstructed for the months, previous July, previous December and October. Winter temperature (December-January) and southwest monsoon (June-September) were reconstructed from ring width for the corresponding years.

14. Monthly rainfall for months previous June, previous September, previous November and current May were reconstructed from mean vessel area. Seasonal climates reconstructed were southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Monthly temperatures reconstructed were of previous August, current May and December.

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

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ABSTRACT

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ABSTRACT

A study was conducted on teak (*Tectona grandis* L. f.) grown in plantations at Nilambur (North) forest division with the objectives of analyzing tree-ring chronologies to find out their dendroclimatic potential and the tree growth-climate relationship and also to 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. In order to achieve the above objectives, cross sectional discs were collected from sites located in Edakkode, Kanakuthu and Conolly's plot. The average ring width and MVA of each year obtained from the different radii were used to cross date and construct the chronology using the TSAP Win software. A cubic smoothing spline was used for standardization of the tree ring data using the software ARSTAN. Bootstrap correlation and response function analyses were carried out with moving intervals to find out tree growth-climate relationship using DENDROCLIM was performed. Statistical parameters such as Signal to Noise Ratio (SNR) and Expressed Population Signals (EPS) of all chronologies have desired levels and the sites had good dendroclimatic potential. Ring width and MVA chronologies of teak for the Nilambur region were developed.

Rainfall in previous July, previous December and current October were correlated with ring width. Winter temperature (December-January) and southwest monsoon (June-September) were the seasonal climatic variables that mostly controlled ring width in the study sites. The monthly temperatures for January and previous June created major response in ring width. Mean vessel area responded to monthly rainfall for months previous June, previous September, previous November and current May. Seasonal climate which influenced vessel area were of southwest monsoon (June-September) temperature and rainfall and northeast monsoon (October-November) rainfall. Mean vessel area responded to monthly temperatures of previous August, current May and December. Using transfer functions climatic data for months and seasons with highest response and the period which is not available (1870-1900) from the instrumental record were reconstructed from tree ring data.